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HEAT TRANSFER STUDIES ON CANNED PARTICULATE NEWTONIAN FLUIDS SUBJECTED TO AXIAL AGITATION PROCESSING

By

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HEAT TRANSFER TO CANNED PARTICULATE NEWTONIAN FLUIDS

ABSTRACT

Heat transfer to canned particulate laden Newtonian fluids was studied during free axial agitation thermal processing in a pilot STOCK retort which was modified to simulate the can motion in continuous turbo cookers. Evaluation of heat transfer coefficients (overall, U and fluid to particle, h_{fp}) associated with canned liquid /particle mixtures, while they are subjected to free axial motion is difficult because of the problems involved with attaching temperature measuring devices to liquid and particles without affecting their normal motion. A new methodology was developed to evaluate Uand h_{fp} in Newtonian liquids. The methodology involved first correlating U and h_{fp} as a function of input variables for cans in fixed axial mode of rotation in which both particle and fluid temperatures were measured using thin wire thermocouples. Subsequently, only liquid temperatures were measured in cans using wireless sensors in the free axial mode, and h_{fp} values were empirically computed from the developed correlations and the measured temperatures. An L-16 orthogonal experimental design of experiment was carried out to select system and product parameters that significantly influence h_{fp} and U for particles in the Newtonian liquid. With significant parameters selected, a response surface methodology and two full factorial experimental designs were used to relate Uand h_{fp} to process variables in each mode of rotation (fixed and free axial modes).

Dimensionless correlations were then developed using the evaluated data for heat transfer coefficients (*U* and h_{fp}), in canned high viscosity Newtonian liquids (with and without particles) using stepwise multiple non-linear-regressions of significant dimensionless groups. In free axial mode, combining the natural and forced convection, Nu = A₁(Gr×Pr)^A₂₊ A₃(Re)^A₄ (Pr)^A₅ Fr^A₆ (ρ_p/ρ_1)^A₇ (e/100-e)^A₈ (d_p/D_c)^A₉ (K_p/K_l)^A₁₀ yielded a higher R^2 (0.93) than using a pure forced convection model when particles were present in the can. Even in the absence of particles, and with the end-over-end mode of agitation where forced convection dominates, introducing natural convection term (Gr×Pr), improved R^2 from 0.81 to 0.97. Artificial neural network (ANN) models were also developed for heat transfer coefficient predictions and the trained models gave better predictions than dimensionless correlations. All ANN models developed could be implemented easily in a spreadsheet as either matrices or a set of equations.

RÉSUMÉ

Le transfert thermique aux fluides newtoniens chargés de matières particulaires, situés dans des boîtes de conserve, fut étudié durant un transformation par traitement thermique sous agitation en axe libre, dans une autoclave-pilote STOCK. Celui-ci fut modifié de façon à simuler le mouvement des boîtes dans un cuiseur-turbo à mode continu. L'évaluation des coefficients de transfert de chaleur (global, U et de fluide à particule, h_{fp}) associés aux mélanges liquide/particule en boîte de conserve, quoiqu'ils soient assujettis à un mouvement axial libre, s'avère problématique face aux difficultés techniques qui se présentent lorsqu'on essaie de mesurer la température des liquides et particules sans enfreindre leur mouvement normal. Une nouvelle méthode fut développée permettant d'évaluer U et h_{fp} dans des liquides newtoniens. Celle ci nécessita d'abord de corréler U et h_{fp} en fonction des variables d'entrée pour des boîtes de conserve en rotation axiale fixe, pour lesquelles les températures de particules et fluides furent mesurées avec des thermocouples en fil fin. Plus tard, seules températures du liquide furent mesurée dans des boîtes de conserve subissant une transformation en mode axe libre, et les valeurs de h_{fp} furent calculées empiriquement à partir des corrélations ayant été développées par rapport aux températures mesurées. Un plan d'expérience orthogonal L-16 servit à sélectionner les paramètres de production ayant une influence significative sur les valeurs de h_{fp} and U pour des particules dans un fluide newtonien. Les paramètres significatifs ayant été sélectionnés avec une méthode par surface des réactions, les données provenant de deux plans expérimentaux factoriels complets servirent à lier U et h_{fp} aux paramètres de traitement pour chaque mode de rotation (axe fixe ou libre).

Utilisant une régression non linéaire multiple pas à pas de groupes non-dimensionnels significatifs, des corrélations non-dimensionnelles furent développés, pour des fluides newtoniens à viscosité élevée dans des boîtes de conserve (avec ou sans particules), à partir des données ayant servi à évaluer les coefficients de transfert de chaleur (U and h_{tp}). En mode axial libre, combinant la convection Nu = A₁(GrPr)^A₂₊A₃(Re)^A₄ (Pr)^A₅ Fr^A₆ (ρ_p/ρ_l)^A₇ (e/100naturelle forcée obtient: et on e)^A₈ $(d_p/D_c)^{A_9} (K_p/K_l)^{A_{10}}$ ce qui donna, lorsque des particules furent présentes dans la boîte, un R^2 (0.93) plus élevé qu'avec un modèle considérant seulement la convection forcée. Même en absence de particules, et avec un mélangeur à tambour vertical où la convection forcée prédomine, l'introduction du terme de convection naturelle ($Gr \times Pr$), améliora le R^2 de 0.81 à 0.97. De plus, des modèles à réseau neuronal (MRN) furent développés afin de prédire les coefficients de transfert de chaleur. Ces MRN, lorsque entraînés, donnèrent de meilleurs prédictions que les corrélations non-dimensionnelles. Tous les MRN développés purent facilement être mis en application dans une feuille de calcul électronique en forme de matrice ou d'un ensemble d'équations.

CONTRIBUTIONS OF AUTHORS

Several presentations have been made based on the thesis research and manuscripts have been prepared for publication. Two authors have been involved in the thesis and their contributions to the various articles are as follows:

Mritunjay Dwivedi is the Ph.D. candidate who planned and conducted all the experiments, in consultation with his supervisor, gathered and analyzed the results, and drafted all the manuscripts for scientific publications.

Dr. H. S. Ramaswamy is the thesis supervisor, under whose guidance the research was carried out, and who assisted the candidate in planning and conducting the research as well as in correcting, editing, reviewing and processing the manuscripts for publications.

LIST OF PUBLICATIONS AND PRESENTATIONS

Part of this thesis has been prepared as manuscripts for publication in refereed scientific journals:

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- **Dwivedi, M.** and Ramaswamy, H. S. 2008. Comparative study of wireless versus standard thermocouples for data gathering and analyses in rotary autoclaves. Journal of Food Processing and Preservation (Accepted).
- **Dwivedi, M**. and Ramaswamy, H. S. 2008. An empirical methodology for evaluating the fluid to particle heat transfer coefficient in bi-axially rotating cans using liquid temperature data. Food Bioprocess Technology (Accepted).
- Ramaswamy, H. S. and **Dwivedi, M**. 2008. Effect of process variables on heat transfer rates to canned particulate Newtonian fluids during free bi-axial rotary processing. Food Bioprocess Technology (Accepted)
- **Dwivedi, M**. and Ramaswamy, H. S. 2008. Dimensionless correlations for convective heat transfer to canned particulate fluids under axial rotation processing. Journal of Food Process Engineering (Accepted).
- Ramaswamy, H. S. and **Dwivedi**, M. 2008. Neural network modeling of heat transfer to canned particulate fluids under axial rotation processing. International Journal of Food Engineering. (Submitted).

Part of this thesis has been presented in scientific conferences:

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- **Dwivedi, M.**, Chen, C. and Ramaswamy H.S. 2005. Heat transfer considerations in thermal processing with container agitation: dual mode axial rotation involving particulates in viscous fluids. Annual Meeting Cincinnati, OH, Nov. 4, 2005.
- **Dwivedi, M.** and Ramaswamy, H. S. 2006. Comparison of heat transfer rates as influenced by modes of rotation, and system and product parameters during agitation processing. IFTPS Annual Meeting, Orlando, FL, Feb. 23-26, 2006.
- Dwivedi, M. and Ramaswamy, H. S. 2006. Comparative study of heating parameters and overall heat transfer coefficients in rotary autoclaves using wireless sensors versus standard thermocouples CIFST - AAFC Joint conference, Montreal, PQ, May 28-30, 2006.
- Dwivedi, M. and Ramaswamy, H. S. 2006. Development of a methodology for evaluation of convective heat transfer coefficients from liquid temperature data in canned liquid/particle mixtures subjected to axial agitation. IFT Annual Meeting, Orlando, FL June 24-28, 2006.
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- Dwivedi, M. and Ramaswamy, H. S. 2008. Dimensionless correlations for convective heat transfer to canned liquid particulate mixtures under axial and end-over-end rotation processing. IFTPS Annual Meeting, San Antonio, TX. Feb. 26 – 29, 2008 [won first place in graduate paper competition].
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4

NOMENCLATURE

A	Surface area, m ²
C_o	Cook value, min
<i>c</i> , <i>C</i> _{<i>p</i>}	Specific heat capacity (J/kg/C)
D	Diameter, m
d_{ch}	Characteristic length, m
D_l	Length of the can, m
d_p	Diameter of particle, m
D_r	Rotation diameter, m
f_h	Heating rate index, min
F_o	Process lethality, min
Н	Head space, m
h _{ap}	Apparent heat transfer coefficient between retort and particle, W/ ($m^2 C$)
h_{fp}	Fluid to particle heat transfer coefficient, W/ $(m^2 C)$
H_s	Headspace, m
j _{ch}	Heating lag factor
L	length, m
m	mass, kg
Ν	rotation speed, rpm
Pt	Process time
R	radius, m
R^2	Coefficient of determination
R_r	Reel radius
RRs	Reel radius of steritort
Т	temperature, °C
t	time, s
T_{ps}	Temperature of particle surface (°C)
U	overall heat transfer coefficient, W/ (m ² C)
U_a	apparent overall heat transfer coefficient, W/ (m ² C)
V	volume, m ³

Subscript

С	Can
FRA	Free axial
Е-О-Е	End-over-end
Fixed	Fixed axial
l	liquid
р	particle
r	retort
S	Surface

Dimensionless groups

(d_p/D_c)	Diameter of particle to can
(K_p/K_l)	Particle/liquid thermal conductivity ratio
(ρ_p / ρ_l)	Relative density of particle to liquid
Fr	Froude number
Gr	Grashof number
Bi	Biot Number
Nu	Nusselt Number
Pr	Prandtl number
Re	Reynolds number

Greek Symbol

W	Can angular velocity
α	Thermal diffusivity, m ² /s
β	Root of the equation: $\beta \cot \beta + B_i - 1 = 0$
3	Particle concentration, % (particle volume/can volume)
μ	Viscosity, Pa s
ρ	Density, kg/m ³
Ψ	Sphericity of the particle (A_{sphere}/A_p)

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CHAPTER 1 INTRODUCTION

Thermal processing, or canning, has proven to be one of the most effective methods of preserving foods while ensuring the product is safe and remains safe from harmful microorganisms. While heat is used to ensure a safe food supply, it can also have effects on the sensory characteristics of the product, such as color, texture and nutritional value. For products heated by convection, such as soups, sauces, vegetables in brine, meat in gravy and some pet foods, high temperature- short time processing (HTST) has proven to be useful in acquiring a balance between a safe product and a product of high quality. This method is successful because, compared with microorganisms, the nutrients in foods have a higher resistance to thermal destruction and a lower sensitivity to temperature changes, making it possible to apply the high temperature short time technique to sterilize the product while retaining high quality (Reuter, 1993). A typical HTST process is aseptic processing and packaging of processed foods. In this system, food products are heated to a high temperature and held for a short time, cooled and then packed into presterilized containers inside a sterile chamber. Since these products are heated outside of the packaging materials, product sterilization is not limited by container configurations and it would thus be possible to optimize / enhance the heat transfer process within the product. Some high efficiency heat exchangers such as plate, tubular and scraped surface heat exchangers have good and rapid temperature equalization inside a narrow flow section. A very short heat treatment is required and the quality can be optimized, however uncertain residence time distribution (RTD) of particles and uncertain fluid to particle heat transfer coefficient (h_{fp}) have limited its use to liquids such as milk and juice and liquids that contain only small particles like that of soups. The technology is yet to be fully realized for canned liquid foods that contain large particles (Ramaswamy et al., 1997). In an effort to solve these problems, several technologies such as microwave and ohmic heating have been used (Willhoft, 1993). HTST processes are not beneficial for conduction-heating food products that heat slowly by comparison, exhibiting large temperature differences between the surface and the center of the container, and so some alternatives have been used to enhance the heat transfer rates in solid and semi-solid

products. Agitating the container to enhance mixing (in particulate fluids which normally heat by conduction) and the use of thin profile packages (retort pouches) are some other approaches used to promote better quality. In these products the overall rate of heat transfer to the packaged food is enhanced either by product mixing or by keeping the heat transfer distance short. Rotary retorts can increase the convection in containers containing liquid-particle mixtures such as high quality peas, corn, asparagus, mushrooms and a variety of semi-solid or viscous foods such as sauces or soups containing meat chunks or vegetables. Rotary processing leads to the rapid heating and uniform temperature distribution inside the product, therefore requiring less energy and shorter process times and providing higher quality retention. Rotary retort processing is more suitable to semisolid products (liquid with particulates) because of the faster heat transfer to the liquid and particles by enhanced convection. Since particulate liquid canned foods are not ideal candidates for aseptic processing, rotary retort processing is a potential alternative to aseptic processing for such products and is not limited by the problems associated with thin profile processing such as slow filling and sealing speed, high manual labor etc., although it needs a special retort in order to agitate the containers.

Presently, designing a thermal process for canned foods in rotary retort processing requires experimentally gathered heat penetration data. Mathematical models based on the heat transfer studies can predict the transient heat penetration of canned foods, hence reducing the number and the cost of the experiments required to achieve product safety and quality (Teixeira *et al.*, 1969). Many thermally processed foods heat by convection to some degree, which can be used to the processor's advantage in reducing process times, increasing production efficiency and in some instances minimizing the ruinous effects of heat. This is achieved by agitating the container of food during the process by agitation, and in doing so, inducing forced convection currents that mix and heat the food more effectively. A key factor in mixing the container's content is the headspace bubble that sits above the food until the container is rotated.

For particulate liquid canned foods in rotary retort processing, both the overall heat transfer coefficient from the retort heating medium to the canned liquid, U, and the fluid to particle heat transfer coefficient, h_{fp} , are needed to predict heat transfer rates to the particle at the coldest point inside the can. Because of the practical difficulty in

monitoring the transient temperature history of the particle moving inside an agitated liquid, the associated h_{fp} is one of the important gaps in our knowledge of heat transfer (Maesmans *et al.*, 1992).

The majority of studies on rotational processing (Conley et al., 1951; Clifcorn et al., 1950; Berry et al., 1979; Berry and Bradshaw, 1980; Berry and Kohnhorst, 1985; Houtzer and Hill, 1977) deal with the effect of agitation on the product's specific heat penetration parameters. Rao and Anantheswaran (1988) provided an overview on Uvalues for canned liquids in rotary retorts. The more recent studies have focused on the fluid to particle heat transfer coefficients, h_{fp} , and overall heat transfer coefficients, U, both of which are important parameters influencing the heating rate of the liquid particulate mixture. A number of studies have been published to evaluate physical parameters that influence the heat transfer coefficients, and it was found that rotational speed, retort temperature, head space volume, system geometry, liquid viscosity, rotation radius, particle size and particle density were all key factors in end-over-end mode (Anantheswaran and Rao, 1985a, 1985b; Ruyter and Brunet, 1973; Naveh and Kopelman, 1980; Sablani and Ramaswamy, 1995, 1996, 1997, 1998; Britt, 1993; Rao and Anantheswaran, 1988; Meng and Ramaswamy, 2007b, 2007c; Lekwauwa and Hayakawa, 1986). Other studies evaluated the effect of E-O-E agitation on nutrient, texture and color retention of the food products (Abbatemarco and Ramaswamy, 1994, 1995).

Some studies (Tattiyakul *et al.*, 2001, 2002; Hughes *et al.*, 2003; Varma and Kannan, 2006; James *et al.*, 2006) used computational fluid dynamics (CFD) as well as experimental work to examine the underlying mechanism of heat transfer in liquid food during rotary processing. Very few studies have been conducted on the determination of U and h_{fp} in free axially rotating cans (Lenz and Lund, 1978; Deniston *et al.*, 1987; Fernandez *et al.*, 1988; Hassan, 1984; Stoforos and Reid, 1992). Furthermore, there were several limitations associated with these methods applied to predict lethality during heating for the real food particle system with finite internal and surface resistance to heat transfer ($0.1 < N_{Bi} < 40$). Therefore, there is still considerable opportunity for further research in this area.

Based on the available knowledge and recognizing the need for heat transfer studies on agitation processing involving canned particulate suspended in Newtonian fluids, the following general objectives were formulated for this study:

- 1. Comparison of heat transfer rates during thermal processing under end-over-end and axial modes of rotation
- 2. Comparative study of wireless versus standard thermocouples for data gathering and analyses in rotary autoclaves
- 3. An empirical methodology for evaluating the fluid to particle heat transfer coefficient in bi-axially rotating cans using liquid temperature data
- 4. Effect of process variables on heat transfer rates to canned particulate Newtonian fluids during free bi-axial rotary processing
- 5. Dimensionless correlations for convective heat transfer to canned particulate fluids under axial rotation processing
- 6. Neural network modeling of heat transfer to canned particulate fluids under axial rotation processing

CHAPTER 2 LITERATURE REVIEW

2.1 Thermal Processing

2.1.1 General overview

In-container and in-flow sterilization are the two major process methods involved in the thermal processing of canned foods (Weng, 2006). Although not discussed here, the in-flow process refers to the aseptic processing and packaging of food. In-container processing, however, generally refers to the canning process where sterilization process takes place after the prepared food is filled and sealed in containers such as metal cans, plastic or glass bottles, retortable pouches or cartons, or rigid and semi-rigid plastic containers.

According to Ramaswamy and Marcotte (2005), thermal processing involves heating foods in hermetically sealed containers for a specific time and temperature to eliminate the microbial pathogens that endanger public health and microorganisms and enzymes that deteriorate food during the storage. Though the term 'sterile' is used often when referring to the thermal process, it is not entirely accurate, for sterile implies the destruction of all viable microorganisms. The term 'commercially sterile' is more suiting, since during the sterilization process the cans are subjected to a process design that kills the microbes linked to spoilage and public health concern and merely limit the growth of all others (especially thermophile) through vacuum sealing, hermetic packaging and moderate storage temperatures. During the twentieth century, the thermal process has been one of the most widely used methods for food preservation, and has had the greatest influence on the nutritional well-being of much of the world's population (Teixeria and Tucker, 1997). Ultimately, the goal of the thermal sterilization process is to produce a product that is safe, of high quality, and at a price the consumer is willing to pay.

2.1.2 Historical Perspectives

Due to their low production costs, convenience and long shelf life, canned foods have been around for many years and will continue to be around for many more. Although the canning process started from Nicholas Appert's time in 1810, food processing via the canning process still provides a universal and economic method for preserving and processing foods.

Although canning was used successfully for 50 years to process foods, it was not implicit until Louis Pasteur in 1864 discovered and understood bacteria and their role in food spoilage. Prescott *et al.* (1987) were able to establish the link between thermophilic bacteria and the spoilage of canned vegetables (Lopez, 1987). The next breakthrough came in 1920, when the classification of microbial spores based on their pH sensitivity to growth and their degree of heat resistance was discovered by Bigelow *et al.* (1920)

In the same year, Bigelow and Ball developed the first scientifically based method for the calculation of the minimum safest sterilization process for the canned foods, and it is still recognized today as the general or graphical method of process calculation. In 1923, Collin Ball continued this work and developed the first mathematical method for process calculations. Following the general process achieved in science and engineering, the process calculations developed quickly with the recognition of the role of mathematical modeling and destruction kinetics.

In 1940, Shultz and Olson developed a nomographic method for process determinations, and in the 1950's Stumbo revised the 'Ball's formula method' and made the process more versatile and accurate, although the general method and formula method are still the basic procedures used for process calculations in the canning industry. In the last 40 years, the mathematical heat process's concepts and determinations have been refined by researchers like Pflug (1968), Hayakawa (1968, 1977), Teixeira *et al.* (1969), Griffin *et al.* (1969a, 1969), Manson *et al.* (1970), Tung and Garland (1979), Ramaswamy *et al.* (1982), Pham (1987). All these attempts have made possible the accurate control of thermal processes and the development of quality assurance procedures and government regulations to further assure the safety of thermal process (Ramaswamy and Marcotte, 2005). Increasing attention is being devoted to this technology from thermal processing specialists to improve both the economy and the quality of canned foods (Durance, 1997).
2.1.3. Principles of thermal processing

An understanding of both the thermal inactivation kinetics of microbial destruction that causes food spoilage (known as the heat resistance of microbes) and the clear understanding of the mechanism of heat transfer that governs the temperature profiles achieved inside the food container (known as heat penetration) is required in order to achieve successful thermal processing. Unlike true sterilization that involves the destruction of all microbes, thermal processing focuses on only destroying pathogenic and spoilage microbes, in order to maintain the highest standards in both safety and product quality. The heat used to destroy the harmful microorganisms is carefully regulated so as to minimize the deterioration of the taste, texture and nutrition of the product being sterilized. In order to determine how long and at what temperature to process each product, the following list of factors must be considered.

- The heat resistance of micro-organisms or enzymes likely to be present in the food.
- The heating conditions and the pH of the food.
- The size of the container and the physical state of the food.

2.1.3.1 Conditions for survival of microorganisms

The thermal processing is used to ensure public health and safety by destroying various microorganisms and enzymes that exist inside the product, and is different for each product depending on what microorganisms may be present. The microorganisms are classified by type depending on their oxygen sensitivity, pH classification and optimum temperature growth. Since obligate aerobes cause food spoilage and are likely to appear with the presence of oxygen in hermetically sealed cans, low oxygen levels are manually produced in these products to thwart these microbes. While this type of harmful microbe can easily be destroyed by heat, there are others like facultative or obligate anaerobes that are far more resilient to heat and can develop even in the absence of oxygen. These obligate anaerobes can grow if conditions are right and release hazardous toxins that may be fatal to humans, and require extra care to ensure their destruction. In Table 2.1 the microbes are classed according to their oxygen sensitivity.

Class	Description	Examples
Obligatory	Require oxygen for growth	Most molds, Micrococcus,
aerobes		Serratia marcescens,
		Mycobacterium tuberclosis
Obligatory	Require absence of oxygen for growth	C. botulinium, C. Sporogenes, C.
anaerobes		thermosaccharolyticum
Facultative	Can grow in the complete absence or	B. coagulans, Staphylococcus
anaerobes	presence of only small amounts of	aureus
	oxygen	

Table 2.1Classification of microorganisms based on their oxygen sensitivity
(Ramaswamy and Marcotte, 2005)

The pH value can also determine what microbes may be present. Low acid food products contain a higher pH than high acid foods and provide a basis for pH classification, which is vital to determining the thermal process requirements. *C. botulinium* is a spore forming anaerobic pathogen that receives special attention from laboratories dealing with thermal processing, since it produces the hazardous and potentially deadly *botulism* toxins, which can cause serious health problems in humans. However, the spores can only produce toxins under favorable conditions, and it is generally accepted that *C. botulinium* cannot produce them when the pH of the food product is below 4.6. Table 2.2 lists the microbes by classification of pH sensitivity. Since spore formers generally grow in low acid foods and are resilient to heat, low acid foods that may provide as hosts are processed at high temperatures of 115 to 125° C. High acid foods, unlikely to contain these microorganisms, are heated at only 80 to 90° C; enough to eliminate other threats.

Besides destroying microorganisms, heat is also used to deter their growth inside the can, since the heat resistance of bacteria is also related to the temperature for their optimum growth. Table 2.3 shows some common microorganism that cause spoilage and lists them based on their temperature and pH requirements. Psychrophilic microorganisms are the most heat sensitive, followed by the mesophiles and thermophiles. Thermophiles such as *Bacillus stearothermophilus*, *B thermoacidurans* and *C. thermosaccharolyticum* are more heat resistant than *C. Botulinium*, which is mesophile in nature. These thermophiles contravene the schedule process which has the optimum growth temperature of $50-55^{\circ}$ C, are not of much concern if the processed cans are stored at temperature below 30° C.

Group	pH	Examples
High acid	<3.7	Fruit juices, apples, berries, cherries (red sour), plums,
		sour pickles, sauerkraut, vinegar
Acid or medium	3.7-4.5	Fruit jams, fruit cocktail, grapes, tomatoes, tomato
acid		juice, peaches, pimientos, pineapples, potato salad,
		prune juice, vegetable juice
Low acid	4.5	All meats, fish, vegetables, mixed entries, and most
		soups

Table 2.2Classification of foods based on pH (Ramaswamy and Marcotte, 2005)

Table 2.3Spore-forming bacteria important in spoilage of food (Ramaswamy and
Marcotte, 2005)

	Acidity of Food		
Approximate Temperature	Acid 3.7< pH <4.5	Low Acid $pH \ge 4.5$	
(°C) Range for Vigorous			
Growth			
Thermophiles	B. coagulans	C. thermosaccharolyticum	
(55 – 35 °C)	S. thermophilus	C. nigrificans	
	L. bulgaricus	B. stearothermophilus	
Mesophiles	C. butyricum	C. Botulinum (A and B)	
(40 – 10 °C)	C. pasteurianum	C. sporogenes	
	B. mascerans	B. licheniformis	
	B. polymyxa	B. subtilis	
Psychrophiles $(35 - \langle 5^{\circ}C \rangle)$	Pseudomonas	C. botulinum E	
	Micrococcus	S. aureus	

Above 30°C, microorganisms like *Bacillus stearothermophilus*, *B.* thermoacidurans and *C*, thermosacaccharolyticum will grow and eventually cause the can to swell and burst. Figure 2.1 describes a step by step establishment of a basic thermal process that is used to destroy bacteria like the ones mentioned above and bring them to a predetermined, economically viable level.



Figure 2.1 Schematic of thermal processing principles (Ramaswamy and Abbatemarco, 1996)

2.1.3.2 Microbial Inactivation kinetics

It is important to know before hand the thermal destruction rate of the test microorganisms or enzymes under the prevailing conditions in the can in order to establish an appropriate thermal processing schedule at a specified temperature. The temperature dependence of the microbial destruction rate or the enzyme inactivation rate is also vital in order to integrate the destruction effect through the specified temperature profiles, particularly due to the come-up-time (CUT) which is needed to attain the processing temperature. Earlier evidences support that the inactivation of microorganisms followed the first order reaction kinetics (Equation 2.1), represented by the following form:

$$\ln(N/N_o) = -kt \tag{2.1}$$

This can also be expressed as:

$$\log_{10}(N/N_{o}) = -kt/2.303 \tag{2.2a}$$

or

$$N/N_o = e^{-kt} \tag{2.2b}$$

For microbial inactivation, the number of organisms, N_o at time zero and N at time t, is used as a measure of concentration.

Survival Curve and Decimal reduction time

Represented as a straight line (also known as survivor curve) in Figure 2.2 is the semi-logarithm plot between the numbers of microorganisms surviving or remaining in a given heat treatment and the heating time at a specified temperature. The standard convention in thermo bacteriology has been used to define a decimal reduction time D, which is the heating time in minutes to give an anticipated inactivation of 90 % of microorganisms, or 10 % survival (Ramaswamy and Marcotte, 2005). On a graph, this represents the time during which the survival curve passes through one logarithmic cycle (Figure 2.2) The value of D is mathematically expressed as follows:

$$D = \frac{t_2 - t_1}{\log\left[\frac{N_1}{N_2}\right]}$$
(2.3)

Where, N_1 and N_2 represent the microbial population at two different time, t_1 and t_2 , in minutes respectively.



Figure 2.2 A typical survivor curve

Thermal death time (TDT)

The thermal death time, or TDT, is used in food microbiology, and its approach is contradictory to that of the logarithmic destruction approach (the survivor curve). It represents the time it takes to completely eliminate the microbes by heat, and it can be obtained by subjecting the microbes to a series of heat treatments of a certain temperature, then testing for survivors. The difference between the shortest destruction time and the longest survival times is either reduced sequentially or geometrically averaged to the estimated TDT data. In this case, the death of the microbes also refers to the failure of the microbes to show growth in the subculture media after the heat treatment. When comparing the TDT approach with the logarithmic destruction approach, it is clear that the value of the TDT is dependent on the initial microbial load, where the D value in the survivor curve does not. Also, always being measured with reference to the standard initial load of the load reduction makes the TDT value simply a multiple of D. For example, TDT represented the time needed to reduce the microbial population

from 10^{12} to 10^{0} , and then TDT is a measure of 12-D values and can be mathematically illustrated as:

$$TDT = nD \tag{2.4}$$

Where, n is denoted as the number of decimal reductions.

Generally the difference in the values of the TDT and D in the survivor curve is attributed to the lag at the start of the heating period when the first order behavior does not fit the observed data and, more frequently, a deviation from first order accounts at the tail end of the survivor curve, referred to as 'tailing'. Stumbo (1973) detailed in his book *Thermo bacteriology in Food Processing*, several factors that caused apparent deviations of the logarithmic order of microbial death and showed typical survivor curves for each situation. He cited things like the heat activation for spore germination, mixed flora, clumped cells, flocculation and deflocculation during heating, the nature of the subculture medium and anaerobiosis. He also summarized various factors that influence the heat resistance of bacteria, including conditions like temperature, ionic environment, organic compounds, lipids and age or phase of growth which are present during sporulation, and conditions present during heat treatment like pH and buffer components, iconic environment, water activity and composition of the medium.

Temperature sensitivity and Z value

Expressed by a thermal resistance curve with log D values plotted on the y-axis and corresponding temperature values on the x-axis, the temperature sensitivity of D must be evaluated, since the D values are largely dependant on temperature. Z is defined as the value that represents a change in temperature resulting in a ten fold change in D values, and is normally used as the temperature sensitivity indicator. Figure 2.3 shows that on a semi-log graph, it is used to represent the temperature range between D values as they pass through one logarithmic cycle. Z value can be obtained as a negative reciprocal slope of the thermal resistance curve when a regression analysis is performed. Z can be mathematically expressed as:

$$z = \frac{T_2 - T_1}{\log \frac{D_1}{D_2}}$$
(2.5)

Where, D_1 and D_2 are the decimal reduction time at temperatures T_1 and T_2 respectively. It is possible to determine D values at any given temperature from a modified form of the above equation, using a reference D value [D_0 at a reference T_0 usually 250 °F (121.1 °C) for thermal sterilization]

$$D = D_0 10^{[(T_0 - T)/z]}$$
(2.6)

Figure 2.3 A typical thermal resistance curve

Process Lethality (F_o value)

Lethality, or F_o value, measures the process of sterilization of a product, and for the purposes of comparing the relative sterilization capacity of the heat process it is defined as a corresponding heat time F_o at a given temperature (generally 121°C for the sterilization process). For this reason, the F_o value would represent a certain multiple or fraction of the D value, depending on the type of microorganism, and can be further explained by the following equation:

$$F_0 = F \times 10^{\frac{T - T_0}{z}}$$
(2.7)

Where F is the heating time at temperature T and T₀ is the reference temperature, an F value of ten minutes at 115°C is equivalent to an F_o value of 2.78 minutes, and the same F value at 125°C is the equivalent of 27.8 minutes when z is 10°C. During a real thermal process, the heating of a food product to the appropriate temperature and the subsequent cooling do not happen instantaneously. The lethal effects through the various combinations of time and temperature are called process lethality, and can be represented by F_o .

Minimal microbial lethality at the thermal center is crucial for safety, while from a quality perspective it is more advantageous to minimize the destruction due to heat throughout the container. The F_o , or minimal process lethality should be based on both the destruction of microbes hazardous to public safety and the reduction in the amount of bacteria that cause spoilage. In products of low acid content, *C. botulinum* is the greatest threat, and therefore the minimal processing lethality is based on the conditions for the destruction of this microbe. It has also been randomly established that the minimum process should be at least as severe to reduce the population of this microbe through 12 decimal reductions (bot-cook). A decimal reduction time of 0.21 to 0.25 minutes at 121.1°C (250°F) is normally assumed for *C. botulinum* based on the information published by Stumbo (1973).

In this case, twelve decimal reductions would be equivalent to F_o value of 12 x 0.21 = 2.52 minutes, and is therefore the minimal process lethality required even though many low-acid foods are processed beyond this minimum. This is done due to the growth of microorganisms that are not of public health concern. The average D_o of these microorganisms that cause spoilage can be as high as one minute, and even with an F_o value of five minutes the process would only be enough to achieve a 5-D process for these particular microbes. It is, therefore, essential to control the raw material quality to keep the initial count of these organisms below 100 per container on average, if the spoilage rate were to be kept below 1 can in a 1000 (10^2 to $10^{-3} = 5$ D).

Cook Value

Another closely related parameter for evaluating a thermal process impact on food is the cook value. Cook value is the measure of heat treatment with respect to nutrient degradation and textural changes that occur during processing. It is given by:

$$C_0 = C \times 10^{\frac{T_{ref} - T_0}{z_c}}$$
(2.8)

Where T_{ref} is the reference temperature of 100°C and z_c is usually taken as 33°C, which is the thermal destruction rate for quality factors analogous to *z*-factor for microbial inactivation. A similar equation has been developed for pasteurization value but with a different reference temperature and *z* value.

2.1.3.3 Characterization of Heat penetration Data

To establish a thermal process schedule of the canned food product, heat penetration tests are performed, and in addition to thermal resistance the characteristics of the test microorganism (z and F_o) is determined. Copper-constantan thermocouples are inserted into the product center through the wall of a can going through the process to gather information on the product temperature history (Figure 2.4).



Figure 2.4 A typical heat penetration curve

The accuracy of the time-temperature profile obtained will depend on the physical and thermal properties of the food product itself, the size and shape of the container and the retort operating conditions. It is therefore imperative that the cans used in the tests are as close to the commercial product that they can be. The process time is calculated by determining heating and cooling rate indices such as f_h , f_c , j_{ch} and j_{cc} from the heat penetration curve obtained. It has been proven that on a linear scale, when the logarithm of the temperature difference between the retort and the product center known as temperature deficit (T_r -T) is plotted against time, creates a straight line after an initial lag. The intercept can be obtained by extending this straight line portion of the curve to the Yaxis representing T_{pih} and is used in the following equation to calculate

$$j_{ch} = \frac{T_r - T_{pih}}{T_r - T_{ih}}$$
(2.9)

In this equation, j_{ch} is the heating lag factor, which is a measure of the thermal lag (or delay) of the beginning of uniform heating in the product. Corresponding values during the cooling are called cooling lag factor or j_{cc} . This factor helps to account for the contribution of cooling lethality to the process calculation and is derived from a semi log plot of the cooling curve.

$$j_{cc} = \frac{T_w - T_{pic}}{T_w - T_{ic}}$$
(2.10)

Part of the lag is due to the slow come-up time of the retort and this is accounted for by determining the new zero time for the process. Ball and Olson (1957) used 58 % of the come-up time as a useful contribution to the process and is widely accepted (Holdsworth, 1977). This implies that 42 % of the come up time should be added to the process time at retort temperature.

The slope of the line (Figure 2.5) demonstrates the time for the curve to traverse one log cycle. The negative reciprocal of this slope is referred to heating rate index (f_h) and is an indicator of the heating rate. The higher the value the longer it takes for the log to traverse one cycle indicating a lower rate of penetration of heat into the product.



Figure 2.5 Heat penetration parameters

The corresponding value for the cooling period is the cooling rate index (f_c) (Figure 2.6).



Figure 2.6 Cooling Curve

2.1.3.4 Thermal process calculations

There are two widely accepted methods for using the data from the heat penetration curve obtained from the laboratory heat penetration data or predicted by a computer model in order to perform thermal process calculations. The process calculation methods are broadly divided into two classes: (1) General methods and (2) Formula methods.

General method

The general method of process calculation is universally acceptable for any type of thermal processing since it is the most versatile. As originally established, the method is a graphical procedure for integrating the lethal effects of the time-temperature profile of the test products under specified processing conditions, and the following describes the calculation procedure. The requirements are the kinetic data (a reference TDT and z value) related to the target microorganism, the representative product heat penetration data and either the required sterilization value of the process for calculating process time, or the process time for calculating the sterilization value. The sterilization is the measure of heat penetration severity. Bigelow (1920) defined the reciprocal of TDT in this method as the lethal rate at the corresponding temperature.

The area under the lethal rate curve obtained when plotting the lethal rate against the heating time will yield the sterilization value of the process. A unit value of sterilization is the minimum requirement with respect to the target microorganism, and if the sterilization value is either greater or smaller than the desired value, a new one is obtained by re-doing the process after manually shifting the cooling curve to the left or right. This is done until the desired sterilization value is met and the corresponding process time is noted. The F_o value is calculated by the basic general method and is used to compare the performance of the formula methods. It is to be noted that while the results of the general method are very specific to the product under the conditions employed for testing, extrapolations and generalizations should be avoided. An improved general method was developed by Ball (1923), and calculated the process lethality value, F_o at the reference temperature, T_o with graphical or numerical integration of Eq. 2.11.

$$F_o = \int 10^{(T-T_o)/z} dt$$
 (2.11)

Formula method

Several formula methods have been developed since the method was first established by Ball (1923). These methods are easier and quicker to estimate the process time or accumulated lethality under a given processing conditions. The Ball formula method is the simplest and most widely used technique for process calculations. In order to estimate the Ball process time, B (min), the following equation was derived from the heat penetration curve:

$$B = f_h \log\left(\frac{j_{ch}I_h}{g_c}\right) \tag{2.12}$$

Where, B is the process time, f_h is the heating rate index, j_{ch} is the lag factor, I_h is the initial temperature difference $(T_r - T_i)$, and g_c is the temperature difference at the end of the cook $(T_r - T \text{ at } t = B)$, T_r is the retort temperature, and T_i is the initial product temperature. The determination of g_c is the key to estimate the process time. Ball provided the relationship between f_h/U and g_c in the form of a Table as well as figure format. U is obtained as the product of the desired process lethality (F_o) and F_i and numerically expressed as:

$$U = F_o F_i \tag{2.13}$$

$$F_i = 10^{\frac{250-T_r}{z}}$$
(2.14)

 F_i is the number of minutes at the retort temperature equivalent to 1 minute at 250 °F. In deriving these relationships, Ball assumed that one of the primary limitations of this method is the use of a constant cooling lag factor (j_{cc}) of 1.41 at z = 18°F and $f_h = f_c$.

Taking into account the variability of j_{cc} values, Stumbo and Longley (1966) published several tables for process evaluations to overcome the above mentioned limitations. The new Stumbo formula is essentially the same as the Ball formula, except that it accounts for the variability of the j_{cc} or the cooling lag factor.

In 1987, Pham developed two sets of simple algebraic equations and simplified tables for thermal process calculation- one for $U/f_h > 1$ and the other for $U/f_h < 1$ and claimed that the values obtained from his method were at least as accurate as Stumbo's. Moreover, he claimed that his was more versatile as well, since the one table developed by his procedure replaced the 57 tables published by Stumbo. This method could be used

for mass-average lethality, similar to Stumbo's method (1973). Recently, Pham amended his equations to cover situations where the heating and cooling rates were not equal (Pham, 1987), and the accuracy of the modified formulae was reported to be as good as the ones reported for $f_h = f_c$ situations.

2.2 Types of retort

2.2.1 Still retorts: A still retort is a batch type, vertical or horizontal, non-agitating pressure vessel, used for processing food packaged in hermetically sealed containers. Generally containers are stacked into racks, baskets or trays for loading and unloading the retort. The high temperature required for sterilization is obtained from steam or super heated water under pressure.

2.2.2 Agitating retorts: Mechanical agitation is commonly used to improve the rate of heat transfer in the product being processed. Rotational retorts have tremendous advantages over still retorts for processing of viscous foods in large containers. However, there are still several roadblocks with reference to the repeatability and reproducibility of heat transfer results. Prediction of temperature history in a particle undergoing conduction or convection heat transfer during an agitated cook is a complex phenomenon (Ramaswamy and Marcotte, 2005). Predictable heat transfer rates are necessary in order to produce a high quality product with minimal overcooking and without compromising public health safety. New products, new packages, and new processes demand thorough testing and predictable performance during retorting operations to assure minimal thermal treatments. Head space, fill of the container, solid-liquid ratio, consistency of the product, and the speed of agitation are crucial factors to be standardized in agitated processing, as well as the type of agitation imparted to a can.

Some common types of agitation used are end-over-end, free axial, fixed axial and Shaka system.

2.2.2.1 End-over-end mode: Clifcorn *et al.* (1950) suggested the use of end-over-end (E-O-E) rotation to increase the heat transfer in canned food products. In E-O-E rotation, the sealed can is rotated around a circle in a vertical plane. As the can rotates, the headspace bubble moves along the length of the can

and brings about agitation of the content of the can. Cans in E-O-E mode are placed as shown in Figure 2.7.

2.2.2.2 Free axial mode: Continuous container handling types of retorts are constructed with at least two cylindrical shells, in which processing and cooling takes place (two shells sometimes used for cooling) and cans are subjected to axial agitation. The shell can be used for pressure processing in steam or cooling with or without pressure. The Sterilmatic (JBT Corp., / FMC Corp., San Jose, CA) is an extensively used continuous agitating retort in which an entering can is carried along by a revolving reel. The steritort is a pilot scale simulator of the thermal process in the Sterilmatic series. The motion of a can in a Steritort takes place in three phases consisting of fixed reel, transitional and free reel motion across the bottom of the retort (Figure 2.7). The fixed reel motion takes place over 220° of a cycle, the free rotation over the bottom 100° , and the transitional motion takes place 20° on either side of the free rotation. Some advantages of continuous retorts over batch retorts are increased production rate, reduced floor space (as fewer auxiliary types of equipments are required), reduced consumption of steam and water (caused by regeneration), and reduced labour requirements. Continuous retorts are a system in which the cans entering the retort are indexed into a revolving reel and are moved through the machine in a spiral pattern. Agitation in continuous retort is provided by allowing the cans to roll freely across the bottom of the retort.

2.2.2.3 Fixed axial mode: In fixed axial rotation, the sealed can is rotated around a circle in a horizontal plane in a single direction (Figure 2.7). As the can rotates, the headspace bubble moves along the length of the can and brings about agitation of the can contents. Naveh and Kopleman (1980) measured the heat transfer rates for a variety of rotational configurations, including head space and rotational speed. Their findings revealed that the heat transfer coefficient (U) in end-over-end rotation was two or three times greater than in the case of axial mode of rotation for high viscosity fluids, which were used over a wide range of rotational speeds. However, their findings were based on fixing the cans horizontally and were subjected to a fixed axial rotation (not in free axial mode).

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2.2.2.4 Shaka system: Shaka technology is a method of batch retorting in which packaged foods, pharmaceuticals or nutraceuticals are rapidly agitated during the retort process. When using Shaka technology, a retort is filled with containers which the retort then shakes vigorously in a back-and-forth motion (Figure 2.7), mixing the container contents thoroughly and allowing for rapid and even heat transfer throughout. Results seem to indicate that for several traditional canned products, heat transfer rates can be greatly improved even in comparison with rotary agitation. The mechanism for this extra efficient agitation is presumably the greater turbulence inside the packaged fluids compared with the agitation induced by rotary motions (May, 2001).



Figure 2.7 Placements of can in different modes inside STOCK retort X. E-O-E Mode Y. Free Axial mode Z. Fixed axial mode



Figure 2.8 Shaka system with back and forth motion

2.3 Heat transfer to canned particulate liquid foods in cans: U and h_{fp}

During the agitation process, the heat transfer process is governed by an unsteady state due to the transient changes in the temperature of the product inside the can. The heating process can be treated as two connected stages, acting on the assumption that the heat the particles receive is from the liquid surrounding them and not from contact with the can wall. The first stage involves the heating of the liquid inside the can from the heating or cooling medium inside the retort. When the heating medium is a liquid, the heat transfer mode in this stage is convection + conduction + convection, and when the heating medium is saturated steam, the heat is transferred by condensation on the outer surface of the can, which offers no resistance to heat transfer (Holdsworth, 1997). With other heating media, the main mode of heat transfer is convection on the outer surface of the wall, and heat resistance must be taken into consideration. After this, the heat is transferred through the wall by conduction; for a metallic container of normal thickness and high thermal conductivity, there is little if any resistance to heat transfer, while glass bottles and plastic containers may offer more resistance. The final part of this stage is when the heat transfers from the interior wall of the can to the liquid by means of convection. This whole process is represented by U, the overall heat transfer coefficient, and is used to describe the temperature exchange between the heating or cooling medium to the liquid inside the can. The second stage is heat transfer to the particle from the

liquid. In this stage heat transfer mode is convection + conduction. Heat is transferred from the liquid inside the can to the particle surface by convection, and then transferred to the particle center by conduction. It is normally expressed by h_{fp} , which is the fluid to particle heat transfer coefficient. In the case of particulate liquid canned foods, heat transfer coefficients U and h_{fp} have been considered crucial for heat transfer models (Deniston *et al.*, 1987). Most heat transfer studies focused on the quantification of U and h_{fp} (Lenz and Lund, 1978; Lekwauwa and Hayakawa, 1986; Deniston *et al.*, 1987; Fernandez *et al.*, 1988; Stoforos and Merson, 1990, 1991, 1992 and Sablani and Ramaswamy, 1995, 1996, 1997, 1998, 1999).

2.4 Determination of U and h_{fp}

The proper estimation of U and h_{fp} under simulated processing conditions is vital for the accurate prediction of the temperature at the particle center. The temperature responses of the particle and liquid under initial and boundary conditions are traditionally used to determine U and h_{fp} (Maesmans et al., 1992), and the temperatures are measured by using thermocouples. Should the particle be attached too firmly inside the can, it will restrict the movement inside the can which would normally take away from real life processing conditions. Since factors like centrifugal, gravitational, drag and buoyancy forces, each and all, can have an effect on the particle motion and therefore U and h_{fp} , to not represent these in a simulation would cause deviations in the measured heat transfer coefficients. Recently, attempts have been made to measure the temperature of a particle moving freely inside a can without inhibiting its natural motion during processing. Aside from the difficulties encountered while trying to measure particle temperature, the governing equation of the energy balance inside the can with both liquid and particles is complex due to time variant temperatures of the canned liquid. The procedures used for the determination of U and h_{fp} are classified into two groups, based on the motion of experimental particle whose temperatures are monitored: (i) fixed particle and (ii) moving particle during the agitation.

2.4.1 Theory for U and h_{fp}

The overall thermal energy balance to a particulate-liquid food system is used to calculate associated convective heat transfer coefficients. The governing equation for heat transfer in such systems can be written as (all symbols are detailed in nomenclature).

$$UA_{c}(T_{R} - T_{l}) = m_{l}C_{pl}\frac{dT_{l}}{dt} + m_{p}C_{pp}\frac{dT_{p}}{dt}$$
(2.15)

The following assumptions are made in the solution of above Eq. 2.15: Uniform initial and transient temperatures for the liquid, constant heat transfer coefficients, constant physical and thermal properties for both liquid and particles, and no energy accumulation in the can wall.

The second term of the right hand side of the equation is equal to the heat transferred to particles from liquid through the particle surface:

$$m_{p} c_{pp} \frac{dT_{p}}{dt} = h_{fp} A_{p} (T_{l} - T_{ps})$$
(2.16)

Heat penetration by conduction is based on Fourier's equation, established by the French physicist Jean Baptiste Joseph Fourier (1768-1830) and written as

$$\frac{\partial T}{\partial t} = \alpha_p \nabla^2 T \tag{2.17}$$

where ρ is the density (kg/m³), c the specific heat or heat capacity (J/kgC), k the thermal conductivity (W/mC), α , the thermal diffusivity (m²/s), and ∇^2 the Laplace operator, given by

$$\nabla^{2} = \frac{\partial^{2}}{\partial x^{2}} + \frac{\partial^{2}}{\partial y^{2}} + \frac{\partial^{2}}{\partial z^{2}}$$
(2.18)

It is also assumed that the particle received heat only from the liquid and not from the can wall when it impacts, i.e. heat is transferred first from can wall to liquid and then to particle. For example, heat flow in a spherical particle immersed in liquid can be described by the following partial differential equation:

$$\frac{\partial T}{\partial t} = \alpha_p \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right)$$
(2.19)

The initial and boundary conditions are:

$$\Gamma(\mathbf{r}, 0) = \mathbf{T}_{\mathbf{i}} \text{ at } t = 0$$
 (2.20)

$$k_p \frac{\partial T}{\partial r} = h_{fp} (T_l - T_{ps})$$
 at $\mathbf{r} = \mathbf{a}$ (2.21)

If the particle and liquid transient temperatures are available, the h_{fp} can be back calculated by solving Eq. 2.19 and using h_{fp} , U can be obtained by solving Eqs. 2.15 and 2.16. The analytical solution for Eq. 2.19, with a convective boundary condition, is complex due to time varying liquid temperatures. Numerical solutions based on finite differences were used to solve this partial differential equation (Teixeira *et al.*, 1969; Weng *et al.*, 1992; Sablani, 1996; Meng, 2006).

2.4.2 Experimental procedures with restricted particle motion

A numerical solution was developed by Lenz and Lund (1978) using the 4th-order Runge-Kutta method and Duhamel's theorem to determine U and h_{fp} for low Biot number (<0.1) situations. To do this they used a lead particle fixed at the center of a can with liquid moving around it and measured its transient temperature, and verified that at all points the particle quickly reached one temperature. They proposed the following solution of Eq. 2.19, for the temperature at any given point in the particle, assuming that the retort temperature reached its operating conditions instantly.

$$\begin{bmatrix} \frac{T_{R} - T}{T_{R} - T_{i}} \end{bmatrix} = \frac{2 Bi}{(r_{a})} \sum_{n=1}^{\infty} \left(\frac{\beta_{n}^{2} + (Bi - 1)^{2}}{\beta_{n}^{2} + Bi (Bi - 1)} \right) \frac{\sin \beta_{n}}{\beta_{n}^{2}} \sin \beta_{n} (r_{a})$$

$$X \left[\exp \left(-\tau_{p} t \right) + \left(\frac{\tau_{p}}{\tau_{p} - \tau_{1}} \right) \left[\exp \left(-\tau_{1} \tau \right) - \exp \left(-\tau_{p} \tau \right) \right] \right]$$
(2.22)

By minimizing the sum of the squared deviations between measured and predicted particle temperature profiles, they estimated h_{fp} . From the above equation they were also able to find the particle's average temperature, and then use it in Eq. 2.15 to calculate the overall heat transfer coefficient.

By integrating Eqs. 2.15 and 2.16 while respectively allowing heating time to approach infinity ($\langle T_p(\infty) \rangle = T_1(\infty) = T_R$), Hassan (1984) was able to derive the following equations for U and h_{fp} .

$$U = \frac{m_1 C_{p_1}}{A_c} \frac{T_R - T_{1i}}{\int_{0}^{\infty} (T_R - T_1) dt} + \frac{m_p C_{pp}}{A_p} \frac{(T_R - T_{pi})}{\int_{0}^{\infty} (T_R - T_1) dt}$$
(2.23)

$$h_{fp} = \frac{m_{p} C_{pp} (\langle T_{p} \rangle_{final} - \langle T_{p} \rangle_{initial})}{A_{p} \int_{0}^{\infty} (T_{1} - T_{ps})}$$
(2.24)

Using an overall heat balance equation and combining it with an equation for the transient heat conduction in a particle, Lekwauwa and Hayakawa (1986) were able to develop a model for cans subjected to end-over-end rotation, and considered the probability function representing the statistical particle volume distribution. Using Duhamel's formula, as well as empirical formulae describing the heat transfer to spherical, cylindrical or oblate spheroidal-shaped particles in a liquid of constant temperature, they were able to obtain the temperature distribution for the individual particles. In their numerical solution, liquid temperatures within each time step were assumed to be a linear function of time, the coefficients of these functions being determined iteratively such that the resulting particle and liquid temperatures satisfied the overall heat balance equation.

Using Eqs. 2.23 and 2.24, Deniston *et al.* (1987) was able to determine U and h_{fp} in axially rotating cans. To satisfy the infinite time limits in the above equations, the heating time of their experiments was long enough to allow the average temperature of both liquid and particle to reach the medium heating temperature, and recognized the errors and difficulties associated with measuring surface temperature using rigid-type thermocouples.

For bean shaped particles in cans processed in an agitated retort, Fernandez *et al.* (1988) were able to determine the convective heat transfer coefficients. In order to give a low Biot number (Bi<0.01) condition, they preferred to use aluminum material with a high conductivity, and for U and h_{fp} evaluations, they used the lumped capacity method. They used rigid thermocouples to measure the time-temperature data for both the particles and the liquid, and solved the heat balance equations by using the scheme developed by Lenz and Lund (1978). In a more recent study, in an attempt to solve the

differential equations governing heat transfer to axially rotating cans containing both liquid and particles, Stoforos and Merson (1995) proposed a new solution. They used an analytical solution of Duhamel's theorem for the particle temperature and a numerical solution based on the 4th order Runge-Kutta scheme for the temperature of the liquid. When they compared predicted values against the experimental data from Hassan (1984), they showed that although it deviated for the particle surface temperature, it showed a good agreement for the liquid temperature, and their solution avoided the need for empirical formulae or a constant heating medium with short time intervals.

2.4.3 Experimental procedure allowing particle motion

Although the particle temperature is difficult to measure due to the problems associated with attaching measuring devices, it is imperative to establish a thermal process. Many researchers, in an attempt to properly monitor particle temperature, have neglected to understand the importance of free particle motion inside the can. Since factors like centrifugal, gravitational, drag and buoyancy forces all can have an effect on the particle motion and therefore U and h_{fp} , to not represent these in a simulation would cause deviations in the measured heat transfer coefficients. Measurements of h_{fp} in a free motion situation, therefore, have been divided into three categories.

2.4.3.1 From liquid temperature only

To estimate h_{fp} for solid particles heated in rotating cans, Stoforos and Merson (1990) proposed a mathematical procedure using the liquid temperature as the only input parameter. They were able to estimate both U and h_{fp} , since the fluid temperature depends on both these coefficients. They had only to systematically vary these two coefficients and minimize the difference between the experimental and predicted liquid temperature to find their two unknowns. The authors reported that the calculated h_{fp} values did not always coincide with those determined from particle surface measurements.

2.4.3.2 Indirect particle temperature measurement

In order to monitor the surface temperature of the particles, Stoforos and Merson (1991) coated their particles with a liquid crystal coating that changed color depending on

temperature, but their experiments were only carried out in the range of 20 - 50 °C. To determine the convective heat transfer coefficients, a combination of time temperature integrators (micro-organisms, enzymes or chemicals) and a mathematical model has been proposed. To gather the temperature history of particles in the pasteurization process, Weng *et al.* (1992) used immobilized peroxidase as a time temperature integrator (TTI). Using α - amylase at reduced water content as a time temperature integrator and residual denaturation enthalpy as response, Haentjens *et al.* (1998) and Guiavarc'h *et al.* (2002b) developed enzyme systems for the purpose of sterilization.

2.4.3.3 Direct particle temperature measurement

In order to measure the transient particle temperature during end-over-end rotation, Sablani and Ramaswamy (1995, 1996, 1997, 1998 and 1999) used a flexible thin wire thermocouple as a measuring device that allowed adequate particle movement inside the can. They were able to study the effects of system parameters on U and h_{fp} based on this technique, and they developed dimensionless correlations and neural network models to predict both U and h_{fp} . The methodology designed by Sablani and Ramaswamy (1996) was used to evaluate the lethality of the particle with the overall heat transfer coefficient U and the fluid to particle heat transfer coefficient h_{fp} , in end-over-end agitation processing of particulate Newtonian fluids. This technique was also used by Meng (2006) to extend the work to other viscous fluids. They adapted it to suit liquids of high viscosity, since previously it was only used in low viscosity situations. When using highly viscous fluids, h_{fp} calculation becomes impractical. In order to predict the temperature lethality of the particle during the process, an apparent heat transfer coefficient, h_{ap} , was proposed and evaluated, and was feasible because of the uniformity in lethality distribution of the liquid even when highly viscous.

2.5 Factors affecting heat transfer coefficients

With enhanced heat transfer rates to both liquid and particle, and the potential to improve quality retention and to reduce processing time, rotary retorts possess several advantages over their still counterparts. The majority of the investigations of convective heat transfer in the presence of the particulate matter focused their attention on the liquid of the canned food (Conley *et al.*, 1951; Hiddink, 1975; Berry *et al.*, 1979; Berry and Bradshaw, 1980; Berry and Dickerson, 1981). From previous studies, it was discovered that the most relevant factors effecting heat transfer rates to liquid particulate canned foods processed under agitation are the mode of agitation, the rotational speed, head space, fluid viscosity, particle size, particle properties and particle concentration (Lenz and Lund, 1978; Hassan, 1984; Lekwauwa and Hayakawa, 1986; Deniston *et al.*, 1987; Fernandez *et al.*, 1988; Stoforos and Merson, 1991; Sablani and Ramaswamy, 1995, 1996, 1997, 1998, 1999 and Meng, 2006). Due to the large variations that characterize the properties of biological systems (foods), many researchers did their studies using model systems.

This section discusses the effects of these various parameters for both liquid and particles during agitation.

2.5.1 Rotational speed: Early literature already documented the impact of rotational speed on heat transfer rates and the resulting processing time (Coonley et al., 1951). In industries, the prediction of time temperature profiles of particles processed in axial or E-O-E rotation is still restricted due to the lack of information of the fluid to heat transfer coefficient, h_{fp} . The heat transfer and the lethality of canned liquid foods containing particles processed in steritort (reel type retort – axial rotation) have been studied by Lenz and Lund (1978), and it was found that changing the reel speed from 3.5 to 8 rpm resulted in an average increase in h_{fp} by 150 W/m²C. Using Teflon, aluminum and potato spheres in cans rotating axially in a simulator, Hassan (1984) measured the convective heat transfer coefficients of all three types of particles, and found that varying the can speed from 9.3 to 101 rpm had more of an effect on U than on h_{fp} but was unable to explain his results. For the potato spheres of 34.9 mm in diameter at a concentration of 30% and for the Teflon spheres at 25.4 mm in diameter at a concentration of 20%, both of which were submersed in water, h_{fp} was reported to be highest at the lowest rotational speed (9.3 rpm). Consequently, it was found that at the highest rotational speed (101 rpm), h_{fp} was intermediate and it was lowest at an intermediate speed of 55.5 rpm (Maesmans et al., 1992). The fluid to particle heat transfer coefficient for potato particles in water during E-O-E rotation was determined by Lekwauwa and Hayakawa (1986), and

it was found that the values of h_{fp} ranged between 60 - 2613 W/ m²C. The heat transfer process of Nylon particles in distilled water and bath oil at a high temperature (100 cst at 38 °C) in end-over-end mode was studied by Sablani (1996). He observed that when the rotational speed increased from 10 rpm to 20 rpm, on average, h_{fp} value increased by 56 % for oil and 53 % for water, and the U value increased by 24 % for oil and 13 % for water.

Stoforos (1988) explained the effect of rotational speed on h_{fp} when he reported that at high speeds (100 rpm) his canned contents behaved as a solid mass and therefore provided little agitation inside the can, and further explained that rpm would affect h_{fp} so long as the increase affected the relative particle to fluid velocity. Stoforos and Merson (1992) showed that by increasing the rotational speed, the U and h_{fp} values could be increased as well. This effect was most notable at lower rotational speeds when using deionized water and silicone fluids together with 1 inch diameter spheres of aluminum or Teflon as liquid/particulate food systems; increasing rotational speed from 9.3 to 101 rpm U increased about 1.2 to 2.0 times. The h_{fp} determined, however, was found to be insensitive to these rotational speeds. Because of the restricted movement of the particles, (due to particle attached to rigid thermocouples) settling effect due to gravity and the centrifugal forces were minimal, the author attributed the unchanging h_{fp} to the small relative particle to liquid velocity. The effect of various parameters on convective heat transfer in axially rotating cans that contained liquid and particulates was studied by Fernandez et al. (1988), and the results were represented in the form of dimensionless correlations. Increasing the Reynolds number, which is based on rotational speed, improved the Nusselt number, which is based on h_{fp} . Meng (2006) reported that while using canned particles/Newtonian fluids in high viscosity glycerin aqueous solutions (from 75 % to 100 %), the effect of rotational speed was significant, and the associated h_{ap} values increased as well.

2.5.2 Fluid viscosity : Hassan (1984) found that increasing the fluid viscosity decreased the overall heat transfer coefficient, and that the same was true for the particle – liquid film heat transfer coefficients, except in the case of large aluminum spheres, (3.17 cm diameter), processed with particle volume fraction ($\varepsilon = 0.21$). For these he

reported increasing values for h_{fp} with increasing viscosity (1.5, 50 and 350 cst), and found by studying the motion of the particle that the particle to fluid relative velocity increased in high viscous fluids. When he compared silicon fluids and deionized water, both containing Teflon particles, he found that the heating rate for the silicon fluids was slower, and he attributed this to the lower thermal diffusivity. Lenz and Lund (1978) found that water had higher values for both U and h_{fp} than a 60% aqueous sucrose solution, and Sablani (1996) studied U and h_{fp} values with Nylon particles in water and oil (100 cst at 38°C), and found that the larger h_{fp} and U values were obtained from water. Sablani (1996) reported in his study with single particle in the Newtonian liquid that the U and h_{fp} values improved with the decrease in liquid viscosity. Using conventional methods for calculating h_{fp} , Meng (2006) computed the heat transfer coefficient and found that the associated h_{fp} values ranged from 215 to 376 W/m²C and U values ranged from 112 to 293 W/m²C. The U values decreased with an increase of the liquid viscosity, which could be explained by the thickness of the associated boundary layer around the particle and inside the surface of the can in higher viscosity fluids.

2.5.3 Mode of rotation: Working with sucrose solutions of Newtonian behavior and carboxy-methyl-cellulose (CMC) solutions of non-Newtonian behavior in a pilot plant spin-cooker-cooler, Quast and Siozawa (1974) reported that the heat transfer rates with axial rotation increased 2 to 4 times compared to stationary processing. During the cooling of tomato paste at 8 to 60 rpm, they further found that the highest heat transfer rates were obtained when there was a 45° angle for the axis of rotation. While working with 84° brix 70 D.E. glucose syrup (a highly viscous liquid) at 20 to 120 rpm, Naveh and Kopelman (1980) noticed the superiority of end-over-end mode when they found that the heat transfer coefficient was 2-3 times higher than that found in axial rotation using stork autoclave positioning the cans horizontally and axially simultaneously, however this study was done using Stork retort, which was not capable of providing similar bi-axial rotation as with FMC continuous sterilizer. Under the intermittent agitation, when the direction of rotation was reversed every 15 to 45 seconds, Hotami and Mihori (1983) reported that heating rates and uniformity were increased and that there was no significant difference between end-over-end rotation and axial rotation. Quast and Sioza (1974) found that there were no significant differences between overall heat transfer coefficients calculated with and without reversing the direction for the CMC experiments. The experimental conditions of their study are unknown, however we can draw the conclusion to the fact that the temperature of the fluid was generally between 69 to 96 °C with a heating medium temperature of 98°C. This means that they used last portion of the heating cycle to calculate the overall heat transfer coefficients and to draw their conclusions. The parameters affecting heating characteristics, however, are generally most predominant at the early stages of the heating where fluid temperature gradients are higher.

2.5.4 Particle concentration: The flow pattern and level of mixing in rotational processing may be influenced by the presence of particulate inside the canned liquid, which also could affect the heat transfer coefficient. The motion of these particles could cause secondary agitation of the liquid, resulting in better mixing and distribution of heat inside the can. The fraction of total effective can volume occupied by the particles is defined as the ratio of the particle volume to the sum of the particle and liquid volume, and can be expressed as ε . Keeping the head space constant at 6.4 mm for 303 × 406 cans closed under 50 cm hg vacuum, Hassan (1984) and Deniston (1984) separately studied the effects of ε on the heat transfer rates. Hassan used Teflon spheres, 2.54 cm diameter in water and reported higher U_o and h_{fp} values, while Deniston (1984) used potato spheres at 2.86 cm in diameter in water processed at 29.1 rpm over a ε range between 0.107 and 0.506 and found that for ε at 0.107, the average U_o values for triplicate experiments was 1300 W/m²C. U_{ρ} exhibited a maximum value of 1640 W/m²C for $\varepsilon = 0.400$ and subsequently U_o declined, having value of 1360 W/m²C at $\varepsilon = 0.506$. Analogous results were observed for the h_{fp} values. At $\varepsilon = 0.107$, h_{fp} was 175 W/m²C, slightly increased up to a value of 190 W/m²C at $\varepsilon = 0.400$, and sharply decreased to a value of 127 W/m²C at $\varepsilon = 0.506$. Deniston *et al.* (1987) summarized that since the spheres were tightly packed in the can, at high ε values the particles were not free to move and the functional dependency of U_o and h_{fp} probably differed compared to loosely packed particles. When the particle concentration was increased from one particle to 29%, Sablani and Ramaswamy (1997) discovered that U increased 20% for oil and 5% for water, but a further increase in concentration to 40% resulted in a decrease of h_{fp} by 12% for oil and 7% for water. Meng (2006) used Nylon particles at 22.225mm in diameter to study the effect of particle concentration using full factorial design, with a rotational speed of 15 rpm, head space of 9% (V/V), retort temperature of 120 °C and a rotation radius of 120 mm in 0.9% CMC concentration, and they found that particle concentration had a significant effect (p<0.05).

2.5.5 Particle size: Hassan (1984) found that, when processed in water, process times for fluid and particles increased when the diameter of potato spheres increased from 2.22 cm to 3.49 cm. He was also able to determine that for the larger particles, the effect of rotational speed on the particle heating times was higher than for smaller particles, and found similar results when he used Teflon and aluminum particles processed in water or silicon liquids. When the particle liquid film transfer coefficient was examined by Deniston (1984), he found analogous results for his potato spheres in water. The overall heat transfer coefficient, however, was reported to have the highest values at all rotational speeds when particles of an intermediate size (2.86 cm) were used. When the rotational speeds were lower, between 9.3 and 29.1 rpm, the largest particles of 3.5 cm gave the lowest U_o values, while at higher speeds (101 rpm) the lowest U_o values were obtained from the smaller particles of 2.22 cm diameter. In all of these experiments, cans of size 303 × 406 were used at a particle volume fraction $\varepsilon = 0.293$. The data collected by Deniston *et al.* (1987) showed that h_{fp} was not greatly influenced by increasing particle size.

Lenz and Lund (1978) reported that increasing particle size resulted in higher overall heat transfer coefficients, but Sablani and Ramaswamy (1997) found that Uvalues decreased by about 9% in oil and 6% in water as the size of Nylon particle increased from 19.05 to 25 mm diameter, and concluded that particle size influenced more h_{fp} than it did U. In their experiments, h_{fp} decreased by 13% in oil when the particle diameter increased from 19.05 mm to 22.25 mm while further increase in size to 25 mm diameter reduced h_{fp} by 24%. Furthermore, h_{fp} decreased by 9% in water when the particle diameter increased from 19.05 mm to 25 mm. Meng and Ramaswamy (2007b, 2007c) reported no significant effect of particle size on U_a and h_{ap} .

2.5.6 Particle shape: To determine the effect of particle shape might have on U, Sablani and Ramaswamy (1997) used Nylon particle of various shape such as cylinders, cubes and spheres, and found that when there were multiple particles inside the can, the U values for the cube-shaped particles were about 6% lower than those of the cylinder, and 6% lower than that of the spheres. When studied in oil, the average U value of the cubes became 3% lower than the cylinders and 6% lower than the sphere-shaped particles. The authors explained this by saying that the different shapes created different void areas between the particles, allowing for different levels of mixing to take place inside the can. Particle shape was already known to have an influence on the heat transfer coefficients due to differences in liquid flow over the different shaped surfaces of the particles. Fluid to particle heat transfer coefficient, h_{fp} was determined to be affected by shape as well, in experiments conducted by Sablani and Ramaswamy (1997) using multiple particles submerged in oil, h_{fp} increased by 6% with cubes compared to that of a cylinder which in turn increased by 20 % compared to that of sphere, and the influence of shape was even more noticeable in water. They explained this by saying that the disturbances in the flow field near the surface of the cylinder and the cube made the effects of the particle shape more predominant. The cube-shaped particle, for example, behaved like an extreme case of a particle with a rough surface (Astrom and Bark, 1994). As for cases with more than one particle, the results were reversed with the sphere having the highest h_{fp} values and the cubes having the lowest, and this was explained by the way the different shapes interlock with each other and pack into the can, creating void spaces of different extents with each different shape.

2.5.7 Particle density: Particle density can affect the particle fluid motion pattern inside the can, thereby affecting the heat transfer coefficient. When using a single particle inside a can, Sablani (1996) found a significant effect of density on the h_{fp} value. He noted that particles of greater density settled in the can faster, resulting in more motion inside the can due to the higher particle-liquid relative velocity and creating a higher h_{fp} . When the particles with densities close to each other (Nylon and Acrylic) had similar h_{fp} values in both oil and water, he concluded that particle thermal properties did not influence h_{fp} . However, Stoforos and Merson (1992) reported that their Teflon spheres

had a higher h_{fp} value than their aluminum particles of the same size, and besides the particle density, the thermal properties of the particle matter were presumed to be the explanation. Meng and Ramaswamy (2007b) reported that the h_{fp} values increased with the increase in particle density

2.6 Prediction models for heat transfer coefficients (U and h_{fp})

Since the heat transfer coefficients in agitation processing are influenced by several outside factors, it is important and necessary to observe and catalogue the influence of these factors. Empirically, dimensionless correlations are widely used in the prediction of heat transfer coefficients, although in recent times such models have also been made from artificial neural networks, and these models have shown great promise (Sablani *et al.*, 1997, Meng and Ramaswamy, 2007a).

2.6.1 Dimensionless correlations

Dimensional analysis is a preferred and widely used technique for generalizing data because it limits the number of variables that must be studied and permits the grouping of physical variables that affect the process of heat transfer (Ramaswamy and Zareifard, 2003). It is also meaningful to generalize these effects in order to broaden their scope for scale-up considerations. In the dimensional analysis of forced convection heat transfer, where fluid is forced over the solid by external means, the Nusset number (Nu), a dimensionless measure of convective heat transfer coefficient, is related with other dimensionless numbers such as Reynolds number (Re) and Prandtl number (Pr). In the case of free or natural convection, where fluid motion is determined by the buoyancy forces, Nusset number (Nu) is correlated to the Rayleigh number (which is the product of two dimensionless numbers, Grashof (Gr) and Prandtl (Pr) numbers). The Grashof number plays the same role in free convection that the Reynolds number plays in forced convection. Where Reynolds number is used to measure the ratio of the inertial to viscous forces acting on a fluid element, the Grashof number indicates the ratio of the buoyancy force to the viscous forces acting on the fluid (Incropera and Dewitt, 1996). These dimensional numbers give a better understanding of the physical phenomenon and can also be easily used for scale-up purposes. Dimensionless correlations involve overall heat

transfer coefficients (U) because earlier studies were focused on the convective heat transfer in liquid foods. Rao and Anantheswaran (1988) presented an insightful review of these studies, however for canned liquid particulate food systems there are scant few studies available.

Sablani et al. (1997a) established correlations for overall heat transfer coefficients, as well as the fluid to particle heat transfer coefficients for liquid/particle mixtures in endover-end rotation. In this study, Nu was correlated with other dimensionless numbers, including Archimedes and Froude numbers, the ratio of head space to the length of the can (H_{a}/H_{c}) , the ratio of the particle to liquid concentration (e/100-e), the ratio of the equivalent particle diameter to the diameter of the can (d_c/D_c) , particle sphericity (Ψ) and the density simplex $(p_p - p_l/p_l)$. In end-over-end rotation, Meng and Ramaswamy (2007a) developed the dimensionless correlations for high viscosity fluid/particle mixtures using apparent heat transfer coefficients h_{ap} and U_a . Lenz and Lund (1978) and Deniston *et al.* (1987) presented correlations in free axial rotation for U relating Nu to Re, Pr and other dimensionless numbers; however they did not develop the relationship between fluid to particle heat transfer coefficient. In the following years Fernandez et al. (1988) presented dimensionless correlations for h_{fp} in cans with axial rotation, adding to their studies. Using the fluidized bed and packed bed approaches and using the modified Stanton number and Colburn j-factor in empirical correlations they were able to model their correlations; however he was unable to develop correlations for U. The time temperature prediction at the particle center requires appropriate correlations for both U and h_{fp} , and cannot be made with only one of these coefficients. Because of the difficulties in obtaining time-temperature measurements of the liquid and particle simultaneously, literature pertaining to free axial agitation lacks the correlations of U and h_{fp} .

2.6.2 Artificial neural network

The term "neural network" resulted from artificial intelligence (AI) research, which attempts to understand and model brain behavior. "Artificial intelligence is the part of computer science concerned with designing intelligent computer systems, that is, systems that exhibit characteristics we associate with intelligence in human behavior". Over the past few years, neural networks have shown great promise, and when solving nonlinear prediction problems they prove to be more powerful than most other statistical methods (Bochereay *et al.*, 1992). The goal of the neural network is to map a set of input patterns onto a set of corresponding output patterns, and Figure 2.9 below shows a typical neural network formed by an interconnection of nodes. Normally a network can have one to three hidden layers, but the network below has one hidden layer, an input layer and an outer layer, and each layer is essential to the success of the network. The entire network can be viewed as a 'black box' into which a specific input to each node is sent in the input layer. Although the entire processing step is hidden, the network processes information through the interconnections between nodes, and finally gives us an output



Figure 2.9 A typical multilayer neural network with one hidden layer.

on the output layer. Figure 2.10 shows that the neural network is made up of neuron arranged in layers, and each neuron in a layer is linked to many other neurons in other layers with varying connection weights (W_{ij}) that represent the strength of these connections. Sometimes the neurons are even connected to neurons in their own layer. Within each neuron threshold value, a bias (B_i) is added to this weighted sum of connection weights and non-linearity transformed using an activation function to generate the output signals response (O) of each neuron (*i*) to the input signals (I) from connecting neurons (J), which can be mathematically expressed as:

$$O_{i} = f\left\{\sum_{j=1}^{m} I_{j}W_{ij} + B_{i}\right\}$$
(2.25)

The architecture and the algorithmic method chosen for training is what will determine the learning ability of the neural network. Due to its relative simplicity and its

stability, back propagation algorithm is very popular (Neural Ware Inc., 1996). In a back propagation algorithm, the learning process starts with random initialization of connection weights. The response of each output neuron during learning is compared with a corresponding desired response. Any errors associated with the output neurons are computed and transmitted from the output layer to the input layer through the hidden layer. The weights are adjusted at the end of the back propagation cycle in order to minimize the errors, and this procedure is repeated over the entire learning cycle for a set number of times, chosen by trial and error. In practice, if sufficient numbers of these input-output combinations are used for the learning of the neural network, it should be able to predict the output for new inputs.

An ANN model was developed by Meng (2006) for the apparent heat transfer coefficients associated with canned particulates in high viscous Newtonian and non-Newtonian fluids during end-over-end rotation in a pilot scale rotary retort. For the overall heat transfer coefficients as well as the fluid to particle heat transfer coefficients for liquid particulate systems in cans subjected to end-over-end mode, Sablani *et al.* (1997b) developed another ANN model. The multi layer neural network had six input neurons and two output layers corresponding to U and h_{fp} , and was developed for the presence of multiple particles inside the can. Using the back propagation algorithm, the optimal neural network was obtained by varying numbers of hidden layers, number of neurons in each hidden layer and the number of learning runs.



Figure 2.10. A typical multilayer neural networks (Chen, 2001)

ANN was used to optimize the conduction of heated foods (Sablani *et al.*, 1995) and a correlation was developed among optimal sterilization temperature, corresponding processing time and quality factor retention with the can dimension, food thermal diffusivity and kinetic parameters of the quality factors. The models developed with ANN were able to predict the optimal sterilization temperatures with an accuracy of ± 0.5 °C and other responses with less than 5 % associated errors.

2.6.3 Comparison between ANN and Dimensionless correlation models

Sablani *et al.* (1997b) developed ANN models and reported that the prediction errors were about 50 % better than those associated with dimensionless correlations; less than 3 % for U and 5 % for h_{fp} . Meng (2006) found that the ANN models were able to predict responses with mean relative error of 2.9 - 3.9 % in Newtonian fluids and 4.7 to 5.9 % in non Newtonian fluids. These results were 27 - 62 % lower than those associated with the dimensionless correlations.

PREFACE TO CHAPTER 3

For the processing of viscous fluids in large containers, the advantage lies with rotational retorts as opposed to their still counterparts. Rotational retorts provide mechanical agitation to the cans resulting in product mixing and there by improving the heat-transfer rate.

In the past, comparisons of the heat transfer rates have been done mostly between end-over-end (E-O-E) mode and fixed axial modes. The E-O-E is common in batch retorts while the axial rotation is common in continuous retorts. The most widely used continuous agitation is free axial agitation, which has several advantages over the other types of rotations. Free axial mode requires less floor space for auxiliary machines, less water consumption caused by regeneration, less labor and a better production rate. Despite the fact that this process is already widely used, there is little information in published literature on the comparison of heat transfer rates in the free axial mode and most comparisons are made between E-O-E and fixed axial modes of rotation.

Only a batch type pilot scale single basket rotary autoclave was available for research. This could only be used for E-O-E and fixed axial rotations. The first task was therefore to modify the retort to accommodate the free axial rotation and to compare the three modes in the same retort which is the purpose of this chapter.

Part of this research has been presented in 2006 IFTPS Annual meeting (Orlando, FL), in 2005 Scientific conference, CRDA, St Hyacinthe, PQ and in 2005 AIChE Annual Meeting, Cincinnati, OH. One manuscript has been prepared for the submission.

The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.
CHAPTER 3

COMPARISON OF HEAT TRANSFER RATES DURING THERMAL PROCESSING UNDER END-OVER-END AND AXIAL MODES OF ROTATION

3.1 Abstract

Thermal processing under conditions enabling container agitation are attractive to food processors since they provide better rates of heat transfer and more uniform temperature due to product mixing. Two common types of agitations are end-over-end-and axial agitation. While end-over-end agitation is common in batch retorts, axial agitation is predominant in continuous cookers in which the cans roll in a helical path along the retort shell. In this study, heat transfer rates to canned Newtonian fluids in end-over-end and axial modes of rotation were evaluated in the same retort. A single basket rotary retort was retrofitted to accommodate simultaneously both end-over-end and two types of axial modes of rotation, free axial and fixed axial. In the free axial rotation, the cans were allowed to rotate on their own axis as they rolled along the retort shell during the bottom third of the rotation, while in the fixed axial mode, the cans in the axial direction were held stationary in the rotating basket. The overall heat transfer coefficient U and heat penetration parameters (f_h , j_{ch} and cook values) associated with cans filled with Newtonian fluids were evaluated using a central composite rotatable design of experiments with glycerin at five concentration level (0-100 %), heating medium temperature (111.6 °C-128.4 °C) and five basket-rotational speeds (4-20 rpm). Higher U, and lower f_h , j_{ch} and cook values were associated with higher rotational speed and retort temperatures for all modes of agitation. The heat transfer parameters associated with free axial rotation were significantly better than in the end-over-end mode which was better than in the fixed axial mode.

3.2 Introduction

Thermal processing is based on reducing the population of heat resistant microorganisms at the slowest heating point, to a level that is statistically considered satisfactory for public health concerns. Even though thermal processing of food is generally viewed as an energy intensive preservation technique, it is the most widely used method of food preservation. Today consumers not only demand high safety standards, but also require high quality, flavorful, colorful, inexpensive, conveniently packaged and properly labeled food products.

Rapid and uniform heating helps to promote higher quality canned products because the target lethality can be achieved with minimum destruction of the food color, texture and nutrients. Moreover, rapid heating not only increases the efficiency of the process equipment, but also leads to reduced energy and reduced production costs. In thermal processing, the majority of thick liquid and particulate liquid food products such as soups, sauces, vegetables in brine, meat in gravy and some pet foods are processed under modes induced by forced convection. This process is advantageous in reducing process times, increasing production efficiency and in some instances minimising the detrimental effects of heat.

Agitation during thermal processing is an effective means of providing inducedconvection, which provides higher and uniform heating rates to the product. Canned food products may be heated by conduction, convection or a combination of both. With convection heating, the rate of heat penetration in the product can be increased by mechanical agitation (Anantheswaran and Rao, 1985a, b) and the product movement within these agitated containers increases the heat transfer within such products. This permits the use of higher temperatures, resulting in shorter processing times and making the temperature distribution within the can more uniform. Agitating these cans can also prevent different ingredients and phases in the food product from separating from each other during thermal processing. Agitating canned food during heating was proven to be an effective means of increasing the rate of heat penetration. The key factor in mixing the container's content is the headspace bubble that sits above the food until the container is rotated.

Some common types of agitation used are end-over-end and axial agitation. Clifcorn et al. (1950) suggested the use of end-over-end (E-O-E) rotation to increase the heat transfer in canned food products. In E-O-E rotation, the sealed can is rotated around a circle in a vertical plane. As the can rotates, the headspace 'bubble' moves along the length of the can and brings about agitation of the can's contents. By comparison the continuous container handling types of retorts are constructed with two cylindrical shells, in which processing and cooling takes place and cans are subjected to axial agitation. The shell can be used for pressure processing in steam or cooling with or without pressure. The Sterilmatic (FMC Corp., San Jose, CA) is an extensively used continuous agitating retort in which an entering can is carried on and advanced by a revolving reel. The Steritort is a pilot scale simulator of the thermal process in the Sterilmatic series. The motion of a can in a Steritort takes place in three phases consisting of fixed reel, transitional and free reel motion across the bottom of the retort. The fixed reel motion takes place over 220° of a cycle, the free rotation over the bottom 100° , and the transitional motion takes place 20° on either side of the free rotation. Some advantages of continuous retorts over batch retorts are increased production rate, reduced floor space (as fewer auxiliary types of equipments are required), reduced consumption of steam and water (caused by regeneration), and reduced labor requirements. The principle of operation of continuous retorts implies that the cans entering the retort are indexed into a revolving reel and are moved through the machine in a spiral pattern. Agitation in continuous retort is provided by allowing the cans to roll freely across the bottom of the retort.

In order to establish a thermal processing schedule for canned liquid food products, experimental time temperature data are commonly used. Theoretical models can also be used for the process design, optimization and validation of these systems. In addition to using the relevant thermo physical properties, a successful temperature prediction for liquid canned food product from these theoretical models requires data on the overall heat transfer coefficient (U) which is a measure of the overall rate of heat transfer from the heating medium to the canned liquid.

There are several factors affecting the overall heat transfer coefficients which can have a great impact on the internal mixing within a container and thus on the rate of heat penetration into the product. Factors such as headspace, retort temperature, rotation speed, and product concentration affect the heat transfer to liquids. A number of authors conducted studies on the can wall heat transfer coefficient in agitated retorts (Lenz and Lund, 1978; Naveh and Kopelman, 1980; Anantheswaran and Rao, 1985a; Soule and Merson, 1985).

In previous literature, the impact of several methods of agitation on heating rates of canned food has also been studied. The agitation method includes end-over-end (Clifcorn *et al.*, 1950; Jowitt and Mynott, 1974; Hiddink, 1975; Naveh and Kopelman, 1980; Duquenoy, 1980, and Anantheswaran and Rao, 1985a, 1985b) and axial rotation (Quast and Sioza, 1974; Merson *et al.*, 1980; Berry and Dickerson, 1981, and Soule and Merson, 1985). Recent studies (Tattiyakul, 2001, 2002; Hughes *et al.*, 2003; Varma and Kannan, 2005 and James, 2006) have used computational fluid dynamics (CFD) as well as experimental work to examine the underlying mechanism of heat transfer in liquid food during rotary processing.

Quast and Siozawa (1974) worked with sucrose solutions (Newtonian flow behavior) and carboxymethylcellulose solutions (non-Newtonian behavior) in a pilot plant spin cooker/cooler (shaft speed 0 to 420 rpm) and reported that the heat transfer rates with axial rotation increased 2 to 4 times as compared to stationary processing. Berry and Bradshaw (1980) found that factors affecting the rate of heat penetration in condensed cream of celery soup processed in steritort include the rotational speed of the can, head space and consistency of the product. Merson and Stofors (1990) reported heat transfer coefficients for a 60 % sucrose solution in a 303×406 can axially rotating in a gas flame.

Naveh and Kopleman (1980) measured the heat transfer rates for a variety of rotational configurations; head space and rotational speed. Their findings revealed that the heat transfer coefficient (U) in end-over-end rotation was two or three times greater than in the case of axial mode of rotation for high viscosity fluids, which were used over a wide range of rotational speeds. However, their findings were based on fixing the cans in a horizontal mode, where the cans were subjected to a fixed axial rotation (not in free axial mode). Naveh and Kopleman (1980) found better heat transfer results under free

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axial mode of rotation. The FMC steritorts are the most continuous retorts used in the industry, in which the movement of the cans is in free axial mode.

In spite of the wide usage of FMC Steritort, there is very limited published literature available on the comparison of heat transfer rates between end-over-end mode and free axial mode. Therefore, the objective of this research is to study the effect of some agitation process parameters such as speed, temperature and product concentration on the over-all heat transfer coefficient, U, in these two modes of rotation. To compare both modes of rotation in the same equipment, the existing cage of a rotary autoclave (with E-O-E rotation mode) was modified to simultaneously accommodate cans in both E-O-E and free axial mode rotation.

3.3 Methodology

3.3.1 Retort cage modifications

A single car rotary retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany) was used in the study. The retort basket was retrofitted with a stainless steel (SS 306) enclosure in which test cans could be held in an axial direction. Cans for E-O-E rotation were positioned inside the normal cage. Cans were positioned by using rear and front stainless steel supports, which were fixed to the retort basket. The fabricated enclosures held two free cans on each side of the frame. On one side, end plates facing the retort shell were removed so that the cans could slide down and roll along the retort shell during part of the rotation (Figure 3.1). These cans rolled on their own axis (in a direction counter to that of retort cage) when inclined the opening was facing downwards (approximately $1/3^{rd}$ of the rotation in facing downward) simulating the action in a Steritort. In the top $2/3^{rd}$ of the cage rotation, the cans were restrained in the enclosure only rotating with the cage. This process caused biaxial rotation of the can in the free axial mode, while only in clockwise direction in the fixed axial mode. The two cans held at the opposite end were held inside in a fixed axial mode and was not allowed to drop on to the retort shell. Details of the attachment can be seen in Figure 3.1a-c.

3.3.2 Newtonian fluid

Glycerin (Fischer Scientific., Montréal, PQ) was used to simulate Newtonian fluids with a broad range of viscosity. Glycerin solutions of different concentrations were prepared by diluting pure glycerin with distilled water. The density of diluted glycerin solution was determined from the mass of a known volume of the glycerin solution. Thermal properties of water and of glycerin solutions at different concentrations were taken from the literature available (Meng, 2006), which are summarized in Table 3.1.

Heat Capacity (J/ kg C)
4.18
3.76
3.34
2.72
2.43

Table 3.1Thermal properties of the test material

3.3.3 Temperature measurements

To measure the temperature of the canned fluid in the end-over-end and fixed axial modes, test cans were fitted with CNS copper-constantan needle-type thermocouples. The male connectors (Locking connector, C-10, Ecklund-Harrison Technologies Inc., Miami, FL), which were attached to the ends of wires (heat penetration cable), were plugged into the thermocouples to record the temperature at the geometric center of the cans. The locking connector included a threaded ring that screwed onto the external thread on the locking receptacle, thereby securing the connection during processing. In order to determine the temperature of liquid inside the can in free axial mode of rotation, cans were fitted with S28 NR rotating thermocouple (Ecklund-Harrison Technologies Inc., Miami, FL). The thermocouple wires from the all test cans and those used to measure retort temperature were passed through a 32 slip ring assembly, and connected to a data acquisition system (HP34970A, Hewlett, Packard, Loveland, CO). Thermocouple signals were recorded at 10 second intervals. The prepared cans were subjected to rotational processing (E-O-E and axial mode) in the Stock rotary retort.

Retort heating medium temperature was monitored using a 24 gauge Teflon coated copper-constantan thermocouple (Omega Engineering Inc., Stanford, CT),



Figure 3.1 Front view of rotation of cans (end-over-end, fixed and free axial modes) in modified STOCK retort (Shell Dia. = 890 mm) similar to sterilmatic continuous pressure retort. Note: See Details A, B, C on next page





Rear SUS 306 attachment for free or fixed axial cans



Detail B. Front attachment for free axial cans. **Detail C**. Front attachment for fixed axial cans

located near the mercury-in-glass thermometer. In order to measure temperature uniformity in test cans (307×409), temperatures were measured at three locations using needle-type thermocouples of varying lengths (L1 = 42 mm, L2 = 33 mm and L3 = 21 mm) at different heights (H1 = 20 mm, H2 = 56 mm and H3 = 85 mm, from the bottom of the can). This is similar to the approach used by Sablani (1996) in his evaluation of heat transfer during E-O-E rotation processing. These cans were processed at a cage speed of 0, 4, 12, 16 and 20 rpm.

3.3.4 Preparation of test cans

All test cans used were of size 307×409 (Home Canning Co., Montreal, QC). The cans were filled with glycerin solutions of different concentrations maintaining a 10 mm headspace in each can. Cans were closed using a manual double seaming machine (Home Canning Co., Montreal, QC). For the end-over-end rotation, the cans were fitted with a needle T-type of thermocouple inserted from the body of the can while for the axial mode they were inserted through the lid. The test can for the free axial rotation held a rotating thermocouple while of regular non-rotating connector was used for fixed axial rotation

3.3.5 Experimental design

In order to compare the overall heat transfer coefficient, U, in the end-over-end and axial modes, a central composite rotatable design (CCRD) (Table 3.2) was used with retort temperature, product concentration and rotational speed as variables. Retort temperature (111.6, 115, 120, 125 and 128.4 °C), glycerin concentration (0, 20, 50, 80 and 100 %) and rotational speed (0, 4, 10, 16 and 20 rpm) were employed at 5 levels. 20 experiments carried out based on CCRD plus 15 additional experiments were employed to gather more data. All tests run were repeated twice.

The regression analysis and analysis of variance (ANOVA) were carried out using the GLM procedure of SAS statistical package (SAS Institute Inc., Cary, NC) to fit the second order polynomial equations for the response given below.

$$Y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_{12} X_1 X_2 + a_{13} X_1 X_3 + a_{23} X_2 X_3 + a_{11} X_1^2 + a_{22} X_2^2 + a_{33} X_3^2 + a_{123} X_1 X_2 X_3$$
(5.1)

(2 1)

CCPD laval and a	Retort speed	Retort temperature	Glycerin concentration
CCRD level codes	(rpm)	(°C)	(%)
-1.68	0	111.6	0
-1	4	115	20
0	10	120	50
1	16	125	80
1.68	20	128.4	100

Table 3.2Experimental design used to evaluate effect of processing parameters on U

In the above equation, a_n refers to constant regression coefficients and X_1 , X_2 and X_3 are coded independent (temperature, glycerin concentration and rotation speed, respectively) variables. Response surfaces were drawn by the fitted quadratic polynomial equation obtained from GLM analysis. Their significance was judged by determining the probability level that the *F*-statistic calculated from the data as less than 5%. The model adequacies were checked by R^2 and prediction error sum of squares (PRESS). Statistically, a good model will have a large predicted R^2 , and low prediction errors.

3.3.6 Experimental set up

During a test run, two cans fitted with S28 NR thermocouples were placed in stainless steel attachments on one side of the cage so that the cans were positioned between the cage and the retort shell (Figure 3.1). These cans provided the free axial mode rotation moving clockwise with the cage (upper 2/3rd rotation) and in addition on its own axis in counter clockwise direction in the lower 1/3rd rotation. The two cans placed on the opposite end were held restrained throughout thereby providing fixed axial rotation. For the end-over-end rotational mode, two cans equipped with the needle-type thermocouples were placed inside the cage between the two perforated spacer mats (Figure 3.1). To support the proper placement of the perforated mats, six dummy cans filled with water were processed simultaneously. All the cans were placed inside the perforated cage which had approximately 60% open space. Perforated spacer mats were used to provide contact between the top layer of the containers and the top layer of the cage.

Water was preheated in the storage vessel as a rule of thumb to at least 10°F higher than the processing temperature. The preheated water was then introduced into the process vessel to reduce the come-up time. Average come-up time of this retort was 4.5 min even though the water was preheated in the storage vessel. Once the transfer was completed, water was constantly circulated though a re-circulating pump. During the sterilization cycle, the water temperature and system pressure were maintained at a preset value through the temperature and pressure controllers respectively. At the beginning of the cooling cycle, the hot sterilizing water was pumped back up to the storage chamber where it was re-heated to the proper set temperature for the next cycle. Cold water was then introduced to the retort to cool the cans. A tacho-generator was used to control the cage rotation speed. The sequencing of the sterilization and cooling cycles in the ROTOMAT was fully automatic.

3.3.7 Heat penetration test

Test cans filled with glycerin of 5 concentrations were subjected to agitation processing under 5 rotational speeds and 5 processing temperatures. In each experiment, the heating time was kept sufficiently long until that the liquid temperature equilibrated to the heating medium temperature. The equilibrated liquid temperature was used to correct the thermocouple signals. Since small differences in initial and retort temperatures were unavoidable; the data were, normalized to an initial temperature of 25°C and the respective set point retort temperatures, according to a procedure detailed in Stumbo (1973).

The heat transferred across the can wall was absorbed by the can liquid, resulting in an increase in its bulk temperature. The overall heat transfer coefficient for a can containing only liquid was obtained by using Equation 3.2 (Ramaswamy *et al.*, 1993):

$$U = \frac{2.303m_{l}C_{pl}}{f_{h}A_{c}}$$
(3.2)

The heat penetration parameters for the canned liquid (heating rate index, f_h and heating lag factor, j_{ch}) were evaluated from the plots of logarithm of temperature difference between the retort and liquid versus heating time. Process lethality, F_o , and cook value, C_o , were calculated for each run by numerical integration of time temperature as represented in the following equations (z = 10 °C) for F_o and (z = 33 °C) for C_o .

$$F_o = \int 10^{(T-121.1)/z} dt \tag{3.3}$$

$$C_o = \int 10^{(T-100)/z} dt \tag{3.4}$$

First the process time to achieve a heating lethality of 10 min was obtained from Eq. 3.3, and then the accumulated C_o up to this time was computed using Eq. 3.4. From these values the C_o/F_o ratio, which is a measure of degree of cooking, was evaluated (Abbatemarco and Ramaswamy, 1993).

3.4 **Results and Discussions**

3.4.1 Temperature profile and temperature uniformity in cans under different modes

The liquid time-temperature profile in 100 % glycerin filled test cans subjected to the three modes of rotation (fixed axial, end-over-end and free axial) at a cage rotation speed of 16 rpm is shown in Figure 3.2. The come-up time of the retort was approximately 4.5 min, which was similar to the results reported by Meng and Ramaswamy (2005) and Sablani (1996). From this figure, it can be seen that the liquid temperature in the can subjected to E-O-E rotation reached the set retort temperature earlier than the one in the fixed axial mode. Furthermore, it can be observed from the same figure that the can in free axial mode heated even faster than in E-O-E mode. Therefore, it can be concluded that the effective heat transfer and the temperature rise in the product is the most rapid in the free axial mode, followed by the E-O-E and then by the fixed axial modes. Naveh and Kopleman (1980) studied hear transfer rates in a variety of rotational configurations and found that the heat transfer in end-over-end rotation was two or three times greater than in the case of fixed axial mode, which is consistent with the trends observed in the present study.



Figure 3.2 Typical experimental time temperature profile of 100 % glycerin in a can under fixed axial, End-over-end and free axial mode at 16 rpm.

The method to calculate U (overall heat transfer coefficient) and h_{fp} (fluid to particle heat transfer coefficient) is based on the assumption that the temperature distribution of liquid in the can is relatively uniform (Sablani, 1996; Anantheswaran and Rao, 1985a). The temperature uniformity in the cans (filled with 100% glycerin) subjected to E-O-E mode and fixed axial mode agitation was evaluated for comparison. It is much easier to attach multiple thermocouples in these two modes than in the free axial mode. By the previous comparison, the free axial was better in heat transfer than the other two, and if the temperature distribution was good in the latter two, obviously it can be expected to be better in the free axial mode. Temperature uniformity in the test cans was evaluated by monitoring temperatures at three locations along the vertical axis of the can. The uniformity could be assessed by using time specific temperatures as it has been done in some previous studies, using the computed variations in the heat penetration parameters, heating rate index, f_h and heating lag factor, j_{ch} . The computed heat penetration parameters at three locations and their coefficients of variations are summarized in Table 3.3a at three different rotation speeds.

		noue						
Rotation								
Speed	Locat	ion 1	Locat	ion 2	Locat	ion 3	C	VC
rpm	fh	j ch	f_h	j ch	f_h	Ĵch	$f_h(\%)$	$j_{ch}(\%)$
4	10.93	1.40	10.92	1.39	10.84	1.31	0.45	3.61
4	10.90	1.39	10.89	1.36	10.80	1.35	0.51	1.52
12	8.24	1.14	8.24	1.20	8.20	1.19	0.28	2.73
12	8.18	1.19	8.15	1.21	8.12	1.17	0.37	1.68
20	6.16	1.16	6.16	1.18	6.06	1.16	0.94	0.99
20	6.15	1.14	6.12	1.15	6.11	1.19	0.34	2.28

Table 3.3aTemperature uniformity of liquid (100 % Glycerin) within the can,
processed at the retort temperature of 120 °C, at three rotational speeds in
E-O-E mode

Under the still retort processing conditions (0 rpm), the prevailing mode of heat transfer is generally natural convection, therefore significant temperature variations in the can content existed. This also resulted in much larger variations in the computed location dependent heat penetration parameters and the associated coefficient of variation. When the rotational speed of the can was varied between 4 to 20 rpm, the resulting location specific heat penetration parameters were more uniform and hence the associated coefficients of variation were small for both modes of rotation. In the case of f_h , the highest coefficient of variation was 0.95 % whereas with j_{ch} it was 3.6 %. These results can also be visualized by the temperature profile and standard deviations in temperatures at different heating times in the two modes of rotation (E-O-E and fixed axial) (Figure 3.3). From these figures it can be realized that the temperature variations along the three different locations were a bit variable in the beginning and stabilized to within 0.5°C standard deviation after 5 minutes and the temperatures were nearly same after 15 min under agitation processing (4 and 20 rpm). With better heat transfer conditions under free axial mode, one can only expect a further improvement in the results.



Figure 3.3 Standard deviations and their temperature profiles as a function of heating time with respect to three thermocouple (42 & 20; 33&56 mm; and 21 & 85 mm, from the can surface and bottom respectively) in cans subjected to end-over-end and fixed axial agitation processing at (a) 4 rpm and (b). 20 rpm.

Rotation			<u>.</u>					
Speed	Locatio	on 1	Locatio	on 2	Locatio	on 3	COV(%	6)
(rpm)	f_h	j ch	f_h	j ch	fh	j ch	$f_h(\%)$	j_{ch} (%)
	(min)		(min)		(min)			
4	11	1.53	11.0	1.54	11.0	1.48	0.18	2.12
4	11.0	1.59	11.0	1.52	11.0	1.5	0.24	3.08
12	8.67	1.23	8.65	1.28	8.63	1.22	0.23	2.59
12	8.69	1.24	8.64	1.29	8.6	1.23	0.52	2.56
20	7.18	1.21	7.15	1.25	7.11	1.21	0.49	1.89
20	7.19	1.21	7.18	1.22	7.15	1.21	0.29	0.48

Table 3.3bTemperature uniformity of liquid (100 % Glycerin) within the can,
processed at a retort temperature of 120 °C, at three rotational speeds,
in fixed axial mode

% COV = Coefficient of Variance (100 × Standard Deviation/Mean)

3.4.2 Heat transfer rate comparison between the modes of agitation (E-O-E & Axial)

Further comparisons between the evaluated heat penetration parameters (f_h and j_{ch}), cook value (C_o), sterilization value (F_o) and overall heat transfer coefficient (U) were then made from the centre point temperature measurement in duplicate test cans filled with glycerin solution simultaneously gathered from all three modes of rotation. The variation in these parameters for the duplicate cans was very low as shown in Table 3.4 for three different rpm of 4, 12 and 20 at 120°C. The overall heat transfer coefficient, U was highest for the free axial mode ($118 - 356 \text{ W/m}^2\text{ C}$) followed by end-over-end mode ($108 - 211 \text{ W/m}^2\text{ C}$) and then the fixed axial mode ($107 - 180 \text{ W/m}^2\text{ C}$). The heating rate index, f_h , varied from 9.21 to 4.18 min for free axial mode, 10.9 to 6.15 min for end-over-end mode and 11.0 to 7.19 for fixed axial mode. Higher heat transfer coefficients and lower heating rate indexes are indicative of better rates of heat transfer which therefore were highest in free axial mode better than in E-O-E and the fixed axial modes. This could be due to counter rotating biaxial agitation possible in free axial rotating cans while in the end-over-end and fixed axial cans, the rotation is only in one single direction. The heating lag factor, j_{ch} , generally decreased with the increasing rotational speed from 4 to

20 rpm in the fixed axial mode, and decreased further as the mode of rotation was switched from fixed axial to end-over-end to the free axial mode.

Table 3.4	Comparison	among	fixed	axial,	end-over-end	and	free	axial	mode
	processed at	the retor	t tempe	erature o	of 120°C, at three	ee rot	ationa	al speed	ls.

Rotati												
on												
Speed]	Fixed A	xial Mod	le	E	ind-over	-end mod	le]	Free Ax	ial Mo	de
(rpm)	f_h	j ch	U	$\frac{C_o}{F_o}$	f_h	j _{ch}	U	$\frac{C_o}{F_o}$	fh	j _{ch}	U	$\frac{C_o}{F_o}$
4	11.0	1.53	107	42	10.9	1.40	108	39	9.21	1.28	118	20
4	11.0	1.59	108	43	10.9	1.39	110	39	9.18	1.35	118	21
12	8.67	1.23	160	27	8.24	1.14	169	22	6.51	1.09	228	11
12	8.69	1.24	160	27	8.18	1.19	171	22	6.42	1.08	231	12
20	7.18	1.21	179	20	6.16	1.16	209	18	4.12	1.04	353	5.10
20	7.19	1.21	180	21	6.15	1.14	210	16	4.18	1.02	356	5.20

Note: U is in W/m²C and f_h is in min

The primary objective of the rotational processing is to provide sufficient heat to food products at the most critical point within a short span of time. F_o value (process lethality) is the common parameter which is usually employed to measure adequacy of a thermal process with respect to microbial destruction. The other closely associated parameter is C_o (cook value), which indicates the cumulative equivalent cooking minute at 100°C. Obviously higher temperatures or other factors that improve heat transfer such as mechanical agitation will also increase process lethality and the cook value as well. The increase is generally accompanied by a reduction in the C_o/F_o ratio, which could be used as a relative measure of degree of cooking especially when the process time is not constant (Ramaswamy *et al.*, 1993). C_o/F_o ratios also followed the same trend and continually decreased as the mode of rotation changed from fixed axial to E-O-E to free axial and in addition decreased with an increasing rpm. Lowest C_o/F_o ratios were achieved in free axial mode. Higher rpm in each mode of rotation reduced the C_o/F_o ratios by 50 to 80% (20 rpm vs. 4 rpm). Similarly free axial rotation had C_o/F_o ratios approximately 50 to 70% lower as compared to E-O-E rotation. Most common modes used in the industries are end-over-end (E-O-E) in batch retorts and free axial modes in continuous retorts, and the fixed axial mode is rarely used. The heat transfer in theses two common modes are usually affected by several product and process related factors. A detailed comparison of these two modes of rotations were further made in this study using several product and process dependent variables using a CCRD where all the factors were selected at 5 different levels.

3.4.3 E-O-E and Axial rotation heat transfer as influenced by system and product parameters

The average and standard deviations of overall heat transfer coefficients, U, for 35 experimental runs (20 based on CCRD plus 15 additional experiments), depicted higher values for free axial mode (U_{FRA}) than the end-over-end (U_{EOE}) mode of rotation (Table 3.5). Student *t*-test showed a significant difference (p < 0.05) between U_{FRA} and U_{EOE} (the overall mean of U_{FRA} value was 340 W/m²C as compared with U_{EOE} of 253 W/m²C). This improvement could be explained by the enhanced mixing of the can contents in axial mode provided by the biaxial agitation of the freely rotating cans. The unidirectional agitation of the can in end-over-end mode resulted in a lower overall heat transfer coefficient. The three major factors; retort temperature, rotational speed and product viscosity (concentration of fluid), are imperative to heat transfer coefficients. Figure 3.4 and 3.5 show the effect of reel speed, glycerin concentration and retort temperature on the overall heat transfer coefficient, U, in axial and end-over-end modes of agitation. Analysis of variance (Table 3.6) showed that all the input parameters had a significant influence (p<0.05) on U, although the degree of influence of each parameter was different on the overall heat transfer coefficient of the liquid in both the modes of rotation. In each mode, the most dominant factor was the speed of rotation (p < 0.001), followed by the glycerin concentration (p < 0.001) and the retort temperature (p < 0.05). Increasing the rotational speed in the free axial mode from 0 rpm to 20 rpm at 120°C processing temperature and 80 % glycerin concentration (Figure 3.4a) resulted in an increase in U from 210 to 380 W/m²C, whereas under the similar processing conditions $U_{\rm EOE}$ increased from 190 to 260 W/m²C (Figure 3.4b). The increase in U with the

	Rotation Temperature Concentration		Rotation	Usos	Um
Run No.	(°C)	(%)	speed	(W/m^2C)	(W/m^2C)
	(0)	(70)	(rpm)	(0/111 C)	(11/11/0)
1	-1	-1	-1	215(1.2)	240(2.2)
2	-1	-1	1	315(0.4)	495(6.1)
3	-1	1	-1	140(0.8)	160(3.2)
4	-1	1	1	210(3.2)	325(2.1)
5	1	-1	-1	235(2.4)	270(1.2)
6	1	-1	1	350(3.9)	550(0.9)
7	1	1	-1	155(4.3)	175(1.7)
8	1	1	1	225(2.2)	345(0.8)
9	0	0	-1.68	80(4.5)	100(3.7)
10	0	0	1.68	380(4.3)	615(3.9)
11	-1.68	0	0	245(3.6)	355(8.2)
12	-1.68	0	1	290(4.3)	455(450)
13	0	1.68	0	170(4.3)	230(304)
14	0	1.68	1	175(3.9)	305(326)
15	1.68	0	0	270(3.9)	455(3.4)
16	1.68	0	1	320(4.6)	515(3.6)
17	0	-1.68	0	320(4.6)	505(3.7)
18	0	-1.68	1	340(3.7)	550(3.7)
19	0	0	0	260(3.7)	380(3.7)
20	0	0	-1	205(2.3)	230(3.7)
21	0	0	1	305(0.8)	485(3.8)
22	-1	-1	1.68	400(3.1)	600(6.4)
23	-1	1	-1.68	45(5.1)	85(3.4)
24	-1	1	0	175(2.1)	230(3.5)
25	1	-1	-1.68	105(2.8)	125(3.1)
26	1	-1	0	305(4.6)	440(5.5)
27	-1	-1	-1.68	85(3.9)	110(5.6)
28	-1	-1	0	270(2.5)	400(3.7)
29	1	1	-1.68	50(2.3)	95(3.7)
30	1	1	0	195(2.3)	255(3.4)
31	0	1.68	-1	110(4.9)	115(4.9)
32	0	1.68	-1.68	25.(4.8)	35(6.4)
33	0	1.68	1.68	210(4.9)	350(6.3)
34	-1	1	1.68	245(5.1)	365(4.7)
35	1	1	1.68	265(2.6)	390(3.7)

Table 3.5Experimental runs following CCRD to study the effect on U_{FRA} and U_{EOE}

• The values in parentheses are coefficients of variation.

increase in the rotational speeds in both modes can be explained by the improved mixing which was due to a higher degree of turbulence (Sablani, 1996; Sablani and Ramaswamy,1997; Anantheswaran and Rao, 1985a). A definite advantage of agitation processing over still processing (0 rpm) is apparent at all reel speeds. Sablani and Ramaswamy (1996) reported that the overall heat transfer coefficient, U, of water in E-O-E was increased from 420 to 800 W/m²C, with the increase in rotational speed from 0 to 20 rpm. Meng and Ramaswamy (2005) also reported a similar increase in the U values for the glycerin solution by increasing the rotational speed. The reported U values by Meng and Ramaswamy (2005) for end-over-end mode of agitation were similar to results obtained in this study. Increase in U with the increase in rotational speed was also in accordance with those of Lenz and Lund (1978), Hassan (1984) and Stofors and Merson (1992).

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	2265	4.55	0.04
Product Concentration (C)	65971	132	<0.0001
Retort rpm (R)	192376	386	< 0.0001
$C \times R$	5595	11.2	0.0023
C×C	3617	7.27	0.0117
$\mathbf{R} \times \mathbf{R}$	9339	18.7	0.0002

Table 3.6aAnalysis of variance (ANOVA) results for U_{EOE}

Table 3.6b	Analysis o	of variance ((ANOVA)) results of <i>l</i>	U_{FRA}
------------	------------	---------------	---------	-----------------------	-----------

T III CO	F 1	D . F
Type III SS	F value	Pr>F
8805	7.97	0.0086
155800	141.07	< 0.0001
628906	569.45	< 0.0001
25277	22.89	<0.0001
5458	4.94	0.0344
9906	8.97	0.0057
	Type III SS 8805 155800 628906 25277 5458 9906	Type III SSF value88057.97155800141.07628906569.452527722.8954584.9499068.97



Figure 3.4 Effect of retort rotational speed and temperature on overall heat transfer coefficient (a) Free axial mode (b) End-over-end mode



Figure 3.5 Effect of retort rotational speed and glycerin concentration on overall heat transfer coefficient (a) Free axial mode (b) End-over-end mode

The glycerin concentration is a measure of the can fluid's internal resistance to flow when subjected to an external stimulus. Higher concentrations will increase the fluid viscosity which imparts a greater resistance to the fluid movement in agitation processing. In free axial mode, when the retort temperature was 120° C and the rotational speed was 20 rpm, an increase in the concentration of glycerin solution from 0 to 100 % reduced the overall heat transfer coefficient (U_{FRA}) from 530 to 310 W/m²C whereas U_{EOE} reduced from 390 to 230 W/m²C (Figure 3.5). Supporting these results, Stoforos and Merson (1992) also observed that the U decreased at an increased liquid viscosity. Sablani and Ramaswamy (1996) found a 76% reduction in U values when the processing liquid was changed from water to oil of high viscosity. Meng (2006) computed the overall heat transfer coefficient with multiple particles in the can and reported that U values decreased from 293 to 112 W/m²C when the glycerin concentration was increased from 80 to 100 %.

The retort temperature had a positive, although the least effect on U in both modes of rotation. The U_{FRA} values increased from 370 to 410 W/m²C while U_{EOE} changed from 260 to 290 W/m²C (Figure 3.4) as the temperature changed from 111.6 °C to 126.4 °C. The heat transfer improving effect of temperature could be due to the reduction in fluid viscosity and greater liquid convection at higher temperature. Trends obtained were again coherent with the available literatures of Sablani and Ramaswamy (1996) and Meng and Ramaswamy (2005).

Regression models were developed for U_{EOE} and U_{FRA} and were considered significant with associated R^2 of 0.89 for U_{EOE} and R^2 of 0.95 for U_{FRA} and a coefficient of variance 9.57% and 5.66%, respectively. The root mean square error for U_{EOE} was 7.0 whereas for U_{FRA} was 10.0. Fitted equations are shown below, and all independent values are represented in coded values:

$$U_{\text{FRA}} = 367.58 + 17.14 \times T - 67.15 \times C + 122.92 \times R$$

-23.19×C×R-13.55×C×C-15.66×R×R (3.5)

$$U_{EOE} = 257.32 + 8.69 \times T - 43.70 \times C + 67.98 \times R$$

-10.91×C×R-11.03×C×C-15.21×R×R (3.6)

With respect to interactions, U was affected significantly (p<0.05) by the combination of R×C, R×T, R×R and C×T in both modes of rotation. The absence of interaction C×C and T×T showed that retort's rotational speed was the most dominant factor among the three processing variables selected.

3.4.4 Influence of system and product parameters on cook values in E-O-E and axial rotation

Cook values are indicative of the damage to product quality and conditions resulting in lower cook value generally give better quality retention. C_o/F_o ratios, rather than cook values, are usually used for comparing different processes where some differences may exist in delivered process lethalities. Variables investigated in this study showed a significant effect on C_o/F_o ratio. Analysis of variance (Table 3.7) showed that the process temperature had the most significant influence on C_o/F_o ratio, hence the product quality, than any other parameters, accounting for more than 99 % of the total variance. Rotational speed was the next significant factor, followed by the fluid concentration (Figure 3.6). These effects were more dominant, and resulted in considerably lower C_o/F_o ratios, in free axial mode than in end-over-end mode of rotation. In free axial mode, C_o/F_o ratio dropped by 94 % (47 to 3 min) for glycerin solution (80%) concentration level) when the temperature was increased from 111.6 to 128.4°C, whereas the end-over-end rotation resulted in a reduction 82 % (52 to 10 min); but the lowest value was still three times higher than in free axial mode than in E-O-E mode. This demonstrates the usefulness of high temperature and short time processes for the product. The glycerin concentration increased the C_o/F_o values in both modes of rotation, and increasing rotational speed under the high viscosity had only a limited effect on the C_o/F_o .

The regression model developed for C_o/F_{oFRA} and C_o/F_{oEOE} were considered significant because of the satisfactory level of R^2 values (0.90 - 0.96) and coefficients of variance (15.6% for C_o/F_{oEOE} and 6.45% for C_o/F_{oFRA}). Fitted equations are shown below, and all independent values are represented in coded values.

Source	Type III SS	F value	Pr>F
Т	3451	563	0.0001
С	83	13.61	0.0011
R	49	8.02	0.009
T × C	14	2.42	0.1322
$T \times R$	7	1.28	0.2686
C × R	0.66	0.11	0.7445
Τ×Τ	176	28.75	< 0.0001
C×C	2.3	0.38	0.5454
R × R	0.006	0	0.9752

Table 3.7a Analysis of variance results for C_o/F_o (E-O-E Mode)

Table 3.7b Analysis of variance result for C_o/F_o (Free Axial Mode)

Source	Type III SS	F value	Pr>F
Т	5393	550	0.0001
С	130	11.3	0.00051
R	76	7.02	0.0014
Τ×C	23	2.3	0.12
T × R	12	1.1	0.16
$C \times R$	1	0.15	0.547
Τ×Τ	275	20.4	< 0.0001
C×C	3	0.2	0.3412
R × R	0.9	0	0.89

Note : T = Retort temperature (°C), C = Glycerin concentration (%) and R = Rotational speed (rpm)





Figure 3.6 Effect of retort rotational speed and temperature on C_o/F_o value. (a) Free axial mode (b) End-over-end mode

$$C_{o} / F_{oFRA} = 13.19 - 10.80 \times T + 1.55 \times C - 1.09 \times R - 0.89 \times T \times P + 0.49 \times T \times R + 0.11 \times C \times R + 3.21 \times T \times T - 0.32 \times P \times P - 0.01 \times R \times R$$
(3.7)

$$Co/Fo_{EOE} = 16.48 - 13.51 \times T + 1.94 \times P - 1.37 \times R - 1.12 \times T \times P + 0.62 \times T \times R + 0.15 \times P \times R + 4.01 \times T \times T - 0.40 \times P \times P - 0.01 \times R \times R$$
(3.8)

3.4.5 Industrial considerations

Due to the differences in the diameters of the FMC laboratory Steritort (1524 mm) and the Stock pilot retort (890 mm), the agitation effect obtained from the two retorts would be different. In order to acquire equivalent agitation effects, the rotation in the pilot retort will have to be maintained at levels 70% higher (1524 / 890 = 1.7) in order to match the rotation effects in the steritort (Table 3.8a). The capacity semblance of the FMC steritort and pilot retort has been done keeping equal center-to-center distances between the two cans (Table 3.8b). It was determined that the capacity of the FMC steritort was higher by 1.7 fold for 211 diameter cans, 1.74 fold higher for 303 can size and 1.75 fold higher for 401 can size. Capacity comparison between FMC and pilot retorts are shown in Tables 3.8a and 3.8b. It was observed that for pilot retort, the cans would make 3.63, 3.03 and 2.39 revolutions for every bottom third reel rotation in comparison to that of the FMC sterilizer, where cans would make 6.22, 5.24 and 4.11 revolutions for each can size respectively.

			FMC]	Lab Steritor	STOCK Retort		
Can size	Can		No. of	Can c-c	Can w-w	Steps	No. of
	diameter	Steps					cans
	(cm)		Calls	(em)	(CIII)		Calls
208 - 211	6.35	56	112	8.55	1.74	33	66
300 - 303	7.62	47	94	10.2	2.10	27	54
307 - 409	8.73	35	70	13.7	3.36	20	40

Table 3.8a Capacity comparison between FMC lab Steritort vs. STOCK retort

	FMC		ST	To achieve same effect	
	Rev. in	Rev. in fixed	Rev. in its	Rev. in fixed	factor to be
Can size	its axis	mode	axis	mode	multiplied
208 - 211	6.22	1	4.66	1	1.7
300 - 303	5.24	1	3.90	1	1.7
307 - 409	4.11	. 1	3.39	1	1.7

 Table 3.8b
 Comparison between FMC lab Steritort and modified STOCK retort per revolution

3.5 Conclusions

Modification of the pilot STOCK (rotomat) retort was accomplished to accommodate the space-restrained rotating cans in a manner similar to those in FMC turbo cooker simulators (FMC Steritorts). The modified STOCK retort facilitated the free axial rotation of the cans (akin to FMC steritort) with an equivalent free rotational angle of 100°. In order to achieve the similar agitation (free axial mode) effect, the rotation speed in STOCK retort had to be augmented by 1.7 times. The heating rate index (f_h), C_o/F_o and overall heat transfer coefficient U were functions of the product and system parameters such as speed, temperature and concentration during the rotational processing (free axial and E-O-E). The overall heat transfer coefficient (U) was significantly higher in the case of free axial mode (340 W/m²C) as compared to the E-O-E mode (253 W/m²C). The C_o/F_o value was significantly lower in the free axial mode than in E-O-E mode. This illustrates a better quality retention potential for the processed product in the free axial mode. Rotation speed and concentration had a major effect (p<0.001) on U, whereas the temperature had the least effect (p<0.05).

PREFACE TO CHAPTER 4

In Chapter 3, heat transfer rates between the end-over-end and free axial modes were compared in detail. To calculate the overall heat transfer coefficient in free axial mode, temperature profiles were recorded using S28NR wired rotating thermocouple (with a slip ring attached to the can lid).

In continuous retorts, the food containers are in constant motion from the time they enter the system to the time they leave it. This makes monitoring of the temperature in these containers using thermocouple and the accompanying wires very cumbersome. Moreover, data from these devices are generally subjected to more noise and lower stability. The wires also can become tangled during the process. To avoid these complications, new wireless sensors have been commercially developed and used in recent thermal processing applications. Concerns have been raised, however, with respect to their appropriateness and accuracy depending on the type of product and container in questions. Obviously these are lot more convenient to use than the thermocouples in rotary systems. This chapter compares the performance of the thermocouple vs. the wireless sensor for data gathering.

Part of this research has been presented in 2006 AAFC Joint conference, Montreal, PQ, and prepared for publications in a scientific journal. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.

CHAPTER 4

COMPARATIVE STUDY OF WIRELESS VERSUS STANDARD THERMOCOUPLES FOR DATA GATHERING AND ANALYSES IN ROTARY AUTOCLAVES

4.1 Abstract

In order to meet the recent industrial demand to optimize the thermal process in rotary autoclaves, it is imperative that time temperature data during processing be accurately gathered. Accurate temperature recording/monitoring makes it possible to adhere to the scheduled process, assure better product quality, consistency, stability and safety. To gather temperature data in rotary retorts, standard thermocouples equipped with a slip ring assembly are used together with a data acquisition set up. A bi-axially rotating can as in continuous autoclave simulators would require two such slip rings; one at the can level and one at the retort level, making the data gathering more cumbersome. In real continuous systems, wired thermocouples become totally impractical because they cannot be attached to cans going in and out of the system through a helix. To assist in such scenarios, self-contained 'wireless' sensors have been created which can be positioned in to a can and a built-in an electronic device would continuously gather the data during the process which is subsequently downloaded to a computer for analyses. This study was carried out to compare the performance of such a wireless temperature sensor with a conventional thermocouple for gathering heat penetration data. A CCRD experimental design with three different processing conditions (glycerin concentration, retort temperature and retort speed) was employed using 307×409 cans containing the particulate fluid to compare the performance of the two devices. Experiments were performed in a fixed axial mode of rotation in a rotary autoclave, and only liquid temperature was measured using both temperature sensors. The heating rate index, f_h , cook value to lethality ratio, C_o/F_o , were evaluated and compared using a T test. Statistically there were no differences in the performance of the two systems with respect to the parameters tested; however, compared to conventional thermocouples, the wireless

sensors were relatively more stable, and more practical for use in rotary autoclaves especially for free axially rotating cans.

4.2 Introduction

One of the practical and assured way for ensuring food safety is the use of thermal sterilization process, and is easily one of the most widely used technique in food industry. It is often important to maximize the production efficiency or throughput in the canning industry by adapting new technologies or implementing more accurate control systems. Based on the knowledge of heat resistance of microorganisms and the heat transfer rate of a specific product, a proper thermal process can be established. In order to successfully establish or implement a sterilization process, it is necessary to gather accurate time temperature data from test cans during the cooking operation. To ensure that each product is adequately processed, the various critical control points in the process calculation need to be satisfied and properly modeled. Theoretical models can be useful tools for the design, optimization and validation of food systems. These mathematical models have also been used to make automatic control and computer-based on-line control for retorts and several examples are reported in the literature (Bown, 1982; Holdsworth, 1983; Lappo and Povey, 1986; Teixeira and Tucker, 1997). The usefulness of these theoretical models depends upon the accuracy of the input physical parameters, temperature being the most important one required for process establishment and verification. Besides the thermo-physical properties of the product itself, the overall heat transfer coefficient from the heating medium to the canned liquid (U) and the fluid to particle heat transfer coefficient (h_{fp}) are important parameters (Sablani and Ramaswamy, 1996) in a prediction model. To accurately predict heat transfer coefficient U and h_{fp} also it is necessary to have accurate time-temperature data. For obtaining time-temperature data in the canning industry, thermocouples are the most commonly used temperature gathering devices. Several types of thermocouples exist and the most commonly used ones are the T-type (copper-constantan) and K type (chromel-constantan). In batch thermal processes, food packages generally remain static, and the thermocouples can easily be inserted in to the can and the tip positioned at an appropriate location. Fitting the temperature

transducer onto the food package (the slowest heating point of the food product, which is also the critical point for the sterilization) and wiring the transducer to the main circuit of the measurement system imposes no practical problems. However, in rotary autoclaves, bringing the thermocouple lead wires out of the retort poses a problem and is usually solved by using a slip ring assembly that detaches the static side from the rotary side thereby preventing twisting of the wires during the cage rotation. In continuous thermal processes such as Steritort, hydrostatic tower sterilizer or rotary tunnels, the food packages are constantly in motion and entering the system from one end and leaving from the other, and monitoring of temperature in such containers becomes very cumbersome. In Steritort or a continuous process simulator, the cans remain in the retort through the process and go through the biaxial rotation in confined spaces along a rotary wheel. A second slip ring is attached to the can lid to allow axial movement of the cans. These attachments would normally result in introducing electrical noises and reduce the relative accuracy/precision of the gathered data. Many alternate indirect methods for thermal processing assessment have also been proposed, such as chemical and biological indicators (Silva et al., 1994 and Hendrickx et al., 1995), but the most attractive alternative to these conventional thermocouples is the self-contained "wireless" sensors which have been developed and used in recent thermal processing applications.

A wireless sensor network is a system comprised of radio frequency transceivers, sensors, microcontrollers and power sources. Deployment of wireless sensors and sensor networks in agriculture and food industry is still at the beginning stage, and the application of wireless sensors is still rare. Their obvious advantage is a significant reduction and simplification in wiring harnesses. It has been estimated that typical wiring costs in industrial applications is US 130 - 650 per meter, and so by adopting wireless technology would eliminate 20-80 % of this cost (Wang *et al.*, 2006). More efficient control of the equipment through effective monitoring of the environment would equal even more savings in the overall cost. For example, Honeywell installed a wireless system to monitor steam traps and saved the company US\$ 100,000–300,000 per year (Crossbow Technology Inc., 2004). The main applications of the wireless sensors in agricultural industry can be classified into five categories: environmental monitoring, precision agriculture, machine and process control, building and facility automation and

traceability systems. The development of wireless sensor technology has had setbacks; despite the fact that the great potential of this technology have been recognized by many and that development of this technology has been supported by enthusiastic industry alliances, adoption of wireless technology has not been as fast as one would imagine. One of the main hurdle is the fact that standardization is not yet completed, early adopters are still "smoothing out the bumps" and many potential adopters are waiting on the sidelines for successful and safe adoptions (Wang *et al.*, 2006). In addition, the reliability of this wireless system is unproven and it is considered too risky for process control.

The concern of using wireless sensors in canning industry stems from the fact that when the WTS (Wireless temperature sensor) is inserted in the cold spot, the domain is defined by the system canned food plus sensor. As the WTS has its own finite volume, it is interesting to investigate how the relative dimensions between can and WTS volume influence the temperature measurement at the critical point. An incorrect measurement of cold spot temperature leads to an incorrect calculation of sterility value: if the WTS influences the temperature profiles into the canned food, the canner will obtain wrong information on the sterility value F, leaving the final product over-processed or unsafe. Francesco and Vittorio (2003) pointed out that the larger the WTS, the larger the expected deviation on temperature measurement. When WTS are used in smaller cans, a safety factor must always be applied, remembering that sterility values provided by the tracer are over-estimated. To avoid this problem, often canners over process foods packaged in small can formats, loosing quality attributes but preferring a safe product than the risk of losing part of the production. Francesco and Vittorio (2003) further reported in their study that when the heat is transported through convection (natural and induced as in the case of rotary sterilizers); in this case the influence of WTS insertion on the evaluation of cold spot temperature is negligible. Lesley (1987) performed comparative studies using internally mounted Data Trace Micropack (Mesa Laboratories, Inc., Lakewood, CO) in 300 X 407 three piece cans containing six food products (single strength chicken broth, tomato soup, whole kernel corn in brine, cut green beans in brine, pumpkin, and pork and beans). These were then processed in a still retort operated at 250°F, using the paired thermocouple-remote sensor approach, and the author found that placing the Micropack inside a 300×407 can did not significantly impact the heating characteristics of the food products tested, with the exception of green beans in brine and tomato soup. The exceptions were attributed to differences in sensor-probe diameter and probe uniqueness.

The overall objective of this study was to compare the performance of a standard T-type thermocouples and a wireless temperature sensor for collecting the time-temperature data, and evaluate heat penetration parameters in canned liquid particulate mixtures. More specifically, they were compared with respect to temperature, heating parameters, f_h , and cook value to lethality ratio, C_o/F_o .

4.3 Methodology

4.3.1 Model liquid particulate system

For this study, a simulated model of liquid and particles were used. Glycerin (100 CST at 38°C, Fischer scientific ltd., Montréal) was used as a liquid as it can give different Newtonian viscosity levels of similar nature at different concentration. Glycerin solutions of different concentrations were prepared by dissolving the required weight of pure glycerin in water. Nylon spheres (Small Parts Inc., Miami, FL, USA), 19 mm in diameter, were used as test particulates. Thermo-physical properties of glycerin solutions were obtained from the available literature and the physical properties of Nylon particles were obtained from Sablani (1996), which were assumed to be constant within the range of experimental variables. Cans of size φ 307 × 409 (Home Canning Co., Montreal, QC, Canada) with 25 % (v/v) Nylon particles in the glycerin solution of different concentrations were used in all experiments.

4.3.2 Temperature Measurements

To gather temperature profiles during rotational processing, two cans in fixed axial mode were fitted with CNS copper-constantan needle (T-type) thermocouples (Ecklund-Harrison, Miami, FL, USA). The wires from these cans positioned inside a rotating cage were passed through a 32 slip ring assembly using 24 AWG copper constantan thermocouple wires (Omega Engineering Corp. Stamford, CT). Thermocouple signals were recorded at 1-s intervals using a data acquisition system (HP34970A,

Hewlett, Packard, Loveland, CO.). TrackSense® Pro, FDA compliant wireless loggers (Ellab Inc., Centennial, CO) were also attached to the same two cans with their tips in close proximity with those from the needle thermocouple (Figure 4.1). The TrackSense® Pro logger had a 25 mm diameter, operating range of -50 to + 150 °C with a 0.007 °C resolution and made use of a platinum resistance temperature sensor (Pt-1000). A four-port Track Sense® Pro Master Reader Station (Ellab Inc., Centennial, CO) connected to a PC via USB, RS232 or Ethernet was used for data downloading. By using the USB port, power is supplied directly from PC reducing the need for an external power source. The TrackSense® Pro loggers communicate via induction greatly improving the speed and reliability of data transfer.





Figure 4.1 Temperature measurement set of liquid and particulate mixture in a can in fixed axial mode using T-type thermocouple and wireless sensors.

4.3.3 Preparation of experimental cans and execution of experiment

Temperature sensor fitted test cans were filled with the glycerin solution maintaining a uniform head space of 10 mm in all experiments. Cans were seamed by a manually operated seaming machine (Home Canning Co., Montreal, QC). The prepared cans were subjected to rotational processing in a pilot scale rotary, single cage, full water immersion retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany). Retort heating medium temperature was monitored with 24

gauge Teflon coated copper-constantan thermocouples (Omega Engineering Inc., Stanford, CT), located near the Mercury-in-Glass Thermometer. With the factory installed temperature and pressure controllers, uniform temperature distribution $(\pm 1^{\circ}F)$ and accurate pressure control could be achieved in the retort during test runs. This batch retort could operate in spray, partial and full immersion modes, and the full immersion mode was used.

Dummy cans filled with water were filled in to the cage to provide ballast. Water was preheated in the storage vessel as a rule of thumb to at least 10°C higher than the processing temperature. The preheated water was moved from the storage vessel to the process vessel through positive displacement pump. The hot water showered over the crate and was drawn out through a suction manifold located along the bottom of the process vessel and returned back from the top after reheating thereby completing the circulation system for the sterilizing water. During the sterilization cycle, water temperature and system pressure were maintained at a preset value through the temperature and pressure controllers respectively. At the beginning of the cooling cycle, the hot sterilizing water is pumped back up to the storage drum where it is re-heated to the proper set temperature for the next cycle. The temperature of the sterilizing water is maintained at approximately 100-105°C by the time it is pumped back into the storage drum. The cans were cooled until all particles attained the required temperature. Average come-up time for the retort was 4.5 min even though the water was preheated in the storage vessel. A tacho-generator was used to control the reel speed. The sequencing of the sterilization and cooling cycles in the retort was automatic.

4.3.4 Experimental Design

A central composite rotatable design (CCRD) was used in the study (Table 4.1) with retort temperature (X₁), product concentration (X₂) and rotational speed (X₃) as input experimental variables. Five levels of retort temperatures (111.6, 115, 120, 125 and 128.4°C), fives level of glycerin concentration (70, 76, 85, 94 and 100 %), and five rotational speeds (4, 8, 14, 20 and 24 rpm) were employed as input processing variables. Total 20 experiments based on CCRD were employed. All tests run were repeated twice.

The regression analysis and analysis of variance (ANOVA) were carried out using
the GLM procedure of SAS statistical package (SAS Institute Inc., Cary, NC, USA) to fit the second order polynomial equations for the response given below.

$$Y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_{12} X_1 X_2 + a_{13} X_1 X_3 + a_{23} X_2 X_3 + a_{11} X_1^2 + a_{22} X_2^2 + a_{33} X_3^2 + a_{123} X_1 X_2 X_3$$
(4.1)

(4 1)

In the above equation, a_n refers to constant regression coefficients and X_1 , X_2 and X_3 are coded independent variables. Response surfaces were drawn by the fitted quadratic polynomial equation obtained from GLM analysis. Their significance was judged by determining the probability level that the *F*-statistic calculated from the data as less than 5%. The model adequacies were checked by R^2 and prediction errors.

4.3.5 Heat penetration parameters (f_h and j_{ch}), F_o and C_o values

The heating rate index, f_h was evaluated from the plots of logarithm of temperature difference between the retort and liquid temperature versus time of heating part of the process data. Process lethality, F_o , and cook value, C_o , were calculated for each run by numerical integration of time temperature as represented in the following equations ($z = 10^{\circ}$ C for F_o and 33°C for C_o).

$$F_{o} = \int 10^{(T-121.1)/z} dt$$

$$C = \int 10^{(T-100)/z} dt$$
(4.2)

$$C_o = \int 10^{(1-100)/2} dt \tag{4.3}$$

From these values the C_o/F_o ratio, which is a measure of degree of cooking, was evaluated (Abbatemarco and Ramaswamy, 1993).

4.4 Results and Discussion

4.4.1 Time-temperature profiles

Product time temperature data gathering in rotary autoclaves has been generally done with standard thermocouples and a slip ring assembly. For free axially rotating cans, a slip ring needs to be installed on the can lid and a multi-channel slip ring assembly at the drive shaft of the rotating cage on the retort generally making the time-temperature gathering more difficult. In order to avoid these problems a wireless temperature logger can be used. These sensors generally have self-contained logging systems and the compiled data can be downloaded after completing the process. Such devices have been commercially used even for static retort because of the ease of inserting them to cans and locating the cans inside the retort without getting entangled with the thermocouple wires. They also cause less interference with the natural movement of the materials inside the can and have less of a tendency to break down or tangle, and hence may provide more realistic temperature data.

Figure 4.2a shows the time-temperature profile for both types of temperature sensors used in this study. While comparing the results of both sensors, it can be seen that the two sets of profiles obtained from the wireless sensors and thermocouples overlap well. The thermocouples, however, required a calibration correction factor ranging from $+ 0.77^{\circ}$ C to -0.66° C while the wireless loggers essentially indicated the same temperature as the MIG. Figure 4.2b shows the detailed comparison in the sterilization zone, both yielding the same mean and standard deviations. The differences between the two sensors were more apparent in the early part of the heating as shown in Figure 4.3, and converged rapidly to the same value thereby reducing the difference between the two close to zero. The overall average temperature difference between temperature profiles from wireless sensor and T-type thermocouples over the cook time (8-30 min) (Figure 4.3) was found to be 0.38°C. When the temperature profiles from both types of thermocouples was examined, T-test revealed no significant difference between the two (p>0.05). Figure 4.4a, 4.4b shows the developed accumulated lethality from the two sensors for a test run at 115°C and 125°C up to a total value of 10 min. Again under both conditions, the computed lethality from the two are almost identical and *t*-test showed no significant difference. The first curve is longer than the second since it would take a longer process time at a lower temperature to deliver the same target lethality.



Figure 4.2a Time - temperature profile of liquid particulate mixture in a can in fixed axial mode using T-type thermocouple and wireless sensors.



Figure 4.2b Mean and standard deviations of Time - temperature profile after come up time of liquid in a can in fixed axial mode using T-type thermocouple and wireless sensors.



Figure 4.3 Temperature difference between the thermocouple and wireless sensor during a test run



Figure 4.4 Comparison of accumulated lethality between wireless sensor and T-Type thermocouple (a) Retort temperature 115°C (b) Retort temperature 125°C

4.4.2 Heating rate index

Before choosing a specific temperature sensor, its performance under processing condition needs to be tested for the intended purpose. In most thermal processing applications, for example, computation of accumulated process lethality (general method) as discussed in the preceding paragraph, or to compute the heat penetration parameters like f_h , accurate data gathering on transient temperature is important. The cook value is another indicator which indicates the degree of cooking and has a direct bearing on the effect of the process on product quality. In rotary processes, the principle process variables are rotation speed, product viscosity (glycerin concentration, in this case) and retort temperature. Using 20 runs based on CCRD, this study compared the computed heating rate indexes from using the two temperature sensors (thermocouple and wireless sensors) (Table 4.1). The other parameters were maintained at a preset level: Nylon spheres of 19 mm in diameter as particles, cans of size 307 × 409, a headspace of 10 mm and a particle concentration of 25%.

SAS software was used to calculate the mean value of 7.38 min from the wireless sensor ($f_{h-wireless}$), which was found to be very close to 7.22 min the mean value from the thermocouples ($f_{h-T-type}$) (Table 4.2a). When compared in a *t*-test, as seen in Table 4.2a, there was no significant difference between the two sets of heating rate indexes. This can be easily recognized by the cross plot of f_h from thermocouple vs. f_h from wireless sensor, which demonstrated the data points to be fairly uniformly distributed along the diagonal line and clearly passing through the origin (Figure 4.5). Regression results indicated an R^2 of 0.94, with a slope coefficient of 0.9936 indicating f_h from thermocouples to be about 0.55% lower than that from the wireless sensor.

The influence of WTS insertion can be thus considered almost negligible especially when large cans are used and convection is the mode of heat transfer, as can be seen by the above results. By performing comparative studies using the internally mounted DataTrace Micropack (Mesa Laboratories, Inc., Lakewood, CO) in 300×407 three piece cans, similar results were found by (Lesley, 1987). The cans used contained six food products; single strength chicken broth, tomato soup, whole kernel corn in brine, cut green beans in brine, pumpkin and pork and beans, and were mostly heated by natural

convection in a still retort operated at 121.1°C, using the paired thermocouple-remote sensor approach. Placing the Micropac inside the can of did not significantly impact the heating characteristics of the food products tested.



Figure 4.5 Heating rate index, f_h (Wireless vs. T-type)

Since the f_h data from the two sensors were not statistically different, the pooled data were used to test the influence of reel speed, glycerin concentration and temperature on the heating rate index. Table 4.2a shows the ANOVA data. Speed of rotation (p<0.001), glycerin concentration (p<0.001) and retort temperature (p<0.05), in that order were found to be the dominating factors affecting the f_h .

Run No.	Temperature (°C)	Glycerin Conc. (%)	Retort Speed (rpm)	f _h -Wireless (min)	f _h -T- type (min)	C₀/F₀ Wireless	C₀∕F₀ T-type
1	115(-1)	76(-1)	8(-1)	8.16	8.16	13.17	13.17
2	115(-1)	76(-1)	20(1)	6.30	6.45	12.52	13.03
3	115(-1)	94(1)	8(-1)	9.43	8.75	11.63	13.70
4	115(-1)	94(1)	20(1)	7.25	6.75	12.12	13.31
5	125(1)	76(-1)	8(-1)	8.00	7.80	3.72	3.76
6	125(1)	76(-1)	20(1)	6.20	6.30	3.07	2.97
7	125(1)	94(1)	8(-1)	8.00	8.40	3.90	4.14
8	125(1)	94(1)	20(1)	6.50	6.40	3.33	3.90
9	120(0)	85(0)	4(-1.68)	8.40	8.10	8.14	8.20
10	120(0)	85(0)	24(1.68)	6.60	6.30	7.29	8.07
11	111.6(-1.68)	85(0)	14(0)	7.65	7.70	21.06	21.96
12	111.6(-1.68)	85(0)	20(1)	6.92	6.70	20.85	23.02
13	120(0)	100(1.68)	14(0)	8.62	8.51	8.23	8.37
14	120(0)	100(1.68)	20(1)	6.30	6.10	7.60	8.51
15	128.4(1.68)	85(0)	14(0)	7.35	7.51	2.28	3.10
16	128.4(1.68)	85(0)	20(1)	6.28	6.40	2.32	1.99
17	120(0)	70(-1.68)	14(0)	6.10	6.40	4.10	4.30
18	120(0)	70(-1.68)	20(1)	4.95	5.10	4.60	4.80
19	120(0)	85(0)	14(0)	7.45	7.90	5.76	6.00
20	120(0)	85(0)	8(-1)	9.00	8.70	5.22	5.67

Table 4.1Experimental runs following CCRD to study the effect on f_h (Wireless vs.
T-type thermocouples)

Description	Wireless Sensor	T-type Thermocouple
Mean	7.38 min	7.22 min
Variance	1.41	1.10
Observations	20	20
df	37	
P (T≤ t) one tail	0.49	
t Critical one-tail	1.68	
P (T≤ <i>t</i>) two-tail	0.98	
t Critical two-tail	2.02	

Table 4.2a. T test between f_h of wireless sensors vs. T- Type thermocouples

Table 4.2b Analysis of variance (ANOVA) results of combined data for heating rate index

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	0.63	8.93	<0.0105
Product Concentration (C)	2.86	40.27	<0.0001
Retort rpm (R)	8.65	121.72	<0.0001
Τ×C	0.46	6.48	0.0244
$T \times R$	0.068	0.96	0.3444
$\mathbf{R} \times \mathbf{C}$	0.00005	0.0007	0.9792

The response plots of f_h vs. two variables taken at a time are shown in Figure 4.6. Increasing the rotational speed from 4 rpm to 24 rpm and the glycerin concentration from 70% to 100% at a processing temperature of 120°C resulted in f_h values increasing from 6.20 to 9.43 min. The regression model (Eq.4) developed from the combined experimental data from the two sensors was considered significant with an R^2 value of 0.93.

$$f_h = 7.46 - 0.22 \times T + 0.46 \times C - 0.80 \times R - 0.24 \times T \times C + 0.093 \times T \times R \tag{4.4}$$



Figure 4.6 Effect of retort rotational speed, retort temperature and glycerin concentration on heating rate index, f_h

4.4.3 Co/Fo

The optimization of the thermal process in terms of quality is possible, considering that the thermal destruction of microorganisms is much more temperature

dependant than the degradation of product quality and nutrition. It is suggested, based on the differences in temperature sensitivity, that high temperature short time processing (HTST) is best. With respect to microbial destruction, F_o value (process lethality) is the common parameter that is employed to measure adequacy of a thermal process. C_o (cook value) indicates cumulative equivalent cooking minute at 100°C, and is the other closely associated parameter. The objective in process optimization is to increase the rate of achieving F_o but limit that of C_o . Since they both depend on the temperature, but with a different sensitivity factor (usually 10°C for microbial spore vs. 33°C for cook value (Eqs. 4.2-4.3), it would be possible to get this at a higher temperature. The objective is simply to decrease the C_o/F_o value (Ramaswamy *et al.*, 1993).

As with F_o and f_h , the influence of using the two different sensors was first tested for C_o/F_o (Table 4.1). The two sets of C_o/F_o values were found to have no significant difference between them, as seen in Table 4.3a. Again, experimental C_o/F_o data obtained from the two types of thermocouples are compared in Figure 4.7 which showed an excellent fit with R^2 of 0.99, passing through the origin. In Table 4.3b, the analysis of variance showed that while the rotation speed within the range studied did not show a significant influence (p>0.05), C_o/F_o values were highly influenced by the temperature (p<0.001) and glycerin concentration (p<0.05). Models for C_o/F_o were developed for the combined data obtained from the T-type and wireless sensors and the R^2 for the model was 0.96.

$$C_o / F_o = 5.63 - 4.91 \times T + 0.69 \times C - 0.21 \times R + 1.89 \times T \times T -$$
(4.5)
$$0.13 \times T \times R + 0.15 \times C \times R$$

Description	Wireless Sensor	T-type Thermocouple	
Mean	8.0455	8.5985	
Variance	31.54	36.57	
Observations	20	20	
df	38		
p (T<=t) one tail	0.38		
t Critical one tail	1.68		
$p(T \le t)$ two tail	0.76		
T Critical two tail	2.02		

Table 4.3a t- test between C_o/F_o of Wireless sensors versus T- type thermocouples

Note: p>0.05 indicates no significant difference.

Table 4.3b	Analysis of variance (ANOVA) results of for the combined data for C_o/F_o
	value

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	328.74	136.90	<0.00001
Product Concentration (C)	56.15	25.17	<0.01
Retort rpm (R)	6.51	8.25	.15
ТХТ	51.96	21.64	<0.01
T X R	0.14	0.058	0.81
RXC	0.19	0.077	0.78



Figure 4.7 C_o/F_o (Wireless vs. T-type thermocouple).

Combined C_o/F_o values from two types of sensors ranged from 2.0 to 23 when the temperature was increased from 111.6 to 128.4 °C and glycerin concentration was raised from 70 to 100% (Figure 4.8). The degree of cooking can therefore be reduced significantly if the process is carried out at a higher temperature, and high temperature short time processing could prove to be very useful. Increasing the rotational speed had a limited effect on C_o/F_o , while concentration increased the C_o/F_o values.



Figure 4.8 Effect of glycerin concentration, rotational speed and retort temperature on C_o/F_o value.

4.5 Conclusions

Performance of wireless temperature sensors were analyzed relative to conventional thermocouple sensors for temperature monitoring during canned food sterilization. Statistically the two sensors were no different (p>0.05) with respect to gathered temperature data, or computed f_h , F_o , C_o/F_o values. Either could be used for the data gathering. Thermocouples are simple, inexpensive and widely available, and can be linked to any one of the thousands of temperature logging equipment (both hand held and the more sophisticated). However, for use in rotary autoclaves they require special equipment in the form of slip rings and are not very convenient. They also need special tools and considerable lengths of thermocouple wires to bring the signal out of the retort. For free axially rotating cans, they become even more complex requiring one more slip ring at the can level. These attachments often result in considerable noise and require accurate calibration. On the other hand, the wireless sensors are simple to attach to cans and simple to use. They require no wiring. The signals are usually processed electronically and the resulting temperature outputs are relatively much smoother. For rotary retorts, they offer terrific advantages and in continuous flow rotary systems they may be the only reliable choice. They are however relatively very expensive and are available only through selected suppliers.

PREFACE TO CHAPTER 5

Temperature data on the liquid and particle undergoing the agitation process are needed to evaluate the fluid to particle heat transfer coefficient, h_{fp} , and the overall heat transfer coefficient, U. Attaching the temperature devices to the particles and liquid in free axially rotating cans poses serious problems. Ideally, the act of measuring the temperature should not affect the normal motion of the can during agitated processing. These problems are compounded when the can being monitored is in axial rotation, because of the two levels of rotation that need to be accommodated; one at the can level to facilitate can rotation around its own axis, and the other at cage level when the cans move in a rotary fashion along with the cage. While these can be accomplished in fixed axial modes, it would be impractical in the free axial mode. Hence evaluation of h_{fp} is difficult in these systems. Much of the reported data only refers to U and even that would be difficult when particles are present in the container.

In this chapter, a methodology was established based on an empirical approach to evaluate the heat transfer coefficients (U and h_{fp}) in free axial mode of rotation using the gathered liquid temperature data (which can be gathered using a wireless sensor). In order to develop typical relationship between U and h_{fp} , they were first obtained using fixed axial system using data gathered for both particle and liquid temperatures.

Part of this research was presented in 2007 Annual Meeting of the IFTPS (San Antonio, TX), and won the Charles Stumbo Graduate Student paper competition award (first place). Part of this research has also been presented in 2006 IFT Annual Meeting, Orlando, FL and 2006 NABEC Annual meeting, Montreal, and prepared for publications in a scientific journal. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.

CHAPTER 5

AN EMPIRICAL METHODOLOGY FOR EVALUATING THE FLUID TO PARTICLE HEAT TRANSFER COEFFICIENT IN BI-AXIALLY ROTATING CANS USING LIQUID TEMPERATURE DATA

5.1 Abstract

An empirical methodology was developed for evaluating the fluid to particle heat transfer coefficient (h_{fv}) and overall heat transfer coefficient (U) in bi-axially rotating cans. Conventional particle temperature measurement during thermal processing is generally difficult in cans undergoing agitation processing, and is even more difficult in cans going through bi-axial free rotation as in continuous flow turbo cookers. Thin wire flexible thermocouples have helped gathering temperature data of both particle and liquid in endover-end batch processes. Wireless temperature loggers have been developed for liquid temperature measurements in continuous flow systems which can be used to estimate U. Evaluation of h_{fp} is still difficult in these systems due to the difficulty in gathering particle temperatures. The proposed method involves developing correlations between h_{fp} and U using real time-temperature data gathered from test cans in fixed axial mode and then coupling them with experimentally evaluated U from fluid temperature gathered with wireless sensors to compute h_{tp} for bi-axially rotating cans. The methodology is based on the assumption that within a can, factors that influence U will also influence h_{fp} , and therefore h_{fp} and U are generally inter-related. A three factor, five level central composite rotatatable design (CCRD) and a response surface methodology was used to develop the correlation models for the U and h_{fp} in fixed axial mode with retort temperature (111.6-128.4°C), glycerin concentration (80-100%) and rotational speed (4-24 rpm) as the main factors. The developed model was used to evaluate the U and h_{fp} in the free bi-axial mode, using a full factorial design $(3 \times 3 \text{ factorial})$. The method was successfully implemented and an analysis of variance study, as expected, indicated all three major factors to influence the U and h_{fp} values. Glycerin concentration and rotation

speed were highly significant (p<0.001), while temperature was marginally significant (p<0.05) with respect to U while all factors were significant with respect to h_{fp} .

5.2 Introduction

Modeling of the heat sterilization of canned food in continuous rotary sterilizers entails knowledge of two parameters which are: the overall heat transfer coefficient (U)between the external heating medium and the can fluid, and the fluid to particle heat transfer coefficients h_{fp} between the can fluid and particles (Sablani & Ramaswamy, 1996). Traditionally for heat transfer coefficient calculations the temperature of the can fluid and the particle temperature must be known as a function of time. Evaluation of the heat transfer coefficients (Overall, U and fluid to particle, h_{fp}) associated with canned liquid particle mixtures in agitating retorts becomes challenging because of the difficulties involved in attaching the temperature measuring devices to the liquid and particles. Usually, the temperature should be measured without affecting the normal motion of the fluid mixture in the can. Secondly, during the motion of the can during the agitation processing, these particles and attachments frequently fail due to breakage or give faulty signals due to mechanical and electrical disturbances. These procedures become even more complex in axially rotating cans because of the two levels of rotation that need to be accommodated, one at the can level to facilitate can rotation around its own axis and the other one at the cage level when the cans move in a rotary fashion along with the cage. Similar to the traditional thermal processing, it is also necessary for the particles and fluid to receive the predetermined minimum heat treatment in the form of minimum process lethality (F_o) during agitation processing. In order to predict the heat penetration data and to fully understand and mathematically describe the mechanism of heat transfer in liquid particle systems, it is necessary to have data on the associated heat transfer coefficients (Deniston et al., 1987; Hassan, 1984 and Merson, 1990). For the proper design and successful optimization of the rotational retort process, a felicitous methodology to predict particle lethality during processing is extremely helpful.

Several studies have been conducted on the evaluation of heat transfer to canned liquid particulate mixtures in end-over-end rotation (Lekwauwa and Hayakawa, 1986;

Sablani and Ramaswamy, 1995, 1996, 1997, 1998, 1999; Krishnamurthy *et al.*, 2000 and Meng and Ramaswamy, 2005); however, there are very few studies available to determine U and h_{fp} in axial mode of rotation (Lenz and Lund, 1978; Hassan, 1984; Deniston *et al.*, 1987; Fernandez *et al.*, 1988 and Stoforos and Merson, 1990, 1991). Furthermore, there are several limitations associated with the axial mode methods applied to predict lethality during heating for the real food particle system with finite internal and surface resistance to heat transfer ($0.1 < N_{Bi} < 40$).

Lenz and Lund (1978) and Fernandez et al. (1988) measured the fluid-to-particle heat transfer coefficient in Steritort using a metal particle to give a low Biot number (Bi<0.01) condition and used lumped capacity approach for h_{fp} evaluation. In addition, the particle movement was completely restricted due to its secured location inside the can. When particle is freely rotating, the h_{fp} will be influenced by the relative velocity between particles and liquid. In such situations, it would not be wise to use metal particles as their density is significantly different from real food particles. Hassan (1984) and Deniston et al. (1987) used an overall energy balance approach to measure the h_{fp} in free axially rotating cans; they acknowledged the difficulties and errors related to the measurement of the surface temperatures. A mathematical procedure was used by Stoforos and Merson (1990) which required only the measurement of liquid temperature to estimate h_{fp} and U. This method allowed a free rotation of the particles. Stoforos and Merson (1990) found that calculated h_{fp} values were not in accordance with those determined from direct particle surface temperature measurements. However, for this procedure, Maesmans et al. (1992) brought up the concern that these measurements were not accurate because the two parameters were estimated from only one input parameter. To facilitate a free rotation of the particles in the can during axial agitation, Stoforos and Merson (1991) coated particles with liquid crystals and used them to measure the surface temperature. However, the study was conducted at low temperatures (20 to 50°C) which are not applicable to the sterilization process. Circular rotation of the can (fixed axial) in the set up used by researchers Hassan (1984), Deniston et al. (1987) and Stoforos and Merson (1990 and 1991) was only one-directional, whereas the motion of the can in a Steritort is bi-axial across the bottom of the retort. Nonetheless, the most widely used continuous sterilization system in industry are Steritorts (FMC Corp., San Jose, CA), providing biaxial rotation of the cans which results in better mixing and enhanced heat transfer in comparison to the unidirectional rotation of the can in end-over-end (E-O-E) rotation systems.

In the free axial continuous rotary systems, the cans are continuously fed onto a revolving helical reel. There are three different phases of rotation which are: fixed reel, transitional and free reel motion across the bottom of the retort. The fixed reel motion occurs at an angle of 220° of a cycle, the free rotation over the bottom angle of 100° , and the transitional motion takes place at an angle of 20° on either side of the free rotation. The beneficial factors generated by using free rotational mode constitutes expeditious and uniform heating which leads to enhanced productivity and efficiency of the process equipment, thereby reducing the production costs including direct labor costs. It also helps in reducing the floor space as only a limited number of auxiliary equipments are required. Furthermore, the steam and cooling water consumption is also decreased due to the regeneration of steam (Fernandez *et al.*, 1988).

Recent studies (Tattiyakul *et al.*, 2001, 2002; Hughes *et al.* 2003; Varma and Kannan, 2005, and James *et al.*, 2006.) used computational fluid dynamics (CFD) as well as experimental work to examine the underlying mechanism of heat transfer in liquid food during rotary processing. Several studies have also been carried out at McGill University to evaluate heat transfer to liquid particle mixtures in cans for end-over-end processing and the methodology has been standardized to measure the heat transfer coefficients. These studies have been done by allowing free movement of the particle inside the can by attaching it to a flexible, thin wire thermocouple (Sablani and Ramaswamy, 1996 and Meng and Ramaswamy, 2005). However, there are only limited studies available on the measurement of heat transfer coefficients in the axial agitation processing similar to FMC Steritort in cans containing a liquid particulate system. Also, the use of wireless sensors to measure the temperature profile for h_{fp} and U evaluation has been limited in previous studies.

The objective of this study is to establish a methodology to evaluate heat transfer coefficients during the thermal processing of the liquid particulate system associated with free axially rotating cans during commonly employed thermal processing conditions.

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5.3 Materials and Methods

5.3.1 Retort cage modifications

A single car rotary retort (STOCK rotomat - PR900; Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany) was used in the study. The retort basket was retrofitted with a stainless steel (SUS 306) enclosure in which test cans could be held in an axial direction. Cans were positioned by using rear and front stainless steel supports, which were fixed to the retort basket. The fabricated enclosures held two free cans on each side of the frame. On one side, end plate facing the retort shell was removed so that the cans could slide down and rolls along the retort shell during part of the rotation (Figure 3.1). These cans rolled on their own axis (in a direction counter to that of retort cage) along the bottom of the retort shell when the opening was facing downwards (approximately $1/3^{rd}$ of the rotation in facing downward) simulating the action in a Steritort. In the top $2/3^{rd}$ of the cage rotation, the cans were restrained in the enclosure only rotating with the cage. This process caused biaxial rotation of the can in the free axial mode, while only in clockwise direction in the fixed axial mode. The two cans held at the opposite end were held inside in a fixed axial mode and was not allowed to drop on to the retort shell.

5.3.2 Test particulates and covering fluid

In order to evaluate the thermal processing system performance, it is preferable to use food simulating materials (rather than real food) with well defined thermo-physical property data so that consistent results could be obtained for evaluated parameters like heat transfer coefficients. This will overcome the uncertainty imposed on the results from the variability associated with the thermo-physical property data which, for real foods often depend on their chemical composition and structure which vary widely. In this study, a model liquid and particle system was used. Glycerin (Fischer Scientific., Montréal, PQ) was used to simulate Newtonian fluids with a broad range of viscosity. Glycerin solutions of different concentrations were prepared by diluting pure glycerin solution with distilled water. The density of diluted glycerin solution was determined from the mass of a known volume of the glycerin solution. Thermal properties of water and of glycerin solutions at different concentrations were taken from the literature available (Meng, 2006), which are summarized in Table 5.1.

Spherical Nylon particles (Small Parts Inc., Miami, FL), 19 mm in diameter, were used as test particulates. Thermo-physical properties of Nylon particles were obtained from Sablani (1996), and were assumed to be constant within the range of experimental variables as summarized in Table 5.1. Cans of nominal size 307×409 with 30% (v/v) Nylon particles in the glycerin solution of different concentrations were used in all experiments.

Material	Density (kg/m ³)	Heat Capacity (J/kgC)	Thermal Conductivity (W/mC)	Thermal diffusivity (m ² /s)
Nylon	1128	2073	0.369	1.52X10 ⁻⁷
Glycerin (100%)	1260	2430	-	-
Glycerin (96%)	1247	2500	-	-
Glycerin (90 %)	1234	2570	-	-
Glycerin (80 %)	1208	2720	-	-

Table 5.1Thermophysical properties of test materials

5.3.3 Temperature measurement

To measure the temperature of the can fluid in the end-over-end and fixed axial modes, test cans were fitted with CNS copper-constantan needle-type thermocouples (Ecklund-Harrison Technologies Inc., Miami, FL) with their tips positioned at the can center. The locking connector (C-10) included a threaded ring that screwed onto the external thread on the locking receptacle, thereby securing the connection during processing. The thermocouple wires from the all test cans and those used to measure retort temperature were passed through a 32 slip ring assembly, and connected to a data acquisition system (HP34970A, Hewlett, Packard, Loveland, CO). Thermocouple signals were recorded at 1 second intervals. The prepared cans were subjected to rotational processing (E-O-E and axial mode) in the Stock rotary retort. Retort heating medium temperature was monitored using a 24 gauge Teflon coated copper-constantan

thermocouple (Omega Engineering Inc., Stanford, CT), located near the mercury-in-glass thermometer.

In order to estimate the heat transfer coefficient at the particle-fluid interface, the temperature of the fluid as well as the center temperature of the test particle are needed. Nylon particles were used in the experiment. The thermocouple wires (diameter 0.0762 mm, Omega Engineering Corp., Stamford, CT) for measuring the particle temperature were introduced into the particle center through a fine hole drilled using a horizontal lathe and were fixed by a small amount of epoxy glue. Thermocouple leads from the retort were connected to the slip ring assembly at the end of the rotating shaft. The procedure for attaching the thermocouple to the Nylon particle and for preparing the test cans was same as detailed in Sablani and Ramaswamy (1996).

For conducting the heat penetration tests in bi-axially rotating cans, Track Sense® Pro (Ellab Inc., Centennial CO), a FDA compliant wireless multi-channel data-logging system, was used to measure the temperature of the liquid (Figure 5.1). Operating ranges of the wireless sensors varied between ⁻50°C to +150 °C and resolution of 0.007°C could be achieved. In order to read the temperature from the wireless loggers, the Track Sense® Pro master reader station was used, which had 4 ports for loggers and was connected to the PC via USB, RS232 or Ethernet. By using the USB port, power was supplied directly from the PC, reducing the need for an external power source. The Track Sense® Pro loggers communicate via induction, thus greatly improving the speed and reliability of the data transfer. Val Suite 2.0 software (Ellab Inc., Centennial CO) was used to record data from the Track Sense® Pro at one second intervals.

Retort temperature and the center temperatures in the cans and particles were measured continuously during the heating period. In each experiment, the heating time was prolonged sufficiently so that the liquid and particle temperatures could be equilibrated to the retort heating medium temperature. The equilibrated liquid temperature was corrected to match the retort temperature as measured by mercury-inglass thermometer installed on the retort. Since small differences in initial and retort temperatures were inevitable, the data was therefore normalized to an initial temperature of 25°C and the respective set points of retort temperatures at 111.6, 115, 120, 125 and 128.4 °C, which was according to a procedure detailed in Stumbo (1973).



a. T-Type Thermocouple (Fixed Axial Mode) b. Wireless sensor (Free Axial Mode)

Figure 5.1 Temperature measurement set up for liquid and particle in a can in fixed and free axial mode using T-type thermocouple and wireless sensors

5.3.4 Experimental set up

In the fixed axial mode, the two cans equipped with T-Type thermocouples placed at the opposite end were secured in a fixed mode and rotated only with the cage (Figure 3.1). Dummy cans of size 307×409 filled with water were fitted in to the cage to provide ballast. Water was preheated in the storage vessel as a rule of thumb to at least 10° C higher than the processing temperature. The preheated water was moved from the storage vessel to the process vessel through a positive displacement pump. The hot water showered over the crate and was drawn out through a suction manifold located along the bottom of the process vessel and returned back from the top after reheating thereby completing the circulation system for the sterilizing water. During the sterilization cycle, water temperature and system pressure were maintained at a preset value through the temperature and pressure controllers respectively. At the beginning of the cooling cycle, the hot sterilizing water is pumped back up to the storage drum where it is re-heated to the proper set temperature for the next cycle. The temperature of the sterilizing water is maintained at approximately 100-105°C by the time it is pumped back into the storage drum. The cans were cooled until all particles attained the required temperature. Average come-up time for the retort was 4.5 min even though the water was preheated in the storage vessel. A tacho-generator was used to control the reel speed. The sequencing of the sterilization and cooling cycles in the retort was automatic.

To process the cans in free axial mode, the two cans outfitted with wireless sensors and placed in between the special attachment were only restrained. During one third of the rotational cycle, these cans were allowed to roll against the shell of the retort; as the can rolled, head space traveled along the cylindrical contour of the can, resulting in a better mixing of the contents.

5.3.5 Governing equations and data analysis

5.3.5.1 Calculation of U and h_{fp} in fixed axial mode

The governing differential equation for the liquid particulate systems during agitation processing are derived from thermal energy balances by assuming that the fluid temperature is uniform, the heat transfer coefficients are constant, the initial temperature for both the fluid and the particles are uniform, the resistance to heat transfer at the particle surface is finite, the diameter of the spherical particles are constant and the physical and thermal properties for both the fluid and particles are isotropic. The overall heat transfer coefficient, U, can be determined by the equation below, provided the amount of heat transferred across the can wall is equal to the heat absorbed by the particle and the fluid (Sablani and Ramaswamy, 1996).

$$UA_{c} \int_{0}^{t_{p_{l}}} (T_{R} - T_{l}) dt = m_{l} C_{pl} \int_{t_{l}=0}^{t_{p_{l}}} dT_{l} + h_{fp} A_{p} \int_{t_{l}=0}^{t_{p_{l}}} (T_{l} - T_{ps}) dt$$
(5.1)

In this equation, the integrating time t_{pt} is the time required to achieve a lethality of 10 minutes at the particle centre, and this could be obtained from the determination of h_{fp} .

The differential equation describing the heat transfer from continuous phase to the particle center is based on Fourier's equation, established by a French physicist, Jean Baptiste Joseph Fourier (1768-1830) and is written as:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{5.2}$$

 $\alpha = k/\rho C_p$, where ρ is the density (Kg/m³), C_p , the specific heat or heat capacity (J/kgC), k the thermal conductivity (W/mC), α , the thermal diffusivity (m²/s), and v^2 , the Laplace operator, given by

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$
(5.3)

It was also assumed that the particles received heat only from the liquid and not from the can walls when it impacts, i.e. heat is transferred first from the can wall to the liquid and then to the particle. For example, heat flow in a spherical particle immersed in liquid can be described by the following partial differential equation:

$$\frac{\partial T}{\partial t} = \alpha_p \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right)$$
(5.4)

The initial and boundary conditions are:

$$T(r, 0) = Ti \text{ at } t=0$$
 (5.5)

$$k_{p}\frac{\partial T}{\partial r} = h_{fp}(T_{l} - T_{ps}) \text{ at } r = a$$
(5.6)

Process lethality, F_{o} , indicates its severity with respect to microbial destruction and is the key in process time establishment. F_o can be calculated for each run by numerical integration of time temperature as represented in the following equations ($z = 10^{\circ}$ C) for F_o .

$$F_o = \int 10^{(T-121.1)/z} dt \tag{5.7}$$

If the particle and liquid transient temperatures are available, then the h_{fp} can be evaluated iteratively by solving Eq. 5.4 (Sablani and Ramaswamy, 1996). This is illustrated in Figure 5.2. First a typical h_{fp} value was assumed and the temperature history of the particles, and the resulting lethality value at the particle center were obtained using Eq. 5.7 based on the experimentally determined liquid temperature data. The computed lethality was then compared with the lethality value of the particle center based on the measured temperature history of the particle. The difference between the two values of lethality (predicted and experimental) (the objective function) was minimized through iteration. The lethality was used as the objective function in this study as used in a previous study (Sablani and Ramaswamy, 1996); however, this can also be based on predicted and experimental particle center temperatures. By sequentially changing the h_{fp} value, the objective function was minimized, which nearly matched the predicted and measured lethality values at the particle center to a preset value of 10 minutes, and the corresponding h_{fp} value was considered to represent the specific processing condition. The overall heat transfer coefficient (*U*) was then computed by solving the energy balance equation Eq. 5.1 by carrying out the integration up to the same process time. Analytical solution for Eq. 5.2, with a convective boundary condition, is complex due to liquid temperatures that varied with time. Numerical solutions based on finite differences are simpler and were used in this study as well as in many other previous reported works (Teixeira *et al.*, 1969; *et al.*, 1992; Sablani and Ramaswamy, 1996 and Meng and Ramaswamy, 2005).

5.3.5.2 Empirical method for the evaluation of h_{fp} in free axial mode

The computational technique for evaluating U and h_{fp} from liquid and particle time temperature data gathered from the fixed axial mode was discussed in the previous section and illustrated in Figure 5.2. A similar technique for the free axial mode was not possible because it was not possible to gather particle temperature data. Therefore, in order to get estimates of these parameters, an empirical approach was used. Under a wide range of similar processing conditions in the fixed axial mode, U and h_{fp} were obtained from the measured liquid and particle temperature data. Then comprehensive relationships were obtained for both U and h_{fp} as a function of processing conditions. The data in general demonstrated a fairly good correlation between the two for any given processing condition. It was then hypothesized that a similar relationship would exist in free axial rotary condition as well, where a higher U normally exists providing a correspondingly higher h_{fp} value. Still it is not simple because to measure the U under free axial rotation, an estimate of h_{fp} is still needed, in Eq. 5.1. To solve this problem, first thus, h_{fp}/U value was obtained from the fixed axial mode (Figure 5.2). Then a value of U was assumed for the free axial mode and multiplied by the h_{fp}/U value to get the estimate of h_{fp} . Then, Eq. 5.1 together with Eq. 5.6 were solved to compute the liquid temperature in the free axial mode. This was then compared with the liquid temperature in the free axial mode and their difference was minimized (see Figure 5.3 for details). The U value that meets the minimization was taken to represent the free axial rotation and the corresponding h_{fp} was then easily computed.

5.3.6 Experimental design and statistical analysis

A response surface methodology was used to develop models for the U and h_{fp} in fixed axial mode with retort temperature (X₁), liquid concentration (X₂) and rotational speed (X₃) as independent input experimental variables. A three variable, five level central composite rotatable design (CCRD) was used. The design consisted of 20 experimental points performed in a random order. All the tests run were repeated twice. The center runs provided a means for estimating the experimental error and to measure lack of fit, and the axial points were added to the factorial design to estimate the curvature of the model. The regression analysis and analysis of variance (ANOVA) were carried out using the GLM procedure of SAS statistical package (SAS Institute Inc., Cary, NC) to fit the second order polynomial equations for the response given below:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + a_{12} X_1 X_2 + a_{13} X_1 X_3 + a_{23} X_2 X_3 + a_{11} X_1^2 + a_{22} X_2^2 + a_{33} X_3^2 + a_{123} X_1 X_2 X_3$$
(5.8)

In the above equation, a_n refers to constant regression coefficients and X_1 , X_2 and X_3 are coded independent variables. Response surfaces were drawn by the fitted quadratic polynomial equation obtained from GLM analysis. Their significance was judged by determining the probability level that the *F*-statistic calculated from the data as less than 5%. The model adequacies were checked by R^2 and root mean square error (RMS). Statistically, a good model will have a large predicted R^2 , and a low RMS.

With the new approach developed to measure the U and h_{fp} in free axial mode, a simple full factorial design (3 × 3 factorial) was used to test their response to input variables (more detailed evaluation of factors affecting U and h_{fp} in free axial mode are detailed in chapter 6). Statistical analyses used to obtain means, SD of means and analysis of variance (ANOVA) were performed through the statistical package of SAS. Values were considered different from each other at p < 0.05.







Figure 5.3 Flow chart to calculate h_{fp} and U in free axial mode

5.4 Results and Discussion

5.4.1 U and h_{fp} in fixed axial mode

Typical temperature profiles of the liquid and particle as well as the retort medium during a test run involving fixed axial rotation is shown in Figure 5.4a. As can be expected the retort reached the set point temperature much faster followed by the liquid and subsequently by the particle. The experiment was conducted for an accumulated lethality value of 10 minutes at the particle center. Figure 5.4b shows the

typical lethality plot used for predicting the fluid to particle heat transfer coefficient, demonstrating an excellent fit for the predicted and experimental lethality when the objective function was minimized (Figure 5.3). As an illustration the predicted lethality curve at an assumed lower value of h_{fp} is also shown in Figure 5.4b which underpredicted the experimental lethality. In Figure 5.4a, predicted time temperature profile at the particle center using the estimated h_{fp} is also shown. Predicted temperatures showed a better match with experimental in the latter part of the heat penetration test curve when the particle temperatures were higher. The better match at the higher temperature level was obviously due to the use of process lethality as the objective function, because of which more weight was given to higher temperatures due to their higher contribution to the lethality. For the same reason, the experimental vs. predicted lethality measured at the center of the particle always showed a better match (Figure 5.4b). Sablani and Ramaswamy (1996) earlier compared both the temperature and lethality approach for h_{fp} determination and recommended the use of lethality as the objective function.

U and h_{fp} values associated with selected conditions in the fixed axial mode are listed in Table 5.2 demonstrating an increase in both values with an increase in the rotation speed.

5.4.2 Effect of process parameters on U and h_{fp}

5.4.2.1 Under fixed axial mode

Most commercial systems use either end-over-end (used in most batch rotary retorts) or free axial (most continuous flow systems) agitation process. The fixed axial system is not widely used in commercial system although with a patented recent system (Shaka, Covington, LA, USA) fixed axial configuration is possible. Hence data presented in Table 5.2 were used to evaluate the influence of some of the process variables on the associated heat transfer in the fixed axial mode. Table 5.4 shows the ANOVA results for the effect of rpm, temperature and concentration on U and h_{fp} in the fixed axial mode. Glycerin concentration and rotation speed were highly significant factors (p<0.001) affecting the overall heat transfer coefficient U, while temperature effect was not significant (p>0.05). All the three factors significantly influenced the fluid-to-particle heat transfer coefficient h_{fp} ; again the most dominant factor was speed of rotation (p<0.001), followed by concentration (p<0.001) and temperature (p<0.05).



Figure 5.4 Typical experimental, predicted time temperature profiles and lethality plot for can processed at 120°C retort temperature and 90 % glycerin concentration with 30 % v/v nylon particle of size 19 mm. (LALD) Approach in fixed axial mode.

Run No.	Temperature (°C)	Glycerin Conc. (%)	Rotation speed (rpm)	<i>U</i> Fixed axial (W/m ² C)	h _{fp} Fixed axial (W/m ² C)	<i>h_{fp}/U</i> (Fixed axial)
1	125(1)	96(1)	20(1)	310	485	16
1	125(1)	90(1) 84(-1)	20(1)	350	500	1.0
2	125(1)	06(1)	20(1)	285	420	1.7
5	115(-1)	90(1)	20(1)	265	450	1.5
4	115(-1)	84(-1)	20(1)	350	545	1.6
5	125(1)	96(1)	8(-1)	220	360	1.6
6	125(1)	84(-1)	8(-1)	295	490	1.7
7	115(-1)	96(1)	8(-1)	230	315	1.4
8	115(-1)	84(-1)	8(-1)	300	445	1.5
9	120(0)	90(0)	24(1.68)	360	585	1.6
10	120(0)	90(0)	4(-1.68)	240	400	1.7
11	128.4(1.68)	90(0)	14(0)	290	480	1.7
12	111.6(-1.68)	90(0)	14(0)	285	395	1.4
13	120(0)	100(1.68)	14(0)	210	390	1.9
14	120(0)	80(-1.68)	14(0)	330	550	1.7
15	120(0)	90(0)	14(0)	280	470	1.7
16	120(0)	90(0)	14(0)	280	485	1.8
17	120(0)	90(0)	14(0)	280	450	1.6
18	120(0)	90(0)	14(0)	280	490	1.7
19	120(0)	90(0)	14(0)	275	480	1.8
20	120(0)	90(0)	14(0)	275	470	1.7

Table 5.2CCRD experimental design (coded values in parenthesis) for evaluating Uand h_{fp} in fixed axial mode

As expected, U values increased significantly with an increase in rotational speed (Figure 5.5). It can be explained by enhanced mixing caused by the movement of the headspace bubble. U values decreased with an increase in glycerin concentration. This is due to the thicker boundary layer with higher viscosity fluids. The temperature effect is seen flat in Figure 5.5a.

Table 5.3U and h_{fp} values in fixed axial mode at different rotation speeds (at 120°C
and glycerin concentration of 100 % at using single and 30 % nylon
particles)

	Single Partic	le	30 % Particle	
RPM	$U(W/m^2C)$	h_{fp} (W/m ² C)	$U(W/m^2C)$	h_{fp} (W/m ² C)
4	110	100	130	170
8	150	135	170	250
12	170	150	195	315
16	175	155	235	400
_20	210	180	295	535

Table 5.4aAnalysis of variance (ANOVA) results for fixed axial U value

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	8.23	0.11	0.7490
Glycerin Concentration (C)	14811.81	192.06	< 0.0001
Rotation Speed (R)	15279.34	198.12	< 0.0001
$\mathbf{C} \times \mathbf{R}$	190.13	2.47	0.1404
C×C	60.22	0.78	0.3929
R × R	1207.34	15.66	0.0016

Table 5.4bAnalysis of variance (ANOVA) results for fixed axial h_{fp} value

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	8364.79	22.04	0.0004
Glycerin Concentration (C)	41975.42	110.61	< 0.0001
Rotation Speed (R)	42500.64	112.00	< 0.0001
$C \times R$	200.00	0.53	0.50
C×C	80.54	0.21	0.7264
$\mathbf{R} \times \mathbf{R}$	486.12	1.28	0.312

Fluid to particle heat transfer coefficient (h_{fp}) followed a similar trend as U with changes in glycerin concentration and rotational speed (Figure 5.6), except the

temperature effect was also significant with higher values of h_{fp} associated with higher temperatures.



Figure 5.5 *U* in fixed axial mode rotation as influenced by process variables: (a) retort temperature and rotation speed at 90% glycerin concentration (b) glycerin concentration and rotation speed at 120°C



Figure 5.6 h_{fp} in fixed axial mode rotation as influenced by process variables: (a) rotation speed and retort temperature at 90 % glycerin concentration (b) Rotation speed and concentration at 120° C

5.4.2.2 U and h_{fp} in free axial mode

As noted in the methodology, computation of U and h_{fp} requires transient data on temperature on liquid and the particle undergoing the rotation process. In the free axial
mode, only the liquid temperature was measured because of the difficulty in attaching the wireless temperature sensor to particle. An empirical approach was used to solve this problem.

The purpose of using the fixed axial configuration in this study, detailed earlier, was to gather some typical relationship between U and h_{fp} under a given set of processing conditions for use later to predict U and h_{fp} in free axial mode. Heat transfer theory supports the existence of a relationship between U and h_{fp} while processing particulate liquids in cans. The overall heat transfer coefficient U in such systems will be related to the combined conduction-convection heat transfer parameters across the can wall. In such cases, there are two values of h (convective heat transfer coefficient); one for the fluid film inside (h_i) and one for the fluid film outside of the can (h_o) . The thermal conductivity of the wall (k) and thickness of the can wall (Δx) must also be accounted for.

The overall heat transfer coefficient, U, between heating medium and the liquid inside the can could be represented by the following formula:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o}$$
(5.9)

where h_i and h_o are the inside and outside film coefficients and k and x are the thermal conductivity and thickness of the can wall. In thermal processing h_o is generally very high and often assumed to be infinity and k/x is also very high due to the high thermal conductivity and small thickness of metal cans. Hence U and h_i are somewhat directly related. As h_i and h_{fp} are both film heat transfer coefficients, they will be somewhat related as well. Hence, the hypothesis that U and h_{fp} are interrelated.

As a first attempt in understanding the empirical relationship, data from previous studies on thermal processing involving end-over-end agitation processing in the same retort with single and multiple particles suspended in Newtonian fluids (Sablani, 1996) were used to determine the relationship between U and h_{fp} and it was observed that a high linear correlation with an R^2 of 0.80 existed between U and h_{fp} values. In order to explore this relationship for the present study, a trial experiment was performed using single and multiple Nylon particles of 19 mm diameter in a can of size 307 × 409 filled with glycerin solution. Only the rotation speed was varied ranging from 4-20 rpm at an interval of 4, with the can headspace fixed at 10 mm and the retort temperature set at 120°C (Table 5.3). As shown below, the relationships between U and h_{fp} for single and multiple particles were found to be linear with R^2 of above 0.85 in both cases:

$$h_{fp} = 0.7355 \ U + 25.41 \ (with a single particle)$$
 (5.10)

$$h_{fp} = 2.2003 U - 115.39$$
(with multiple particles) (5.11)

From the above equations, it is clear that although there is a linear relationship between the U and h_{fp} as related to the rotation speed; however, the relationship for single and multiple particles were markedly different. It is likely other parameters such as glycerin concentration, temperature, etc., would also influence the nature of relationship between U and h_{fp} . Hence, to develop a comprehensive relationship between U and h_{fp} in fixed axial mode, further studies involving a broader range of temperature, glycerin concentration and rotation speed were carried out using a CCRD experimental design with five levels for each variable. In this study, only multiple particles were used as they better represent commercial processing. The experimental details (with both real and coded values for levels for each variable) and the resulting data on U and h_{fp} are summarized in Table 5.2. Composite models were developed for both U and h_{fp} as a function of the three variables. These quadratic equations are shown below for fixed axial mode with R^2 of above 0.95 in both cases:

$$U_{Fixed axial} = 281.0159 + 0.776T - 32.94C + 33.46R - 4.875CR - 2.03C^{2} + 9.123R^{2}$$
(5.12)

$$h_{Fixed axial} = 461.89 + 24.75T - 55.46C + 55.81R + 5CR - 1.82 \times C^{2} + 5.78 \times R^{2}$$
(5.13)

Eqs. 5.12 and 5.13 were used for computing the h_{fp}/U value (for fixed axial mode, see also Table 5.3. With this value, Eq. 5.1 could be solved for the free axial mode by the iterative approach indicated in Figure 5.3. The task involved predicting the liquid temperature using Eq. 5.1 and Eq. 5.6 by trial error approach. Similar to the computation of h_{fp} in the fixed axial mode, an approximate value was assumed for U which was multiplied by the h_{fp}/U to get the corresponding h_{fp} . Knowing both h_{fp} and U, the liquid temperature could be predicted numerically. This predicted value was compared with the liquid temperature data obtained in the free axial mode using the wireless sensors. Table 5.5 shows that by sequentially changing the values of free axial U value (U_{FRA}), the difference in the sum of squares between the measured and predicted liquid temperature profiles were minimized. When U was of 250 W/m²C, SS was found to be high, 27895, and as a result the time temperature profiles for predicted and measured profiles did not match well. In these cases, the time temperature profiles were found to be underestimated (Figure 5.7). As the U_{FRA} was gradually increased, the associated SS values decreased converging to a minimum value of 2189 at the U_{FRA} of 355 W/m²C. Further increase in U_{FRA} increased the SS reaching 23819 at 450 W/m²C. The overestimation can also be seen in Figure 5.7. Therefore U_{FRA} of 355 W/m²C was taken as the representative value for these set of input processing conditions (Retort temperature of 125°C, glycerin concentration of 90 % and retort rotational speed of 8 rpm). Using the h_{fp}/U value of 1.60 used for this run, the associated h_{fp} was computed to be 568 W/m²C.

The fluid to particle heat transfer coefficient associated with either end-over-end or axial agitation mostly depends on the particle properties, fluid properties and the fluid to particle relative velocity; for a given processing condition under specified particle and liquid properties, the relative fluid to particle velocity in free axial mode, it will be higher than the fixed axial mode of rotation resulting from the improved biaxial agitation of the can. Hence, the free axial rotation process will generally yield a higher U, which will in turn yield a higher h_{fp} value for the free vs. fixed axial rotation. We have used the h_{fp}/U value in both fixed and free axial modes. The fact that U in free axial mode is higher than in fixed axial mode would also suggest perhaps a higher h_{fp}/U value in the free axial mode as compared to the fixed axial mode. Since the two have been assumed to be same, the calculated h_{fp} value from this empirical method will be relatively conservative as compared with the actual h_{fp} value, provided it was possible to calculate the h_{fp} value from the direct measurement of both liquid and particle temperature in the freely rotating cans. Consequently, predicted particle lethality obtained from this method will also be conservative which will facilitate a safer process for food.

U_{FRA} (W/m ² C)	$h_{fp \ FRA} (W/m^2C)$	SS
250	400	27895
300	480	5330
320	510	2612
340	545	2331
355	570	2189
360	575	2288
370	590	2844
400	640	10715
450	720	23819

Table 5.5Convergence of U and h_{fp} values in free axial mode

Lenz and Lund (1978) used similar method to determine the heat transfer coefficient, U, with the can only containing liquid. They selected the value of heat transfer coefficient which minimized the sum of squares of deviation between the actual temperature of product and the predicted obtained by solving the energy balance equation. A mathematical procedure was also used by Stoforos and Merson (1990) which required only the measurement of the liquid temperature to estimate h_{fp} and U. Maesmans *et al.* (1992) expressed uncertainty for this method because the two parameters were estimated from one input parameter therefore this method was not used in subsequent references.

There are various product and process parameters which will affect the U and h_{fp} values obtained in the free axial mode (as detailed in the earlier section for fixed axial mode). The established methodology should be sensitive enough to respond to these variables and indicate the appropriate trends. This was tested by using the developed methodology to calculate U_{FRA} and h_{fp} under a set of conditions involving temperature, glycerin concentration and rotation speed at 3 levels using a 3×3 factorial design.



Figure 5.7 Measured and predicted time temperature profiles at different U and h_{fp} values under free axial mode

5.4.3 Sensitivity of developed U and h_{fp} method in free axial mode to process variables

Experimental conditions and results obtained for U_{FRA} and h_{fp} in the factorial design are summarized in Table 5.6. The ANOVA results for the significance of the effect of input variables on the heat transfer coefficient of U_{FRA} and h_{fp} in free axial mode are shown in Table 5.7. Analysis of variance revealed that glycerin concentration and retort speed were significant (p<0.001), whereas temperature was not significant (p>0.05) on the overall heat transfer coefficient U which is consistent with the earlier observation with the fixed axial mode. Again, all the factors studied were significant with respect to the fluid-to-particle heat transfer coefficient h_{fp} . The most dominant factor was concentration (p<0.001) followed by speed of rotation (p<0.001) and temperature staying at a distant third. The interaction $R \times R$ had a significant effect (p<0.05) on U and h_{fp} . The absence of interaction $T \times T$ showed that retort temperature played a minor role with respect to the axial heat transfer among three processing variables studied. These findings were consistent with Meng (2006) and Sablani and Ramaswamy (1996). Convective heat transfer to Teflon, aluminum and potato spheres in a single can in an axially rotating process simulator was studied by Hassan (1984); from the measurement of particle surface temperature. Increasing the can rotation speed from 9.3 to 101 rpm increased h_{fp} values. Hassan (1984) also reported that, in axial mode under equal processing conditions, the heat transfer coefficient to Teflon particles was lower when more viscous fluids (silicon oil, 1.5, 50, 350 centistokes) were used instead of water. This is consistent with the lower levels of heat transfer coefficients with higher concentration of glycerin. Stoforos (1988) indicated that increasing rotating speed would yield higher h_{fp} as long as the increased rotation speed was reflected in a higher relative particle to fluid velocity.

Figures 5.8 shows the mean values of the overall heat transfer coefficients U_{FRA} and h_{fp} as influenced by process variables. The U values varied from 350 to 564 W/m²C, whereas the h_{fp} varied from 496 to 947 W/m²C. These results show trends that were similar to those observed with fixed axial mode of rotation (as predicted by model Eqs. 5.12 and 5.13). As expected, U_{FRA} values were higher than the end-over-end mode reported by Sablani and Ramaswamy (1996) and Meng (2006). This could be the result of enhanced mixing of the can content, which occurred due to the biaxial agitation of cans rotating freely in axial mode as compared to end-over-end mode where can agitation takes place only in one direction.

From the above discussion, it is clear that the new approach was responsive enough to study the effect of process parameters on U and h_{fp} . under free axial rotary processing. When compared with the values obtained from free axial mode (Table 5.2 and 5.5), it was found that the heat transfer values were higher for free axial mode, but the trends were similar.

		Glycerin	Rotational		hfn FRA
Run	Temperature	Concentration	Speed	U_{FRA}	
No.	(°C)	(%)	(rpm)	(W/m^2C)	(W/m ² C)
1	125	96	20	490	760
2	125	96	14	400	690
3	125	96	8	355	570
4	125	90	20	520	885
5	125	90	14	455	785
6	125	90	8	415	705
7	125	84	20	550	925
8	125	84	14	505	870
9	125	84	8	475	790
10	120	96	20	475	760
11	120	96	14	395	650
12	120	96	8	350	563
13	120	90	20	520	845
14	120	90	14	455	745
15	120	90	8	415	665
16	120	84	20	560	920
17	120	84	14	500	830
18	120	84	8	470	760
19	115	96	20	460	700
20	115	96	14	395	610
21	115	96	8	360	495
22	115	90	20	520	805
23	115	90	14	450	705
24	115	90	8	415	625
25	115	84	20	565	875
26	115	84	14	500	790
27	115	84	8	480	705

Table 5.6Sensitivity of free axial mode U_{FRA} and h_{fp} values to process variables

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	42.92	1.62	0.2571
Glycerin Concentration (C)	24503.59	923.37	<0.0001
Rotation Speed (R)	25609.48	965.05	< 0.0001
RXC	22.03	0.83	0.5419
T X R	34.42	1.30	0.3484
R X R	186.09	7.01	0.0100

Table 5.7bAnalysis of variance (ANOVA) results for free axial h_{fp} value

Source	Type III SS	F value	Pr>F
Retort Temperature (T)	13634.11	448.24	<0.0001
Glycerin Concentration (C)	79548.77	2615.30	<0.0001
Rotation Speed (R)	71470.11	2349.70	<0.0001
RXC	109.38	3.60	0.0582
T X R	75.89	2.49	0.1262
R X R	291.55	9.59	0.0038



Figure 5.8 Sensitivity of (a) overall heat transfer coefficient U and (b) fluid to particle heat transfer coefficient h_{fp} in free axial mode rotation (cage rotation at 4, 14 and 24 rpm) to temperature and glycerin concentration



h_{fp Fixed Axial Mode} (Experimental)



h_{fpfree axial} (Experimental)

Figure 5.9 Estimated vs. Experimental (heat transfer coefficient). (a) Overall heat transfer coefficient in free axial mode (U); (b) Fluid to particle heat transfer coefficient (h_{fp}) in free axial mode

5.5 Conclusions

An empirical methodology was successfully developed for the measurement of convective heat transfer coefficients (U and h_{fp}) in canned liquid/particle mixtures subjected to free axial agitation similar to the Steritort. In the absence of a proper means of measuring particle temperatures in free axial rotation as is common in continuous flow systems, this technique would provide a valid method for conservative estimation of associated heat transfer coefficients. This will permit optimization of the operation of continuous retorts which make use of free biaxial rotation in cans as they move through a rotating helical cage. The overall heat transfer coefficient U and the fluid to heat transfer coefficient h_{fp} in free axial mode were higher than in the fixed axial mode of rotation. The method could be used for heat transfer evaluation under varying levels of rotational speed, temperature and concentration. Rotational speed and concentration had the most effect (p<0.001) on U and h_{fp} , both for fixed and free axial rotation whereas the temperature effect was not significant (p>0.05) with U values. The overall heat transfer coefficient U varied from 495 to 945 W/m²C.

PREFACE TO CHAPTER 6

In Chapter 5, a methodology was developed to measure the associated heat transfer coefficients (U and h_{fp}) in free axially rotating cans. This chapter provides a detailed evaluation of effect of system and process variables on the associated heat transfer coefficients U and h_{fp} .

Part of this research has also been presented in 2007 IFT Annual meeting, Chicago, IL and prepared for publications in a scientific journal. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.

CHAPTER 6

EFFECT OF PROCESS VARIABLES ON HEAT TRANSFER RATES TO CANNED PARTICULATE NEWTONIAN FLUIDS DURING FREE BI-AXIAL ROTARY PROCESSING

6.1 Abstract

Effect of process variables on overall (U) and fluid-to-particle (h_{fp}) heat transfer coefficients in canned particulates suspended in Newtonian fluids (glycerin solutions at concentrations of 80 - 100%) undergoing free axial rotation was evaluated in a pilot scale rotary autoclave. Six influencing factors affecting U and h_{fp} were selected using L16 Taguchi model for detailed evaluation. With the significant factors identified, a response surface methodology and two full factorial experimental designs of experiments were used to relate U and h_{fp} to the various process and product variables in each mode of rotation (fixed and free axial modes). The analysis of variance showed that the rotational speed, glycerin concentration (contributing to fluid viscosity), retort temperature, particle material (contributing to particle density), particle concentration and particle size were significant factors (p < 0.05) for h_{fp} and U. Headspace was not significant in the range of 5 to 10 mm studied. With an increase in rotational speed, particle density and retort temperature, there was an increase in the associated h_{fp} and U values; however, increasing the glycerin concentration resulted in the opposite. An increase in particle concentration showed an initial increasing trend in h_{fp} and U values which subsequently decreased with a further increase in particle concentration. T-tests revealed that both U and h_{fp} were significantly higher (p < .01) in the free axial mode as compared to the fixed axial mode.

6.2 Introduction

In the search for higher quality canned products with suspended particles, industries have started leaning away from conventional methods and more towards methods of high temperature, short time processing (HTST processing) (Ramaswamy *et*

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al. 1993). As the activation energy for the reactions which results in microbial death are higher than those which results in quality loss, HTST processes offer the potential to give the same level of sterility for a reduced level of quality loss (Holdsworth, 1997). In order to effectively use the HTST technique, it is necessary to have systems that provide rapid heating conditions. These conditions can be realized in convection heating foods under normal commercial canning conditions. They are also possible in conduction heating foods if processed in thin profile forms or independently processed and packaged under aseptic processing conditions. Yet another technique that provides faster heating to particulate or viscous foods is agitation processing. Heat transfer to particulate fluids that normally heat by conduction in static processes is accelerated through the use of agitation processing which induces forced convection in these products. It also promotes good product mixing there by achieving a more uniform temperature in the can which helps to promote better quality retention.

Thermal processing is one of the few processes in the industry which relies on mathematical models for process optimization. Heat penetration parameters are commonly used in combination with the process calculation methods like Ball and Stumbo for the establishment and optimization of the thermal process. Theoretical models can be useful tools for the design, optimization and validation of such food systems; however the usefulness of the theoretical models depends upon the accuracy of the input physical parameters. Data on overall heat transfer coefficient (U) and the fluid to particle heat transfer coefficient (h_{fp}) are necessary parameters, besides the thermo physical properties of the product, required for the modeling programs (Sablani and Ramaswamy, 1996). There are currently two methods of inducing agitation in containers, namely end-over-end rotation (E-O-E) and free axial rotation. In end-over-end processing, a retort crate containing vertically placed cans rotates around a central horizontal axis, and is common in batch processing systems. In the second approach of axial rotation, cans are rotated in the horizontal plane, and this mode of rotation is encountered with continuous systems such as reel and spiral cookers.

The early studies on rotational processing (Berry and Bradshaw, 1980; Berry and Kohnhorst, 1985; Berry and Pflug, 1979; Clifcorn *et al.*, 1950) dealt with the effect of agitation on the specific heat penetration parameters of the product. Rao and

Anantheswaran (1988) provided an overview on U values for canned liquids in rotary retorts. The more recent studies have focused on the h_{fp} and U, both of which are important parameters influencing the heating rate of the liquid particulate mixture. A number of studies have evaluated the different process variables that influence the heat transfer coefficients, and it has been found that rotational speed, retort temperature, head space volume, system geometry, liquid viscosity, rotation radius, particle size and particle density are key factors in end-over-end mode (Anantheswaran and Rao, 1985a, 1985b; Britt, 1993; Lekwauwa and Hayakawa, 1986; Meng and Ramaswamy, 2007b, 2007c; Sablani and Ramaswamy, 1995, 1996, 1997). Other studies evaluated the effect of E-O-E agitation on nutrient, texture and color retention of food products (Abbatemarco and Ramaswamy, 1994, 1995).

Some studies have also been carried out in free axially rotating cans evaluating the effect of process variables on U and h_{fp} (Lenz and Lund, 1978; Deniston *et al.*, 1987; Fernandez et al., 1988; Hassan, 1984; Stoforos and Reid, 1992). Particles are fixed inside the can, and hence do not simulate the real and free motion of the particles during axial agitation processing. Stoforos and Merson (1992) used liquid crystal coated particles for allowing a free rotation of the particles inside the can. However, the study was carried out at a low temperature range of 26 to 50°C, which was not applicable to a sterilization process. Also, contrary to the bi-axial motion of the particles across the bottom of the retort found in continuous systems, the can set used by Deniston et al. (1987), Hassan (1984), and Stoforos and Merson (1992) had only a circular, one directional motion, further compromising their results. Some studies (Weng et al., 1992; Hendrickx, et al., 1992; Haentjens et al., 1998; Guiavarc'h, et al., 2002a, 2002b) used time temperature integrators (TTI) in the form of microorganisms, chemicals or enzymes in combination with a mathematical model to determine the convective heat transfer coefficient without affecting a particle's motion in real processing conditions where these kinds of methods were not easy to apply.

The major reason for the lack of in depth studies on U and h_{fp} in axially rotating cans is the difficulty in measuring particle and liquid temperatures under commercial processing conditions. While some special techniques could be used to measure the liquid temperature, it is impractical to accurately gather particle temperature data. Traditional computation of U and h_{fp} , however, require data on both particle and liquid temperatures. In chapter 5, a useful methodology was established for evaluating U and h_{fp} in free axially rotating cans under commercial processing conditions. The method involved developing correlations between h_{fp} and U using real time-temperature data gathered from test cans in the <u>fixed axial mode</u> of rotation and then coupling them with experimentally evaluated U from fluid temperature gathered with wireless sensors to compute h_{fp} for bi-axially rotating cans. The methodology was based on the assumption that within a can, factors that influence U will also influence h_{fp} , and therefore h_{fp} and U are generally inter-related. The method was tested under different processing conditions and was found to be predictably responsive to process variables.

Various factors affect the heat transfer in free axially agitating cans, and quantifying their influence on associated heat-transfer rates to the product (h_{fp} and U) is important for the establishment of a safe thermal processing procedure in rotary retorts. The objective of this study was therefore to use the previously established methodology to evaluate the heat transfer rates for axially rotating canned foods comprised of liquid and solid particles, and to quantify the effects of system and product parameters such as rotation speed, retort temperature, liquid viscosity, particle material, particle concentration and particle size on h_{fp} and U.

6.3 Materials and Methods

6.3.1 Sample Preparations

Glycerin (Fischer scientific ltd., Montreal) was used as the Newtonian fluid in the study and at different concentrations the glycerin solution could provide a range of viscosities, simulating a variety of liquid canned foods. Propylene, Nylon and Teflon spheres of 19, 22.25 and 25 mm (Small Parts Inc., Miami, FL) were used as food simulating particulates. Only spherical shaped particles were used for this study to avoid non-uniformity associated with other geometries, so that heat transfer to the particle center was uniform from all directions. Table 6.1 summarized the thermo-physical properties of the liquid and particles which were extracted from available literature (Sablani and Ramaswamy, 1997; Meng and Ramaswamy, 2007c). The metal cans of size

 Φ 307 × 409 (Home Canning Co., Montreal, QC) were used in the study. All cans were seamed by a manually operated seaming machine (Home Canning Co., Montreal, QC).

Material	Density (kg/m ³)	Heat Capacity (J/kg C)	Thermal Conductivity (W/m C)	Thermal diffusivity (m²/s)	Viscosity (Pa.s)
Nylon	1128	2073	0.369	152×10^{-9}	
Polypropylene	830	1842	0.359	235×10^{-9}	
Teflon	2210	984	0.290	135×10^{-9}	
Glycerin (100%)	1260	2430	-	-	0.942
Glycerin (96%)	1247	2500	-	-	0.553
Glycerin (90 %)	1234	2570	-	-	0.211
Glycerin (84 %)	1213	2650			0.105
Glycerin (80%)	1208	2720	-	-	0.070

Table 6.1Thermo physical properties of test material

6.3.2 Retort cage modifications for free and fixed axial rotation

A pilot scale rotary single cage retort (Stock Rotomat PR 900; Herman Stock Maschinenfabrick, Neumünster, Germany) was modified to simulate the rotational motion of a continuous cooker. The modified retort used the same control system for pressure, temperature and cage rotation operation as in the regular retort and hence the performance was not affected. The can rotation principle was similar to that in a Steritort (FMC Corp., San Jose, CA). In the modification, the retort basket was retrofitted with a stainless steel enclosure in which test cans could be held in an axial direction (Figure 6.1). The fabricated enclosures held two free cans on each side of the frame. On one set of these enclosures, the end plates facing the retort shell was removed so that the cans could slide down and roll along the retort shell during part of the rotation. These cans rolled on their own axis (in a direction counter to that of retort cage) when inclined downward (approximately 1/3rd of the rotation). In the top 2/3rd of the cage rotation, the cans were restrained in the enclosure only rotating with the cage. This process caused biaxial rotation of the can in the free axial mode, while only in clockwise direction in the

fixed axial mode. The other two cans held at the opposite end were restrained all the way and therefore provided fixed axial mode (only rotating with the cage). Additional details of the modification are provided in figure 3.1



Figure 6.1 Sectional drawing of rotation of a can in modified STOCK retort (Shell Dia = 890 mm) similar to Sterilmatic continuous pressure retort.

6.3.3 Thermocouple fitting

Cans of size 307×409 were filled with the prepared sample (glycerin solution and particles) to a specified headspace. The temperatures of the liquid inside the cans in fixed axial mode were monitored using CNS copper constantan needle-type thermocouples (locking connector, C-10, Ecklund Harrison Technologies, Inc. Cape Coral, FL) with tips located at the geometric center. The thermocouples (wire diameter 0.0762 mm, Omega Engineering Corp., Stamford, CT) measuring the particle temperature were introduced into the particle center through a fine hole drilled using a horizontal lathe and were fixed by a small amount of epoxy glue. Thermocouple leads from the retort were connected to a slip ring assembly at the end of the rotating shaft. The thermocouple outputs were recorded using a data acquisition system (HP34970A, Hewlett Packard, Loveland, CO) at one second intervals. In the free axial mode, the liquid temperatures were measured using Track Sense® Pro (Ellab Inc., Centennial CO), a FDA compliant wireless multi-channel data-logging system, was used to measure the temperature of the liquid. Additional details on thermocouple fixtures, data logging etc are available in chapter 5.

6.3.4 Processing of Cans

The prepared cans were held in place in the modified retort. Some dummy cans were placed in the cage to provide ballast. Water was preheated in the storage vessel to about 10° C higher than the processing temperature and transferred to the process vessel. During the sterilization cycle, water temperature and system pressure were maintained at the preset value through the retort control system. At the beginning of the cooling cycle, the hot sterilizing water is pumped back up to the storage drum where it is re-heated to the proper set temperature for the next cycle. The cans were then cooled by circulating cold water in the retort.

6.3.5 Experimental design and statistical analysis

6.3.5.1 Preliminary screening

Experiments were initially conducted using a Taguchi's L16 design (Taguchi, 1987) which follows three main steps; planning a matrix experiment to determine the effects of the control factor, conducting the matrix experiment and then analyzing and verifying the results. Taguchi's analysis is an efficient way to analyze the relative importance of a large number of parameters on the response of a system. For the 2 level L16 matrix used in this analysis, only 16 experiments were needed to analyze the effects

of as many as eight parameters (seven were used in this study. The variables were selected based on previous literature.

6.3.5.2 CCRD design for studying the effect of variables

To study the detailed effects of process variables on U and h_{fp} in fixed and free axial mode, a response surface methodology was used with retort temperature (X_1) , glycerin concentration (X_2) and rotational speed (X_3) as independent input experimental variables, each with 5 levels [central composite rotatable design (CCRD)]. The design consisted of 20 experiments performed in a random order. All tests run were repeated twice. The center point runs provide a means for estimating the experimental error and to measure lack of fit, and the axial points were added to the factorial design to estimate the curvature of the model. The regression analysis and analysis of variance (ANOVA) were carried out using the GLM procedure of SAS statistical package (SAS Institute Inc., Cary, NC) to fit the second order polynomial equations for the response given below.

$$y = \beta 0 + \sum_{i=1}^{3} \beta_{i} x_{i} + \sum_{i=1}^{3} \beta_{ii} x_{i}^{2} + \sum_{i < j=1}^{3} \beta_{ii} x_{i} x_{j}$$
(6.1)

Where, y is the response (U or h_{fp}), x_i and x_j are the coded independent variables and β_0 , β_i , β_{ii} and β_{ij} are intercept, linear, quadratic and interaction constant coefficients respectively.

The coded values of the factors were calculated from the original values with the help of the following equations:

$$T = \frac{(Original value - Midpoint value) \times 1.68}{8.4}$$
(6.2)

$$C = \frac{(Original value - Midpoint value) \times 1.68}{10}$$
(6.3)

$$R = \frac{(Original value - Midpoint value) \times 1.68}{10}$$
(6.4)

Response surfaces were drawn from the fitted quadratic polynomial equation obtained from the GLM analysis. Their significance was judged by determining the probability that the *F*-statistic calculated from the data as less than 5%. The model adequacies were checked by R^2 and the prediction errors.

Further, the influence of particle density, particle concentration and particle sizes were studied using two sets of additional full factorial designs for each mode of rotation i.e. fixed and free axial modes. Statistical analyses of variance (ANOVA) with the factorial design were performed through the statistical package of Microsoft Excel soft ware. Values were considered different from each other at P < 0.05.

6.4 Results and Discussion

6.4.1 Requirements for the evaluation of U and h_{fp}

Evaluation of U and h_{fp} under fixed axial mode itself is a tedious task, and because of the lack of a proper means to measure the particle temperature when the cans are subjected to the free axial rotation, U and h_{fp} is even more difficult and almost impractical under commercial processing conditions. A methodology was established (chapter 5) to overcome this problem and evaluate the heat transfer coefficients associated with free axial rotation using an empirical approach. The technique involved first obtaining a relationship between U and h_{fp} in the fixed axial mode and assumed a similar relationship would exist in the free axial mode. As demonstrated previously this is a reasonable and conservative assumption and allows computation of free axial U and h_{fp} . To do this, the liquid temperature in cans (using wireless sensors) in the free axial rotation is simultaneously measured along liquid particle time-temperature data in fixed axial cans. U associated with the free axial mode is then coupled with h_{fp} using h_{fp}/U value from fixed axial rotation to compute and match the measured liquid temperature. It should be noted that without this assumption, it is not possible to compute even U for free axial rotation when particulates are included in the can.

Models were developed in the previous study (Chapter 5) for U and h_{fp} under fixed axial rotation to get h_{fp}/U values for a limited range of experiments. However, in order to be able to use them under a broader range of experimental conditions, additional data over a broader range of processing conditions are needed so that more comprehensive models could be developed relating U and h_{fp} in fixed axial mode. In this study, the effect of six input parameters that may affect U and h_{fp} were studied, and two comprehensive models were developed incorporating all variables [temperature, 110 – 130 °C; rotation speed, 4-24 rpm; glycerin concentration, 80 – 100 %, particle concentration, 20 - 40 %; particle density, 830 - 2210 kg/m³ and particle size, 19 - 25 mm]. These quadratic models are given below (Eqs. 6.5 and 6.6)

$$U_{Fixed Axial} = 2.47 \times D + 17.70 \times P + 9.79 \times R - 3.85 \times S + 0.15 \times T$$

- 2.41×C - 0.00014×D² - 0.28×P² + 0.362×R² - 0.22×C²
- 0.00027×D×P + 0.0031×D×R + 0.29×D×C - 1842 (6.5)

$$h_{Fixed axial} = 3.14 \times D + 32.99 \times P + 17.46 \times R - 13.15 \times S + 4.97 \times T - 6.41 \times C$$

- 0.000342 \times D² - 0.54 \times P² + 0.642 \times R² - 0.07 \times C² + 0.00105 \times D \times P
+ 0.0082 \times D \times R - 0.0205 \times D \times C - 2114 (6.6)

 R^2 values for the models U and h_{fp} were 0.90 and 0.92 respectively whereas the root mean square errors were 23.92 and 21.24 respectively

6.4.2 Selection of variables

Seven parameters with possible influence on the heat transfer rates in liquid particulate systems were selected for the L16 experimental design and are shown in Table 6.2 along with the results for both fixed and free axial mode heat transfer coefficients. Experiments covered a broad range of conditions for each variable and were selected from the previous literature. To obtain a reliable database each experiment was repeated twice and the results are presented as mean values in Table 6.2. The analysis of variance results (Table 6.3a, b) revealed that glycerin concentration, retort speed, particle density, particle size, particle concentration and retort temperature were significant factors (p < 0.05) for U and h_{fp} under both fixed and free axial rotation. Surprisingly headspace effect was not significant in the range of 5 to 10 mm studied, even though headspace volume in agitating cans (total volume of can minus volume of the fill weight) is one of the critical factors that influence the heat transfer rates. Anantheswaran and Rao (1985a) found that the headspace volume between 3 and 9% did not affect the heat transfer coefficients. Meng and Ramaswamy (2007c) further supported the above results by reporting that the effect of headspace on the heat transfer rates to canned liquid particulate high viscosity non-Newtonian fluids during end-over-end rotation was found to be non-significant in the range of 6% to 12%. With a single particle in the can, Sablani (1996) established that head space and radius of rotation were significant for U and h_{fp} ,

whereas in the case of multiple particles the effect of headspace was not considered as the significant factor in their study. It is possible that the influence of other parameters is much more dominant and overshadows the contribution from the headspace within the range of parameters studied. Berry and Kohnhorst (1985) studied the effect of headspace on the heat transfer rates by performing tests on the commercial cans filled with milk based concentrates and concluded that decreasing headspace resulted in lower heat transfer rates. This difference in results could be due to the differences in the variables studied and their difference in ranges.

L16 Orthogonal Experiment design (True values of system variables) Free and Fixed Axial Mode Table 6.2

R	T	H	S	C	W	Р	U_{FRA}	h _{fp-Free}	UFixed	h _{fp-Fixed}
(rpm)	(°C)	(mm)	(mm)	$(0_0')$	(kg/m ³)	(\mathscr{Y}_{0})	(W/m^2C)	(W/m^2C)	(W/m^2C)	(W/m^2C)
4	110	5%	19	80%	PP(830)	20%	305	490	190	305
4	110	10%	25.4	80%	PP(830)	30%	280	365	175	230
4	110	10%	19	80%	NYL(1128)	20%	405	610	255	385
4	110	5%	25.4	80%	NYL(1128)	30%	335	480	210	300
4	110	10%	25.4	100%	PP(830)	30%	410	570	255	355
4	110	5%	19	100%	PP(830)	20%	500	760	315	480
4	110	5%	25.4	100%	NYL(1128)	30%	400	570	250	355
4	110	10%	19	100%	NYL(1128)	20%	510	780	320	490
24	130	10%	19	80%	PP(830)	30%	720	1085	450	680
24	130	5%	25.4	80%	PP(830)	20%	415	620	260	390
24	110	5%	19	80%	NYL(1128)	30%	490	1105	305	069
24	110	10%	25.4	80%	NYL(1128)	20%	345	555	215	345
24	110	5%	25.4	100%	PP(830)	20%	455	660	290	425
24	110	10%	19	100%	PP(830)	30%	585	845	365	525
24	130	10%	25.4	100%	NYL(1128)	20%	710	1140	445	715
24	130	5%	19	100%	NYL(1128)	30%	810	1325	505	825
R=rotatio	in speed,	$T = retort t_i$	emperature	, H = Hea	d space, $S = Pa$	rticle size, (C = Glycerin co	ncentration,	-	

M = Particle material, P = Particle concentration, PP = Polypropylene, NYL = Nylon

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	Free	axial mode		Fixed	axial mode	<i>;</i>
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
R	15251	0.019	0.019	6016	7.94	0.022
Т	76050	0.0002	0.0002	29403	38.1	.0003
Н	4064	0.168	0.160	1501	1.98	0.196
S	59414	0.0004	0.0004	22876	30.20	.0006
С	73576	0.0002	0.0002	29326	38.71	0.0003
Μ	60014	0.01	0.012	6626	8.54	0.01
Р	51462	0.035	0.025	5164	6.18	0.032

Table 6.3aAnalysis of variance (ANOVA) results for U in L16 experiments

Table 6.3b Analysis of variance (ANOVA) results for h_{fp} in L16 experiments

	Free	axial mode		Fixed	l axial mode	:
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
R	121126	10.72	0.0113	47704	10.29	0.0125
Т	126253	11.18	0.0102	48828	10.53	0.0118
Н	225	0.02	0.89	126	0.03	0.87
S	260100	23.02	0.0014	100014	21.57	0.0017
С	112225	9.93	0.0136	44626	9.63	0.0146
М	85556	7.75	0.0250	31951	6.89	0.0304
Р	73306	6.95	0.049	21298	5.67	0.0427

R=rotation speed, T= retort temperature, H = Head space, S = Particle size, C = Glycerin concentration, M = Particle material, P = Particle concentration, PP = Polypropylene, NYL = Nylon

In this study, the effect of other process parameters except that of the particle size on U and h_{fp} were in line with other researchers (Sablani and Ramaswamy, 1996; Meng and Ramaswamy, 2007b, 2007c; Lenz and Lund, 1978; Hassan, 1984). The analysis of variance revealed that with the increase in particle size, heat transfer coefficient decreased. Meng and Ramaswamy (2007b) concluded that in the presence of multiple particles in non Newtonian fluids, no relation could be established between the particle size and heat transfer coefficients (U and h_{fp}) (p>0.05). Similar to the current study, Sablani and Ramaswamy (1997) reported the decrease in heat transfer coefficients with the increase in particle size whereas Lenz and Lund (1978) reported the increase in U values with the increase in particle size.

6.4.3 Effect of process variables on U and h_{fp}

6.4.3.1 Effect of Temperature, glycerin concentration and rotation speed 6.4.3.1.1 Fixed axial rotation

Most commercial systems use either end-over-end (used in most batch rotary retorts) or free axial (most continuous flow systems) agitation process. The fixed axial system is not widely used in commercial system although with a patented recent system (Shaka, Covington, LA) fixed axial configuration is possible. Detailed results on the influence of temperature, glycerin concentration and rotation speed on U and h_{fp} in both fixed and free axial mode are presented in Table 6.4. During these experiments, Nylon particles of 19 mm diameter, can size of 307 × 409, headspace of 10 mm, particle concentration of 30% were fixed. Table 6.5 shows the ANOVA results for the effect of rpm, temperature and glycerin concentration on U and h_{fp} in the fixed and free axial modes.

In the fixed axial mode, glycerin concentration and rotation speed were highly significant factors (p<0.001) affecting the overall heat transfer coefficient U, while temperature effect was not significant (p>0.05). All the three factors significantly influenced the fluid-to-particle heat transfer coefficient h_{fp} ; again the most dominant factor was speed of rotation (p<0.001), followed by glycerin concentration (p<0.001) and temperature (p<0.05).

As expected, U values increased significantly with an increase in rotational speed (Figure 6.2). It can be explained by enhanced mixing caused by the movement of the headspace bubble. U values decreased with an increase in glycerin concentration. This is due to the thicker boundary layer with higher viscosity fluids. The temperature effect was flat as shown in Figure 6.2. Fluid to particle heat transfer coefficient (h_{fp}) followed a similar trend as U with changes in glycerin concentration and rotational speed (Figure

6.3), except for the temperature effect which was significant with higher values of h_{fp} associated with higher temperatures.

		Glycerin	Rotation	U Free	h _{fp Free}	$U_{ m Fixed}$	h _{fp} Fixed
Run	Temp.	Conc.	speed	Axial	Axial	Axial	Axial
No.	(°C)	(%)	(rpm)	(W/m^2C)	(W/m^2C)	(W/m^2C)	(W/m^2C)
1	125(1)	96(1)	20(1)	490	760	310	485
2	125(1)	84(-1)	20(1)	565	950	350	590
3	115(-1)	96(1)	20(1)	460	700	285	430
4	115(-1)	84(-1)	20(1)	565	875	350	545
5	125(1)	96(1)	8(-1)	355	570	220	360
6	125(1)	84(-1)	8(-1)	475	790	295	490
7	115(-1)	96(1)	8(-1)	360	495	230	315
8	115(-1)	84(-1)	8(-1)	480	705	300	445
9	120(0)	90(0)	24(1.68)	580	945	360	585
10	120(0)	90(0)	4(-1.68)	395	655	240	400
11	128.4(1.68)	90(0)	14(0)	455	775	290	480
12	111.6(-1.68)	90(0)	14(0)	460	630	285	395
13	120(0)	100(1.68)	14(0)	345	635	210	390
14	120(0)	80(-1.68)	14(0)	525	885	330	550
15	120(0)	90(0)	14(0)	450	760	280	470
16	120(0)	90(0)	14(0)	450	790	280	485
17	120(0)	90(0)	14(0)	455	730	280	450
18	120(0)	90(0)	14(0)	450	785	280	490
19	120(0)	90(0)	14(0)	445	780	275	480
20	120(0)	90(0)	14(0)	450	760	275	470

Table 6.4CCRD experimental design and results (true values and coded values) for
the effect on fixed and free axial agitation on U and h_{fp}

	Free	e axial mode	Fiz	ked axial mo	de	
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
Т	9.86	0.15	0.705	24.8	0.46	0.51
С	38246	581	<0.0001	14946	275	< 0.0001
R	38076	578	0.0001	14946	275	<0.0001
T×T	275	4.18	0.063	298	5.51	0.036
C×C	185	2.82	0.12	38	0.71	0.41
R×R C×R	3234 450	49.2 6.84	<0.0001 0.022	1160 200	21.42 3.69	<0.001 0.078

Table 6.5aANOVA results for U in fixed and free axial mode demonstrating the
effect of retort temperature, glycerin concentration and rotation speed

Table 6.5bAnalysis of variance (ANOVA) results for h_{fp} in fixed and free axial modedemonstrating the effect of particle size, concentration and rotation speed

	Free	e axial mode	2	Fixe	ed axial mod	le
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
Т	21260	38.9	<0.0001	8117	53.69	<0.0001
С	108189	198	<0.0001	41092	271	<0.0001
R	107691	197	<0.0001	41312	273	<0.0001
T×T	11132	20.4	< 0.001	3160	20.9	< 0.001
C×C	800	1.47	0.24	158	1.05	0.32
R×R	646	1.19	0.29	311	2.06	0.17
C×R	528	0.97	0.34	200	1.32	0.27

T= retort temperature, R=rotation speed, C = Glycerin concentration



Figure 6.2 U in fixed axial mode rotation as influenced by process variables: (a) Temperature and rotation speed at 90% glycerin concentration (b) Concentration and rotation speed at $120^{\circ}C$

.



Figure 6.3 h_{fp} in fixed axial mode rotation as influenced by process variables: (a) Rotation speed and temperature at 90 % glycerin concentration, (b) Rotation speed and concentration at 120°C

6.4.3.1.2 Free axial mode

Tables 6.4a, b also summarizes the overall heat transfer coefficients U and fluid to particle heat transfer coefficient h_{fp} for free axial mode for all the 20 experiments including 6 replications of the center point, and the ANOVA results are shown in Table 6.5.

As with fixed axial mode, glycerin concentration and retort speed were significant factors (p < 0.001), while the temperature effect was not significant U. All three factors were significant on the fluid-to-particle heat transfer coefficient h_{fp} . Speed of rotation was the most dominant factor (p < 0.001), followed by glycerin concentration (p < 0.001) and then by temperature (p < 0.05).

The following models were developed for the response surface plot for U and h_{fp} in the free axial mode as influenced by the process variables (temperature, T; rotation speed, R and glycerin concentration, C):

$$U_{Free axial} = 452.95 + 1.23 \times T - 52.95 \times C + 53.06 \times R + 7.70 \times C \times R - 4.01 \times C^2 + 14.76 \times R^2$$
(6.7)

$$h_{Free \ axial} = 744.46 + 40.02 \times T - 89.59 \times C + 8.02 \times R + 8.02 \times C \times R + 8.17 \times C^2 + 32.89 \times R^2$$
(6.8)

Figures 6.4 and 6.5 demonstrate the influence of glycerin concentration, temperature and rotation speed on U and h_{fp} , respectively, in free axial mode. An increase in glycerin concentration resulted in a decrease in U and h_{fp} by 26 and 40% respectively, while an increase in retort temperature yielded a slight increase. The decrease related to glycerin concentration could be attributed to higher viscosity and the larger thickness of the associated boundary layer. The increased viscosity would diminish the fluid mixing and reduce the particle to fluid relative velocity, and hence contribute to a lower rate of heat transfer. Lenz and Lund (1978) also found a lower h_{fp} for particles in a higher viscosity solution (60% sucrose syrup) than in water. Hassan (1984) found a similar trend with U and h_{fp} associated with Teflon particles in silicone oils of kinematics viscosities (1.5 × 10⁻⁶, 50× 10⁻⁶ and 350 × 10⁻⁶ m²/s) instead of water. They observed same pattern for aluminum particles. Similar results were observed by Stoforos (1988). During end-over-end experiments, Sablani and Ramaswamy (2007b) reported a decrease in apparent heat transfer coefficients (h_{ap} and U_a) with the increase in viscosities of glycerin.



Figure 6.4 Effect of system and processing parameters on U in free axial mode rotation. (a) Effect of temperature and RPM on U at 90% glycerin concentration (b) Effect of concentration and RPM on U at 120 °C temperature



Figure 6.5 Effect of system and processing parameters on h_{fp} in free axial mode rotation (a) Effect of temperature and RPM on h_{fp} at 90 % glycerin conc.
(b) Effect of concentration and RPM on h_{fp} at 120 °C

In this study, U and h_{fp} in free axial mode increased from 285 to 640 W/m²C and 480 to 1075 W/m²C respectively, with the combined increase in rpm from 4 to 24 rpm and with an increase in temperature from 111.6 to 128.4°C. Better mixing in the can, resulting in a higher fluid to particle relative velocity, could explain these increases concerning rpm, and with respect to temperature the increase could be due to the greater liquid convection at higher temperatures. Similar results were observed by Lenz and Lund (1978) who found that changing the rotational speed from 3.5 to 8 rpm resulted in an average increase in h_{fp} of 150 W/m²C. Surprisingly, Hassan (1984) studied potatoes, Teflon and aluminum spheres heating in a single axially rotating can, suspended in deionized water and silicon fluids of various kinematic viscosities and found that varying the rotation speed of the can (9.3-55.5-101 rpm) had no significant effect on h_{fp} . Stoforos (1988) reported that as long as the rpm was increased enough to change the fluid to liquid relative velocity, there would be a noted change in h_{fp} . Centrifugal forces could cause the contents of the can to act as a solid body when observed at 100 rpm. Stoforos (1988) found that when rpm was increased from 54.5 to 100 rpm, the Teflon particles heated in silicon fluid at 50°C experienced a tremendous drop in h_{fp} from 2071 to 410 W/m²C. Sablani and Ramaswamy (1996) observed that when the rotational speed increased from 10 rpm to 20 rpm, h_{fp} values of Nylon particles in water increased by 53% and U increased by 13%. The increasing trend of U and h_{fp} with respect to the temperature was again consistent with the findings observed by (Sablani and Ramaswamy, 1996; Meng and Ramaswamy, 2007c).

Meng (2006) reported U values of 293, 237 and 178, and h_{fp} values of 376, 334 and 305 W/m²C for glycerin concentrations of 80, 90 and 100% with 30% Nylon particles in a can of size 307 × 409 at 120°C during end-over-end retort processing. Under similar conditions, in this study of free axial mode, U and h_{fp} were higher by approximately 40% and 60% respectively. This could be the result of enhanced mixing of the can content, which occurred due to the biaxial agitation of the cans rotating freely in axial mode as compared to end-over-end mode where can agitation takes place only in one direction. In almost every processing condition in this study, on an average, free axial mode had higher U and h_{fp} values than in fixed axial mode (U of 345 to 565 W/m²C and h_{fp} of 500 to 945 W/m²C for free axial mode, as compared to U of 210 to 360 W/m²C and h_{fp} of 313 to 590 W/m²C in fixed axial mode). Thus, one could expect better heat transfer with free axial rotation (continuous rotary systems) as compared with the batch mode end-over-end systems.

6.4.3.2 Effect of particle size and particle concentration on U and h_{fp}

The effects of particle size, particle concentration and particle density in free and fixed axial modes, were evaluated in combination with one of the other prominent variable, rotation speed. Glycerin concentration was maintained at 100% providing the most viscous fluid within study and the higher headspace of 10 mm and the midpoint retort temperature of 120° C were used at fixed levels. Full factorial experiments were used for these studies. The first full factorial design of these experiments focused on particle size, particle concentration and rotational speed. The results for *U* and h_{fp} in fixed and free axial mode are in Table 6.6 and the ANOVA results are shown in Table 6.7.

From the ANOVA results (Table 6.7), it can be seen that in both free and fixed axial modes, particle size and concentration had significant effects on U and h_{fp} . The effect of particle size at three different concentrations (20, 30 and 40%) are shown in Figures 6.6 and 6.7, respectively for free and fixed axial rotation. The results show that free axial mode has a better agitation effect than fixed axial mode, as seen by the U and h_{fp} which were higher for free axial mode at each concentration level. The U values in free axial mode for the three concentrations observed (20, 30 and 40%) were found to decrease by 33, 25 and 29% as the size of the particles increased from 19.05 to 25 mm. Under the same increasing size conditions, the h_{fp} also decreased, possibly due to the thicker boundary layers associated with larger particle diameters. Comparing Figures 6.6 and 6.7, it can be seen that the increasing diameter had a greater influence on h_{fp} than on U (h_{fp} decreased by 32, 34 and 41\% as the size went from 19.05 to 25 mm in the three concentrations).

			U_{Free}	h_{fpFree}	U_{Fixed}	$h_{fpFixed}$
<u> </u>	P(%)	<i>R</i> (rpm)	(W/m^2C)	(W/m^2C)	(W/m^2C)	(W/m^2C)
19	20	4	235	400	200	330
19	20	14	340	605	170	300
19	20	24	410	765	235	440
19	30	4	250	425	205	350
19	30	14	335	620	210	390
19	30	24	430	910	240	510
19	40	4	245	410	205	345
19	40	14	345	620	165	345
19	40	24	430	890	240	510
22.25	20	4	225	345	170	260
22.25	20	14	285	450	145	245
22.25	20	24	380	720	200	380
22.25	30	4	240	370	175	270
22.25	30	14	300	515	175	330
22.25	30	24	390	805	200	420
22.25	40	4	220	345	160	260
22.25	40	14	270	490	145	270
22.25	40	24	370	765	195	405
25	20	4	135	215	105	170
25	20	14	180	300	150	270
25	20	24	255	510	185	370
25	30	4	180	245	145	200
25	30	14	245	365	185	295
25	30	24	320	590	190	400
25	40	4	155	210	125	165
25	40	14	200	315	155	250
25	40	24	300	525	210	370

Table 6.6Effect of particle size, particle concentration and rotational speed on h_{fp} and U in fixed and free axial rotation

S = Particle size, P = Particle concentration, R=rotation speed
	Free axial mode			Fixed axial mode		
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
S	2776	12.10	0.002	1087	4.64	0.045
Р	1073	4.68	0.045	982	4.52	0.049
R	2439	10.64	0.004	2275	9.71	0.006
S*S	3868	16.86	<0.001	1649	5.77	0.030
P*P	2962	12.92	0.002	2268	9.68	0.006
R*R	535	2.33	0.145	3189	13.61	0.001
S*P	168	0.73	0.403	151	0.65	0.433
S*R	1537	6.70	0.019	1414	6.03	0.251
P*R	75	0.33	0.574	8	0.04	0.852

Table 6.7aAnalysis of variance (ANOVA) results for U in fixed and free axial mode
demonstrating the effect of particle size, concentration and rotation speed

Table 6.7bAnalysis of variance (ANOVA) results for h_{fp} in fixed and free axial mode
demonstrating the effect of particle size, concentration and rotation speed

	Free axial mode			Fixed axial mode		
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
S	10171	8.78	0.008	9519	15.10	0.008
Р	13123	11.33	0.003	8882	18.13	0.0005
R	11037	9.53	0.006	3863	7.89	0.012
S*S	11701	10.10	0.005	1101	2.25	0.1521
P*P	9335	8.06	0.011	7704	15.73	0.0010
R*R	8689	7.50	0.014	10837	22.12	< 0.001
S*P	4318	3.73	0.070	2001	4.08	0.590
S*R	11390	9.83	0.006	2240	4.57	0.047
P*R	2700	2.33	0.145	602	1.23	0.283

 \overline{S} = Particle size, P = Particle concentration, R=rotation speed



Figure 6.6 Effect of particle concentration and particle size on heat transfer coefficients in free axial mode (rotational speed of 4, 14 and 24 rpm and glycerin concentration of 100 %) (a) Overall heat transfer coefficient (U) (b) Fluid to particle heat transfer coefficient (h_{fp})





Figure 6.7 Effect of particle concentration and particle size on heat transfer coefficients in fixed axial mode (rotational speed of 4, 14 and 24 rpm and glycerin concentration of 100 %) Overall heat transfer coefficient (U) (b) Fluid to particle heat transfer coefficient (h_{fp})

In their experiments, Sablani and Ramaswamy (1997) reported that an increase in particle diameter would decrease the U and h_{fp} . They noted that when the particles in their experiment were increased from 19.05 to 22.25 mm in diameter, the fluid to particle heat transfer coefficient h_{fp} in oil decreased by 13%, and further increasing the size to 25 mm reduced the h_{fp} by 24%. This trend of decreasing h_{fp} was less pronounced when the particles were in water; when the particles were increased in size from 19.05 to 25 mm, the decrease was only around 9%. Since glycerin at 100% is more viscous than water, the drop in the value of h_{fp} will be even higher than in oil, as indicated in this study. Deniston et al. (1987) reported that decreasing the particle size from 35.0 to 22.2 mm in diameter would yield a small increase in h_{fp} . Hassan (1984) agreed, showing in his reports that h_{fp} increases when the particle size was reduced from 34.9 to 22 mm. Lenz and Lund (1978) reported higher overall heat transfer coefficients with increased particle diameter. They also reported higher values for liquid-particle film transfer coefficients when increasing particle diameters in water. However, when studying the three particle diameters in 60% sucrose solution, the lowest h_{fp} values found were for the 0.813 inch particles, followed by the 0.375 inch and then 1.187 inch particles. Lekwauwa and Hayakawa (1986) reported higher heating rates for both liquid and particles for particles with a smaller mean size, and also found that temperature gradient between the liquid and particles increased as the mean particle size increased.

It was determined by Rao and Anantheswaran (1988) that the flow pattern of a pure liquid could be altered by the presence of particulate matter during agitated processing, thus affecting the heat transfer coefficient. The amount of solid particulate in the can influences the heat transfer rate by affecting the relative particle to fluid velocity inside the can. As this particulate matter causes secondary agitation with its motion, contributing to the mixing of the contents of the can, there was an expected and significant effect (p < 0.05) for h_{fp} and U values (Table 6.7a, b).

Particle concentration influence on the heat transfer coefficients U and h_{fp} , is also shown in Figures 6.6 and 6.7 (see also next section). The influence of particle concentration was greater in free axial mode than in fixed axial. Illustrating this influence, Figure 6.7 shows that for a particle size of 25 mm, U and h_{fp} increased with particle concentration ranging from 20 to 30%, while further increase in concentration to 40% decreased both U and h_{fp} . Such a decrease could be due to restricted free movement attributed to shrinking space inside the can with increasing particle concentration. Deniston *et al.* (1987) showed that increasing the particle concentration from 10.7 to 40% would give an increase in U and h_{fp} , but higher concentrations (45.3 to 50.6%) would result in a decrease. Stoforos (1988) noted that for highly viscous products, the moving particles would create a mixing effect inside the can and contribute to a homogeneous temperature distribution. Sablani and Ramaswamy (1997) reported that when the particle concentration was raised from a single particle to 20%, U increased by 5% in water and 20% in oil. However, when the concentration was raised to a further 40%, U experienced a decrease of 27% and 31% in the same liquids. When h_{fp} was examined, it was found that in oil the values increased 3 fold, and in water 3.4 times under the same conditions, and decreased to 7% and 12% when the particle concentration reached 40%. Lenz and Lund's findings agreed that increasing concentration would lower U and h_{fp} values. Hassan (1984) and Deniston et al. (1987) studied the effect of particle concentration on heat transfer rates when they kept the head space height constant (6.4 mm for 303×406 cans closed in 50 cm hg vacuum). They reported that for their Teflon spheres (2.54 cm in diameter) in water the U and h_{fp} where higher when the particle concentration rose from 20 to 31%.

6.4.3.3 Influence of particle concentration and particle density on U and h_{fp}

The effects of particle concentration and particle density in free and fixed axial modes were evaluated in combination with rotation speed using a second full factorial design of experiments. Glycerin concentration was maintained at 100%, headspace of 10 mm and temperature at 120°C. The results for U and h_{fp} in fixed and free axial modes are in Table 6.8 and the ANOVA results are shown in Table 6.9.

From the ANOVA results (Table 6.9), it can be seen that in both free and fixed axial modes, particle concentration and particle density had significant effects on U and h_{fp} . The effect of particle density at three different concentrations (20, 30 and 40%) is shown in Figures 6.8 and 6.9, respectively for fixed and free axial rotation. The effect of particle concentration was discussed earlier in combination with particle size and rotation

D (mm)	P (%)	R (rpm)	U_{FRA} (W/m ² C)	$\frac{h_{fpFRA}}{(W/m^2C)}$	U _{Fixed} (W/m ² C)	<i>h_{fpFixed}</i> (W/m ² C)
1128	40	24	425	890	275	575
1128	40	4	245	410	145	245
1128	40	14	350	720	150	315e
1128	20	24	410	765	255	475
1128	20	4	240	400	135	230
1128	20	14	340	700	145	260
1128	30	24	430	910	280	590
1128	30	4	250	430	145	245
1128	30	14	335	750	210	390
2210	40	24	495	1030	345	720
2210	40	4	310	505	190	315
2210	40	14	410	840	200	405
2210	20	24	500	920	345	635
2210	20	4	310	510	190	310
2210	20	14	420	730	200	350
2210	30	24	545	1140	380	800
2210	30	4	340	565	200	340
2210	30	14	505	920	245	450
830	40	24	310	500	185	300
830	40	4	160	225	80	115
830	40	14	255	405	85	140
830	20	24	320	495	155	240
830	20	4	165	230	80	110
830	20	14	265	390	90	130
830	30	24	340	635	260	485
830	30	4	175	265	85	130
830	30	14	320	530	125	205

Table 6.8Effect of particle density, particle concentration and rotational speed on h_{fp} and U in fixed and free axial modes.

D = Particle density P = Particle concentration, R=rotation speed

Table 6.9aAnalysis of variance (ANOVA) results for U in fixed and free axial mode
demonstrating the effect of particle density, concentration and rotation
speed

	Free axial mode			Fixed axial mode		
Source	Type III SS	F value	Pr>F	Type III SS	F value	Pr>F
D	13776	37.34	<0.0001	10307	32.66	<0.0001
Р	5196	14.09	0.001	6572	20.83	<0.001
R	7911	21.44	< 0.001	3607	11.43	0.003
DxD	9948	26.96	< 0.0001	8037	25.47	<0.0001
P×P	5601	15.18	0.001	6890	21.84	<0.001
R×R	3424	9.28	0.007	12757	40.43	<0.0001
D×P	6.00	0.02	0.899	84	0.27	0.611
D×R	879	2.38	0.141	1674	5.31	0.034
P×R	0.000	0.00	1	133	0.42	0.524

Table 6.9bAnalysis of variance (ANOVA) results for h_{fp} in fixed and free axial mode
demonstrating the effect of particle density, concentration and rotation
speed

Pr>F
<0.0001
< 0.001
0.002
<0.0001
< 0.001
<0.0001
0.751
0.0024
0.133

D = Particle density P = Particle concentration, R=rotation speed



Figure 6.8 Effect of particle concentration and particle density on heat transfer coefficients in fixed axial mode (rotational speed of 4, 14 and 24 rpm and glycerin concentration of 100 %) (a) Overall heat transfer coefficient (U) (b) Fluid to particle heat transfer coefficient (h_{fp})



Figure 6.9 Effect of particle concentration and particle density on heat transfer coefficients in free axial mode (rotational speed of 4, 14 and 24 rpm and glycerin concentration of 100 %) Overall heat transfer coefficient (U) (b) Fluid to particle heat transfer coefficient (h_{fp})

speed. The effects were somewhat similar in the presence of particles of different densities (contributed by different particle materials as shown in Tables 6.8 and 6.9 and Figures 6.8 and 6.9).

In Figure 6.9, at 20 % particle concentration, polypropylene particles are shown to have the lowest h_{fp} (495 W/m²C), and Teflon particles the highest (920 W/m²C) while Nylon particles fell in between with h_{fp} of 765 W/m²C. While, with the same concentration of the particle, fixed axial mode shown lower h_{fp} values; Polypropylene particles had lowest h_{fp} (240 W/m²C), and Teflon particles the highest (635 W/m²C) while Nylon particles fell in between with h_{fp} of 475 W/m²C. This difference could be due to the different particle fluid motion pattern inside the can in two different modes of rotation thereby affecting the heat transfer coefficient to different degree. When using a single particle inside a can, Sablani (1996) found a significant effect of density on the h_{fp} value. He noted that particles of greater density settled in the can faster, resulting in more motion inside the can due to the higher particle-liquid relative velocity and creating a higher h_{fp} . When the particles with densities close to each other (Nylon and Acrylic) had similar h_{fp} values in both oil and water, he concluded that particle thermal properties did not influence h_{fp} . However, Stoforos and Merson (1992) reported that their Teflon spheres had a higher h_{fp} value than their aluminum particles of the same size, and besides the particle density, the thermal properties of the particle matter were presumed to be the explanation. Meng and Ramaswamy (2007b) found that the Teflon particles yielded the highest h_{ap} values, followed by Nylon and then by polypropylene particles with the lowest values for h_{ap} .

6.5 Conclusions

A detailed study has been made describing the influence of significant product and system parameters (obtained from L16 design) such as rotational speed, temperature, concentration, particle density, particle concentration and particle size on the overall heat transfer coefficient U, and the fluid to heat transfer coefficient h_{fp} in free and fixed axial mode. A CCRD and two full factorial experiments involving those significant factors showed that with the decrease of liquid viscosity and increase of rotational speed, particle density and retort temperature, h_{fp} and U values increased. With the increase in particle concentration, h_{fp} and U values increased while with further increasing the particle concentration, the heat transfer coefficients decreased. *t*-tests revealed that both U and h_{fp} were significantly higher (p<0.01) in the free axial mode as compared to the fixed axial mode.

PREFACE TO CHAPTER 7

In the previous two chapters, a methodology was established and the heat transfer coefficients U and h_{fp} were evaluated in detail in bi-axially rotating cans. Effect of system and process variables on U and h_{fp} were studied providing good database of heat transfer coefficients under different modes of heat transfer.

Traditionally dimensionless correlations are used to model heat transfer coefficients, and these have been generally found to have a great value in scale up considerations and predictions. Therefore the objective of this chapter was to develop dimensionless correlations for the heat transfer coefficient U and h_{fp} for canned particulates suspended in Newtonian liquid during the axial agitation processing.

Part of this research was presented in 2008 Annual Meeting of the IFTPS (San Antonio, TX), and won Charles Stumbo Graduate Student paper competition award again, two years in a row. Part of this research has also been presented in 2008 IFT Annual meeting, New Orleans, USA and prepared for publications in a scientific journal. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.

CHAPTER 7 DIMENSIONLESS CORRELATIONS FOR CONVECTIVE HEAT TRANSFER IN CANNED PARTICULATE FLUIDS UNDER AXIAL ROTATION PROCESSING

7.1 Abstract

Dimensionless correlations for heat transfer coefficients in canned Newtonian liquids, both with and without particles, under mixed and pure forced convection heat transfer were investigated using multiple non-linear regressions of statistically significant dimensionless groups using tangent as an estimate and Newton as search method. Data on overall heat transfer coefficient U and fluid to particle heat transfer coefficients h_{fp} were obtained for several processing conditions and were analyzed separately for particle and particle-free conditions. Dimensionless correlations were formulated by including the contribution of both natural and forced convection heat transfer to the canned liquid in free axial rotation. The combination of reel radius, can radius and particle radius was used as the characteristic length for the correlation. In mixed convection mode, Nusselt number (Nu) was correlated to Reynolds (Re), Prandtl (Pr), Grashof (Gr) and Froude (Fr) numbers, relative density of particle to liquid (ρ_p/ρ_l) , particle concentration (e/100-e), diameter of particle to can (d_p/D_c) and particle/liquid thermal conductivity ratio (k_p/k_l) . For particulate fluids, an excellent correlation of $(R^2>0.93)$ was obtained between the Nu and the other dimensionless groups in the following general form: Nu=A₁(GrPr)^A₂+A₃(Re)^A₄(Pr)^A₅(Fr)^A₆(ρ_{p}/ρ_{1})^A₇(e/100-e)^A₈(d_p/D_c)^A₉(K_p/K₁)^A₁₀. In the absence of particles, Nu was correlated only to the Re, Pr, Gr and Fr. With the particle free fluids in end-over-end mode, the R^2 was only 0.81 when the pure forced convection model was used; however, introduction of the natural convection $(G_r \times P_r)$ factor increased the R^2 to 0.97 indicating the presence of some natural convection even with forced convection systems. The validity of the mixed convection equations for U in free axial mode was limited to Re in the range 61 to 2.75×10^3 ; Pr, 5.76×10^2 to 8.04×10^3 ; Fr, 2.1×10^{-3} to 7.5×10^{-1} ; Gr, 4.89×10^{4} to 8.12×10^{6} ; ρ_{p}/ρ_{l} , 0.65 - 1.75; d_{p}/D_{c} , 0.21 to 0.28 and e/100-e, 25 to 66 %, whereas for h_{fp} the Re ranges were between 57 to 2.60×

10³; Pr , 5.76 × 10² to 8.04 × 10³; Fr, 2.0 × 10-3 to 7.3 × 10⁻²; Gr, 4.48 × 10⁴ to 7.43 × 10⁶; ρ_p/ρ_l , 0.65 – 1.75; d_p/D_c , 0.21 to 0.28 and *e/100-e*, 25 to 66 %.

7.2 Introduction

In order to establish a proper thermal process, data on the heat resistance of pathogenic and spoilage micro-organisms, and data on heat transfer rate into a specific product in a given container are required. Continuous rotary sterilizers, like multi-shell rotary reel cookers, were designed to be fully automated, with a high product throughput, lower energy consumption and rapid and uniform heating to promote better quality in the processed product. These systems rely on the induced agitation and enhanced heating principle by intermittently rotating the cans along their own axis as well as around the retort shell, in opposite rotary directions, in order to maximize the rate of heat penetration. The system also utilizes the principle of high-temperature short-time processing in order to obtain the best results in product quality and throughput.

Process modeling plays an important role in optimizing the sterilization process while at the same time ensuring food safety. Due to concerns about product quality and process efficiency, there is an increasing interest in the canning industry for using new process modeling, process calculation and process optimization techniques. Based on the retort temperature and relevant thermo-physical properties, lethality of the product can be estimated by modeling the heat sterilization process of canned food using two principle heat transfer parameters; the overall heat transfer coefficient (U) between the external heating medium and the internal rotating liquid, and the fluid to particle heat transfer coefficients (h_{fp}) between the rotating liquid and particles (Sablani *et al.* 1997). In addition to these two parameters, the boundary conditions and thermo-physical properties of particles and liquid also must be known.

A number of studies have been published evaluating the parameters that influence the heat transfer coefficients (U and h_{fp}) for canned liquid foods with and without particles (Meng and Ramaswamy 2007b).. These factors include rotational speed, retort temperature, rotational radius, system geometry, headspace volume, product viscosity, off-center axis of rotation, particle density and particle size. These studies cover both modes of agitation, i.e. end-over-end mode (Anantheswaran and Rao, 1985a, 1985b; Britt, 1993; Lekwauwa and Hayakawa, 1986; Meng and Ramaswamy, 2007b, 2007c; Naveh and Kopelman, 1980; Ruyter and Brunet, 1973; Sablani and Ramaswamy, 1995, 1996, 1997, 1998; Rao and Anantheswaran, 1988 and Stoforos and Merson, 1992) and continuous free axial mode of agitation (Deniston *et al.*, 1987; Fernandez *et. al*, 1988; Hassan, 1984; Lenz and Lund, 1978; Stoforos and Merson, 1990, 1992). Some studies on E-O-E agitation concentrated on evaluating nutrient, texture and color retention of the food products (Abbatemarco and Ramaswamy, 1994, 1995).

Dimensional analysis is a preferred and widely used technique for generalizing data because it limits the number of variables that must be studied and permits the grouping of physical variables that affect the process of heat transfer (Ramaswamy and Zareifard, 2003). In the dimensional analysis of forced convection heat transfer, where fluid is forced over the solid by external means, the Nusselt number (Nu), a dimensionless measure of convective heat transfer coefficient, is related with other dimensionless numbers such as Reynolds number (Re) and Prandtl number (Pr). In the case of free or natural convection, where fluid motion is determined by the buoyancy forces, Nusselt number (Nu) is correlated to the Rayleigh number (Ra) [which is the product of two dimensionless numbers, Grashof (Gr) and Prandtl (Pr) numbers]. The Grashof number plays the same role in free convection that the Reynolds number plays in forced convection. Reynolds number is used to measure the ratio of the inertial to viscous forces acting on a fluid element, while Grashof number indicates the ratio of the buoyancy force to the viscous forces acting on the fluid (Incropera and Dewitt, 1996). These dimensionless numbers give a better understanding of the physical phenomenon and can also be easily used for scale-up purposes. Most earlier dimensionless correlations involve overall heat transfer coefficients (U) because the studies were focused on the convective heat transfer in liquid foods. Rao and Anantheswaran (1988) have presented a comprehensive review of these studies; however for canned liquid particulate food systems there are scant few studies available.

Sablani *et al.*, (1997a) and Meng and Ramaswamy (2007a) established correlations for overall heat transfer coefficients, as well as the fluid to particle heat transfer coefficients for liquid/particle mixtures in end-over-end rotation. In their studies,

Nu was correlated with other dimensionless numbers, including Archimedes and Froude numbers (Ar and Fr), the ratio of headspace to the length of the can (H_s/L_c) , the ratio of the particle to liquid concentration (e/100-e), the ratio of the equivalent particle diameter to the diameter of the can (d_p/D_c) , particle sphericity (Ψ) and the density simplex $(p_p$ p_l/p_l). In end-over-end rotation, Meng and Ramaswamy (2007a) developed the dimensionless correlations for high viscosity fluid/particle mixtures using apparent heat transfer coefficients h_{ap} and U_a . Lenz and Lund (1978) and Deniston et al. (1987) presented correlations in free axial rotation for U relating Nu to Re, Pr and other dimensionless numbers, although they did not develop the relation for the fluid to particle heat transfer. Fernandez et al. (1988) presented dimensionless correlations for h_{fp} in cans with axial rotation. Using the fluidized bed and packed bed approaches, and using the modified Stanton number and Colburn j-factor in empirical correlations, they were able to model their correlations. They were unable, however, to develop correlations for U. The time temperature prediction at the particle's center requires appropriate correlations for both U and h_{fp} , and cannot be made with only one of these coefficients. Because of the difficulties in obtaining time-temperature measurements of the liquid and particle simultaneously, literature pertaining to free axial agitation lacks the correlations of U and h_{fp} .

Anantheswaran and Rao (1985a) tried different variables to determine characteristic length, and found that using the sum of the diameter of rotation and the length of the can using Newtonian liquid resulted in a statistically acceptable R^2 (0.92) for U values in E-O-E mode. In axial rotation, reel radius was used as the characteristic length, as demonstrated by Lenz and Lund (1978). Deniston *et al.* (1987a) used the diameter of the can as the characteristic length in equations to describe the heating behavior of liquid in the presence of multiple particles. Fernandez *et al.* (1988) used the diameter of the particle in the dimensionless correlation for h_{fp} . Sablani *et al.* (1997a) tried different variables and concluded that in order to obtain the most appropriate U correlations, it was best to use the sum of the rotation diameter and the diameter of the can as the characteristic length, and the particle's shortest dimension for h_{fp} correlations.

For end-over-end agitation processing of canned liquid-particle mixtures, Sablani et al. (1997a) and Meng and Ramaswamy (2007a) developed their correlation on the

assumption that forced convection was the dominant mechanism for heat transfer. On the contrary, Fand and Keswani (1973) assumed that even in forced convection situations, the natural convection phenomenon would continue since buoyant forces resulting from density differences exist.

For axial agitation, because the can rotates only over one-third of the cycle, Rao *et al.* (1985a, 1985b) reported that natural (free) convection can be expected to be an important mode of heat transfer. Since the fluid flow agitation during the upper $2/3^{rd}$ part of the retorts are low, the mechanisms involved in modeling the dimensionless number in these systems (like Steritort) are the complex combination of the natural and forced convection. In mixed convection, buoyant as well as inertial forces operate simultaneously within the fluid, and in some situations may have the same order of magnitude (Fand and Keswani, 1973; Chapman, 1989). Marquis *et al.* (1982) acknowledged that natural convection was important during the heating of liquids in bottles subjected to axial rotation, and Lenz and Lund (1978) correlated their data with a two term model which can be interpreted as the sum of natural and forced convection, they supplied only a fixed value to free convection and concentrated their work on forced convection.

There is little information available in published literature for combined U and h_{fp} correlations in the free axial mode, while some individual correlations do exist. Despite the fact that this concept of modeling the time-temperature profile shows promise in a wide range of industrial applications, little research has been done to explore its potential in free axial rotation. The objective of this study was to develop the dimensionless correlations for overall as well as fluid to particle heat transfer coefficients in canned particulate fluids subjected to thermal processing under fixed and free axial agitation conditions, and also to compare the correlations between end-over-end mode and free axial mode using only liquid in the cans. Additionally, the objective was to evaluate the role of natural convection in forced convection heat transfer correlations.

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7.3 Theoretical Background

In cans with axial agitation, the heat transfer to liquid and particles is affected by the thermo-physical properties of the contents and retort operating conditions. When modeling dimensionless correlation for these processes, the mechanisms are the complex combinations of natural and forced convection (Rao et al., 1985). The dimensionless group Gr/Re² describes the ratio of buoyant forces to inertia forces and governs the relative importance of free to forced convection regimes (Ozisik, 1985; Chapman, 1989). Generally, the combined effects of free and forced convection must be considered when $Gr/Re^2 \approx 1$. When $Gr/Re^2 < 1$, free convection effects may be neglected and Nu = f (Re, Pr). Conversely, if $Gr/Re^2 > 1$, forced convection effects can be neglected and Nu = (Gr, Pr). According to Johnson *et al.* (1988), mixed convection occurs when the ratio Gr/Re^2 falls between 0.08 and 5.10. For a horizontal cylinder in cross flow, Fand and Keswani (1973) found forced convection to dominate when $(Gr/Re^2) < 0.5$, whereas natural convection dominated when the ratio exceeded 40. Between 0.5 and 2, the natural convection contributed 10 % of the overall heat transfer. According to the authors, both forced and natural convection are of the same order of magnitude when the ratio falls between 2 and 40 for a cylinder. Awuah and Ramaswamy (1996) reported that in their study on the development of correlations for mixed and forced convection heat transfer in an aseptic processing holding tube simulator, the Gr/Re² ranged from 1.3 to 23.5 for spherical particles. They developed the correlations by accounting for both natural and forced convection and found that introducing the terms G_r and G_r/Re^2 resulted in better statistical correlations of $R^2 = 0.99$:

$$N_{\mu} = 2.0 + 0.32(0.4G \,\mathrm{Re}^{0.5} + 0.06G \,\mathrm{Pr}^{0.46}) \left(\frac{d}{D}\right)^{0.17} \left(\frac{GGr}{GRr^2}\right)^{-.04}$$
(7.1)

Rao *et al.* (1985) formulated an equation on the assumption that the heat transfer to canned liquids in a Steritort takes place by combined natural and forced convection.

$$N_{uD} = A_1 (Gr \operatorname{Pr})^{A_2} + A_3 (\operatorname{Re} \operatorname{Pr} \frac{D}{L})^{A_4}$$
(7.2)

For natural convection, it is well known that the term $Gr \times Pr$ is well suited to correlate experimental data.

Lenz and Lund (1978) correlated their heat transfer coefficient data for liquid canned food and interpreted the developed correlation as the sum of natural and forced convection contributions. The following correlation was proposed

$$Nu = 115 + 15 \,\mathrm{Re}^{0.3} \,\mathrm{Pr}^{0.08} \tag{7.3}$$

Lenz and Lund (1978) also developed dimensionless correlations (Eq. 7.4) for the canned liquid particulate food system for the low Biot number (<0.1) situation. In this study a lead particle was fixed on a rigid thermocouple within freely moving liquid, and similar correlations for U were developed, as mentioned above.

$$Nu = -33 + 53 \,\mathrm{Re}^{0.28} \,\mathrm{Pr}^{0.14} \left[\frac{d_s}{S(1-\varepsilon)}\right]^{0.46}$$
(7.4)

Deniston *et al.* (1987) used the following correlations without including the Grashof number in their study to calculate U relating Nu to Re, Pr and other dimensionless correlations as follows:

$$Nu = 1.87X10^{-4} \operatorname{Re}^{1.69} \left[\left((\rho_p - \rho_f) / 6C_D \rho_l \right) \left((\omega^2 D_c + 2g) / \omega^2 D_c \right) (d_s / D_c) \right]^{0.530} \cdot \left(\alpha_p / \omega D_p^2 \right)^{0.126} \\ \left[(1 - \varepsilon) (H_{ce} / D_{ci}) (\omega D_c^2 / \alpha_f) \right]^{-0.17}$$
(7.5)

Fernandez *et al.* (1988) used the following correlations in their study in axial mode agitation and developed a correlation for h_{fp} without taking into account free convection as in Eq. 7.6.

$$Nu = 2.7 \times 10^4 \text{ Re}^{0.294} \text{ Pr}^{0.33} \psi^{6.98}$$
(7.6)

The heat transfer correlations reported in the literature for U and h_{fp} for thermal processing of liquid-particle in end-over-end rotation are summarized in Sablani *et al.* (1997a), and additional heat transfer correlations as applied to aseptic processing situations are available in Awuah and Ramaswamy (1996).

The dimensionless correlation developed in this study take into account both free and forced convection as explained by Rao *et al.* (1985), Awuah and Ramaswamy (1996) and Lenz and Lund (1978), and further supported by the above theoretical explanations of Gr/Re^2 . The Gr/Re^2 values for U and h_{fp} range between 0.26 to 18.7 in free axial mode and between 0.22 to 16.79 in fixed axial mode, and therefore are within the range where mixed convection (free and forced) should be taken into account.

7.4 Materials and methods

7.4.1 Materials, physical properties and experimental range

In order to calculate the dimensionless numbers, the thermo-physical properties of the material were employed at the average bulk temperature. The glycerin at 100% concentration (at 38°C) was used (Fischer Scientific Ltd., Montréal, PQ). By changing the concentration of the glycerin solution, the viscosity could be changed to simulate a variety of liquid food products. The densities were determined from the weights of known volumes of the glycerin solution. Propylene, Nylon and Teflon spheres of size 19, 22.5 and 25.4 mm (Small Parts Inc., Miami, FL) were taken as food particulate models, the individual particle concentrations varied from 20 - 40 %. The thermo-physical properties of the liquid and particles of the simulating solutions were extracted from the available literature (Sablani and Ramaswamy 1997; Meng and Ramaswamy 2007b). The different thermo-physical properties are summarized in Table 7.1.

Material	Density	Heat	Thermal	Thermal	Kinematic
	(kg/m^3)	Capacity	Conductivity	Diffusivity	Viscosity
		(kJ/kgC)	(W/mC)	$(m^2/s) \times 10^{-7}$	$(Pa.s) \times 10$
Glycerine (100 %)	1260	2.430	0.284		9.42
Glycerine (96 %)	1247	2.500	0.293		5.53
Glycerine (90 %)	1234	2.570	0.301		2.11
Glycerine (84 %)	1213	2.650	0.3096		1.05
Glycerine (80 %)	1208	2.720	0.330		0.701
Polypropylene	830	1.842	0.359	2.35	
Nylon	1128	2.073	0.369	1.52	
Teflon	2210	0.984	0.290	1.35	

Table 7.1Physical properties of test materials used in this study

7.4.2 U and h_{fp} in fixed and free axial mode

A single car rotary retort (STOCK rotomat - PR900; Herman STOCK Maschinenfabric, Neumünster, Germany) was used in the study. The retort basket was retrofitted with a stainless steel enclosure in which test cans could be held in an axial direction. Cans were positioned by using rear and front stainless steel supports, which were fixed to the retort basket. The fabricated enclosures held two free cans on each side of the frame. On one side, end plate facing the retort shell was removed so that the cans could slide down and roll along the retort shell during part of the rotation. These cans rolled on their own axis (in a direction counter to that of retort cage) along the bottom of the retort shell when the opening was facing downwards (approximately 1/3rd of the rotation in facing downward) simulating the action in a Steritort. In the top $2/3^{rd}$ of the cage rotation, the cans were restrained in the enclosure only rotating with the cage. This process caused biaxial rotation of the can in the free axial mode, while only in clockwise direction in the fixed axial mode. The two cans held at the opposite end were held inside in a fixed axial mode and were not allowed to drop on to the retort shell. The range of parameters related to liquid, particles and retort operating conditions are summarized in Table 7.2.

S.No. Parameters Symbol Experimental range 1 Т 111.6,115,120, 125,128.4°C Retort temperature 2 Rotation speed R 4,8,14,20,24 rpm 3 Can headspace Η 5 mm and 10 mm 4 Test liquids Newtonian: 80,84,90,96,100 % C (Glycerin) 5 Test particles M (PP, NYL, TF) density: 830, 1128, 2210 kg/m³ 6 Particle Size S 0.019, 0.02225 and 0.254 meters 7 Particle Ρ 20 %, 30 % and 40 % concentration

Table 7.2Range of system and product parameters used in the determination of
convective heat transfer coefficients (U and h_{fp})

Note: R=rotation speed, T= retort temperature, H = Head space, S = Particle size, C = Glycerin concentration, M = Particle material, P = Particle concentration, PP = Polypropylene, NYL = Nylon, TF = Teflon

Few in depth studies have studied U and h_{fp} in axially rotating cans due to the difficulty in measuring particle and liquid temperatures under commercial processing conditions. While some special techniques could be used to measure the liquid temperature, it is impractical to gather particle temperature data. Traditional computation of U and h_{fp} , however, require data on both particle and liquid temperatures. While some special techniques could be used to measure the liquid temperature, it is impractical to gather particle and liquid temperature, it is impractical to gather particle temperature data. Traditional computation of U and h_{fp} , however, require data on both particle and liquid temperatures. While some special techniques could be used to measure the liquid temperature, it is impractical to gather particle temperature data. In the previous work (Chapter, 5), a useful methodology was established for evaluating U and h_{fp} in free axially rotating cans under commercial processing conditions. The method involved developing correlations between h_{fp} and U using real time-temperature data gathered from test cans in the *fixed axial mode* of rotation and then coupling them with experimentally evaluated U from fluid temperature gathered with wireless sensors to compute h_{fp} for bi-axially rotating cans. The methodology was based on the assumption that within a can, factors that influence U will also influence h_{fp} , and therefore h_{fp} and U are generally inter-related. The method was

tested under different processing conditions and was found to be predictably responsive to process variables.

In order to develop the dimensionless correlations, the heat transfer coefficients data were obtained from previous chapters. To develop the model for U and h_{fp} , data from 148 set of experiments were used in both fixed and free axial modes each, with particles in can, whereas 70 set of experiments used for free axial and end-over-end modes each, without particle in the can.

7.4.3 Characteristics Dimensions

The dimensionless groups (Re, Nu, Pr and Gr) are widely affected by the characteristic dimensions to diversified degree of magnitude, therefore one should be careful while selecting the appropriate one when the comparison is to be made with published correlations (Awuah and Ramaswamy, 1996). In some studies, the characteristic dimension used was the diameter of the can (Teixeira *et al.*, 1969; Duquenoy, 1980; Deniston *et al.* 1987), while in others it was the radius of rotation (Lenz and Lund, 1978; Anantheswaran and Rao, 1985a, 1985b; Meng and Ramaswamy 2007a and Sablani *et al.* 1997a). Sablani *et al.* (1997a) found that using the sum of the rotation diameter and the diameter of the can as the characteristic length was more appropriate for U correlations, whereas the particle shortest dimension was well-suited for h_{fp} correlations. The diameter of the can (D_c) , the particle radius (R_p) and the rotation radius of the correlations (Meng, 2006). For both Newtonian and non-Newtonian fluids, a high R^2 was obtained with $RR_c + D_c/2$ as the characteristic length for the correlation of U_a and $RR_c + R_p$ for h_{ap} .

Anantheswaran and Rao (1985) used a number of combinations involving the diameter of the can, D_c , and the diameter of the rotation, D_r , as the characteristic length and found that for Newtonian fluids the characteristic length as the sum of rotation (D_r) and the length of the can (D_l) resulted in the highest R^2 value for the model, while D_c gave a poor fit to the experimental data. Lenz and Lund (1978) reported that the heat transfer coefficients (U) were not dependent on the size of the container used in the study. Therefore, the diameter of the can, D_c , was not used as the characteristic dimension. They

further summarized that the characteristic velocity was dependent on the radius of the reel, and so it was used as the characteristic length in the dimensionless correlations with axial rotation. Moreover, they also reported that it was not feasible to vary the reel radius while developing the correlations. In order to develop the correlations for h_{fp} . Fernandez *et al.* (1988) tried two different dimensions; the diameter of the beans being used under the assumption that free convection was significant in the process (Antheswaran and Rao, 1985a, 1985b) and the reel diameter under the assumption that forced convection was the most important heat transfer mechanism occurring in the system (Lenz and Lund, 1978). They revealed that the equivalent particle diameter used as the characteristic length in their correlations provided higher R^2 by 30-50% than those obtained when the reel diameter was used.

In this study the dimensionless correlations for U and h_{fp} have been developed assuming that the heat transfer in Steritort is the complex combination of free and forced convection. As a consequence, the diameter of the can, D_c , the particle radius, R_p , and the reel radius, R_r , were evaluated as the characteristic dimension in the correlations in different combinations.

7.4.4 Dimensionless correlations of U and h_{fp} in fixed and free axial mode

Based on the analysis of variance performed with the heat transfer coefficients data, it was found that the overall heat transfer coefficient, U, and fluid to particle heat transfer coefficient h_{fp} in free and fixed axial mode were affected significantly by the range of process and system parameters studied (Table 7.2). Headspace did not significantly affect the heat transfer coefficient and therefore it was excluded in developing the correlations. The extent of the significance of the other parameters such as rotational speed, product concentration, retort temperature, particle density, particle size and particle concentration were varied (p < 0.05 to p < 0.001).

Heat transfer by natural (or free) convection involving motion in a fluid results from the interaction of gravity with density differences within a fluid. The differences may result from gradients in temperature, concentration, or composition. As natural convection heat transfer is influenced mainly by the gravitational force from thermal expansion, viscous drag, and thermal diffusion, for this reason the gravitational acceleration, the coefficient of performance, the kinematic viscosity and thermal diffusivity directly affect natural convection. These parameters, Nusselt, Grashof, and Prandtl numbers, depending upon the fluid properties, temperature differences between the surface and the fluid, and the characteristic length of the surface involved are correlated in order to predict the convective heat transfer coefficients in the following form:

$$Nu = \frac{h_{fp}(U)d_{c}}{k} = a(Ra)^{m}$$
(7.7)

Where a and m are the constants, Ra is the Rayleigh number, which is a product of two dimensionless numbers; Grashof number and Prandtl number.

$$Ra = Gr \times \Pr \tag{7.8}$$

In forced convection, a fluid is forced to move over a solid surface by external mechanical means. The general correlation between the dimensionless numbers is given as:

$$Nu = f(\text{Re}, \text{Pr}) \tag{7.9}$$

The Froude number was included in the dimensional analysis as it explains the effect of centrifugal forces, which is described as the ratio of the inertial force to the gravitational force. To account for the effect of particle concentration and particle density and size, the ratio of the particle volume to the volume of the liquid (e/100-e), the ratio of the particle density to the liquid density (ρ_p / ρ_l) and the ratio of particle diameter to the diameter of the can (d_p/D_c) were included. The magnitudes of the dimensionless groups were calculated using the physical and thermal properties of materials at the average bulk temperature of the process. In the present study, a number of combinations involving the reel radius, the radius of the can and the radius of the particle were tried as the characteristic length.

To accommodate the complex combination of natural and forced convection heat transfer mechanisms involved in modeling dimensionless numbers in the case of axially rotating cans, the following form of the dimensional correlation was developed:

$$Nu = A_{1} (Gr \operatorname{Pr})^{A_{2}} + A_{3} (\operatorname{Re})^{A_{4}} \times (\operatorname{Pr})^{A_{5}} \times (Fr)^{A_{6}} \times \left(\frac{\rho_{p}}{\rho_{l}}\right)^{A_{7}} \times \left(\frac{e}{100 - e}\right)^{A_{8}} \times \left(\frac{d_{p}}{D_{c}}\right)^{A_{9}}$$
(7.10)

A step-wise multiple non linear regression analysis was performed using the different dimensionless correlations, using a tangent as an estimate and Newton as a search method, as shown in the above equation.

7.5 Results and Discussions

7.5.1 Characteristic length

Determination of the characteristic length is a key issue before the development of appropriate correlations could be made. Regression analysis was used to evaluate the suitability of the reel radius, radius of the can and the radius of the particle in combination as the characteristic dimension in the different correlations. This combination allows the data obtained with zero radiuses to be included in the analysis. This was evaluated for the data on the Newtonian liquid by means of multiple nonlinear regression analysis using tangent as an estimate and Newton as a search method. The sum of the squares (SS) of the difference between the experimental data and the fitted data was used for the comparison of the different correlation forms and characteristic dimensions. The optimum characteristic dimension was defined as the dimension which vielded the highest R^2 and lowest SS (difference between the experimental data and the fitted data). Since the ranges in the magnitudes of the dimensionless groups were a result of different combinations of the characteristic dimension, rotation speed of the reel and the physical properties of the test liquids, it is important to choose an appropriate characteristic length. Table 7.3 summarizes the coefficient of correlations and the associated sum of squares (SS) for different characteristic lengths tested in developing the dimensionless correlations. For overall heat transfer coefficient U, characteristic length as $RR_s + R_s/2$ resulted in the highest R^2 of 0.95 and 0.93 in free and fixed axial mode respectively, with the sum of squares of 123540 and 89208, respectively. These R^2 values were the highest among the four different characteristic lengths tested, while the sum of squares was minimum. Although the reel radius and the can size were not varied in this study due to experimental limitations, their combination was used as the characteristic dimension. Lenz and Lund (1978) also reported that in their study, it was not possible to

vary the reel radius while developing the correlations; they still used the radius of the reel as the characteristic length in the development of their dimensionless correlations. The reason for using the reel radius as the characteristic length was due to its influence on the characteristic velocity while developing the dimensionless correlations. Meng and Ramaswamy, (2007a) also reported that the combination of D_c , R_p and RR_c was successfully used as the characteristic length, since it was included in more than one dimensionless group (Nu, Re and Fr). They found that the sum of the rotation radius (RR_c) and the radius of the can (R_c) provided the highest R^2 even though neither had a significant impact on the overall heat transfer coefficient (U). These were supported by the findings of Anantheswaran and Rao (1985a, 1985b), who found that the can size and the rotation radius were not significant for U. They successfully used the sum of the diameter of the rotation (D_r) and the length of the can (D_l) as the characteristic length in their correlation for U. For fluid to particle heat transfer coefficient (h_{fp}) , using characteristic length as $RR_s + d_p$ resulted in the greatest magnitude of R^2 0.92 and 0.95 in free and fixed axial mode respectively whereas the sum of squares were 95485 and 126434 respectively. These R^2 values were the highest among the four different characteristic lengths tested, with lowest sum of squares. Meng and Ramaswamy (2007a) used $RR_c + R_p$ as the characteristic length for h_{ap} ; (Sablani et al., 1997a) applied the shortest particle dimension as the characteristic length in the correlation of h_{fp} and Fernandez et al. (1988) used the equivalent particle diameter as the characteristic length in the correlation for h_{fp} .

7.5.2 Overall heat transfer coefficient in free and fixed axial mode

The Gr/Re² for the overall heat transfer coefficient in free and fixed axial mode ranged from 0.26–13.51 and 0.38–18.7, respectively, and fell below the lowest limit (1.3– 23.5) suggested by Awuah and Ramaswamy (1996). Although the lowest limit of Gr/Re² fell within limits (0.08–5.10) set forth by Johnson *et al.* (1988) for mixed convection, pure forced convection was modeled as an initial approximation. Regression analysis between the Nusselt number and other dimensionless numbers resulted in a number of correlations with different coefficients of determination (R^2) and sum of squares (SS). The following final form of the correlations was achieved for pure forced convection in free axial mode for U. The coefficient of determination (R^2) of 0.85 and sum of squares (SS) of 213947 were achieved.

$$Nu = 52.90 \times (\text{Re})^{0.27} \times (\text{Pr})^{0.10} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.47} \times \left(\frac{e}{100 - e}\right)^{0.015}$$
(7.11)

Types of agitation	Characteristic	Regression	Sum of	
Modes	Dimension (d_{ch}) (m)	Coefficient (R^2)	squares (SS)	
U free axial Mode	RRs	0.87	201020	
	$RR_s + R_c$	0.91	176892	
	$RR_s + 2 R_c$	0.89	215061	
	$RR_s + R_c/2$	0.96	123540	
U in fixed axial mode	RR_s	0.82	116834	
	$RR_s + R_c$	0.85	97988	
	RR_s+2R_c	0.85	125475	
	$RR_s + R_c/2$	0.93	84388	
h_{fp} in fixed axial mode	<i>RR</i> _s	0.86	153245	
	$RR_s + d_p$	0.95	126434	
	RR_s+2d_p	0.90	131857	
h_{fp} in free axial mode	$RR_s + d_p/2$	0.93	128302	
	RR_s	0.81	141352	
	$RR_s + d_p$	0.97	54079	
	RR_s+2d_p	0.85	112354	
	$RR_s + d_p/2$	0.88	99124	

Table 7.3 Regression analysis with various characteristic dimensions

Contributions from natural convection were accounted for by introducing additive terms rather than multiple terms. For natural convection, it is well known that the term (Gr \times Pr) is suited to correlate experimental data (Incropera and Dewitt, 1996). After introducing this term, the following correlation for *U* in free axial mode was obtained:

$$Nu = 29(Gr \operatorname{Pr})^{-0.02} + 0.03306(\operatorname{Re})^{0.66}(\operatorname{Pr})^{0.49} \times (Fr)^{-.1635} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.42} \times \left(\frac{e}{100 - e}\right)^{0.09} \times \left(\frac{d_p}{D_c}\right)^{-0.70}$$
(7.12)

The sum of squares (SS) and R^2 calculated from Eq. 7.12 were 175873 and 0.92 respectively. The R^2 was higher and SS was lower than obtained from Eq. 7.11, which demonstrated that adding the Gr × Pr term in Eq. 7.12 resulted in an improvement of the model. The terms Fr and d_p/D_c were also added in this correlation which further improved R^2 to 0.94 and reduced SS to 160879. Experimental vs. predicted data from Eq. 7.12, is shown in Figure 7.1, which showed a good correlation. The contribution of natural convection to the total heat transfer was calculated from the first term of Eq. 7.12, and was only 3.24%. From this result it can be inferred that the forced convection (due to the rotation of the can) was more effective than natural convection. Lenz and Lund (1978) developed the dimensionless correlations presented in Eq. 7.3 and 7.4, with and without particles in the can for the overall heat transfer coefficients. From these equations it can be inferred that the contribution of natural convection with the particles in liquid (-33) was much smaller in magnitude than without particles (115).



Figure 7.1Experimental versus predicted (Nu) from equation 7.12 for overall heat
transfer coefficient (U) with multiple particles in free axial mode.

The percent of natural convection was of similar magnitude to that of results obtained in this study, although the percentage was lower than the contribution reported by Rao *et al.* (1985) in Eq. 7.2 (without particle). This difference in the results could have been due to the presence of multiple particles ranging from 20 to 40% which would have caused secondary agitation on the upper $2/3^{rd}$ as well as bottom $1/3^{rd}$ part of the can during the free axial rotation leading to higher forced convection. It was not possible to compare the contribution of natural convection with the correlations developed by Awuah and Ramaswamy (1996) and Ramaswamy and Zareifard (2003) because apart from using unbound flow in their model, in their correlations Gr and Gr/Re² terms were modeled as the multiple term rather than the additive term. Fand and Keswani (1973) reported that in all forced convection situations, the natural convection phenomenon

continues to operate since buoyant forces resulting from density differences exist. Sablani *et al.* (1997a) and Meng and Ramaswamy (2007a) suggested that for end-over-end rotation, forced convection was the dominant mechanism for heat transfer for the canned liquid-particle mixture, and modeled their particulate laden products on this basis, therefore comparisons with their model was not possible. The validity of Eq. 7.12 is limited to Re in the range 61 to 2.75×10^3 ; Pr, 5.76×10^2 to 8.04×10^3 ; Fr, 2.1×10^{-3} to 7.5×10^{-1} ; Gr, 4.89×10^4 to 8.12×10^6 ; ρ_p / ρ_l , 0.65 - 1.75; d_p/D_c , 0.21 to 0.28 and *e/100-e* in the range of 25 to 66 %.

The Nusselt number (Nu) was proportional to $(e/100-e)^{0.009}$ (the term signifying particle concentration) implying that with the increasing particle concentration; Nu increased slightly. Similarly, Meng and Ramaswamy (2007a) also reported a slight increase in Nu with the increase in particle concentration $(V_p/V_l)^{0.091}$. With multiple particles in Newtonian fluids during end-over-end rotation, Sablani et al. (1997) reported that increasing particle concentration reduced the heat transfer to the liquid and a negative component of $(e/100-e)^{-0.37}$ was obtained. In the correlation developed by Lenz and Lund (1978) with axial rotation, it was found that Nu was proportional to $(1-V_p/V_l)^{-1}$ ^{0.46}, and Deniston *et al.* (1987) reported that Nu was proportional to $(1-V_p/V_l)^{-0.171}$, which implies that the increase in Nu is proportional to the increase in V_p/V_1 , similar to the current study. The exponent of Reynolds number (0.66) and Prandtl number (0.49) appearing in Eq. 7.12 are higher than 0.44 (Re) and 0.36 (Pr), which were reported by Sablani et al. (1997). Re and Pr reported in this study were also higher than the reported values of 0.57 (Re) and 0.478 (Pr) in the case of single particle in Newtonian liquid, and 0.62 (GRe) and 0.294 (GPr) for multiple particles in non-Newtonian liquids as reported by Meng and Ramaswamy (2007a). Higher Re and Pr could be due to better agitation in free axial mode than those of the end-over-end rotation. The exponents of Re and Pr were also higher than those reported by (Rao et al., 1985) for non particulate Newtonian fluids processed in Steritort. Although Fr was excluded from the correlation for U by Sablani et al. (1997a) due to its insignificance, it was included in this study. Despite the negative component of Fr in Eq. 7.12, Nu increased with rpm, since the associated Re increased by a higher margin. Re (0.28) and Pr (0.14) values reported by Lenz and Lund (1978) were smaller than found in this study. The difference may be due to the restricted particle

motion and heavier particles having a low Biot number that were used in their study. The influence of particle density and particle concentration was represented by the ρ_p / ρ_l and d_p/D_c . Increase in particle density increased Nu whereas an increase in diameter reduced Nu, resulting in lower heat transfer.

The same procedure as described above was used for the development of dimensionless correlations for overall heat transfer coefficient U in fixed axial mode. When pure forced convection was considered, R^2 and SS were 0.84 and 115585 respectively with the following correlation:

$$Nu = 7.12 \times (\text{Re})0.41 \times (\text{Pr})^{0.184} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.80} \times \left(\frac{e}{100 - e}\right)^{0.04}$$
(7.13)

Contributions from natural convection were accounted for by introducing an additive term as $(Gr \times Pr)$ in the model and the following correlation was obtained:

$$Nu = 0.07(Gr \operatorname{Pr})^{0.37} + 0.0379(\operatorname{Re})^{0.50}(\operatorname{Pr})^{0.43} \times (Fr)^{-.06} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.6342} \times \left(\frac{e}{100 - e}\right)^{.012} \times \left(\frac{d_p}{D_c}\right)^{-1.27}$$
(7.14)

The R^2 was improved to 0.93 whereas the sum of squares (SS) was reduced to 84388, implying a better fit of the model. A graph of experimental vs. predicted data from Eq. 7.14 is presented in Figure 7.2, which shows further improvement in the model. The contribution of natural convection to the total heat transfer was calculated from the first term of Eq. 7.14, which was observed to be 21.50%. From this result it can be concluded that natural convection contributes significantly in fixed axial mode. This could be due to the lesser agitation effect in fixed axial mode than in free axial mode, as there is no free rotation on the bottom one third of the retort in the former. In the case of fixed axial mode, the exponents of Re (0.50) and Pr (0.43) were lower than in free axial mode, further enforcing the theory that free-axial rotation provides better agitation to the product than in fixed axial mode. The validity of Eq. 7.14 is limited to Re in the range 61 to 2.75 × 10³; Pr, 5.76 × 10² to 8.04 × 10³; Fr, 2.0× 10⁻³ to 7.5 × 10⁻²; Gr, 4.89 × 10⁴ to 8.12 × 10⁶; ρ_p / ρ_l , 0.65 – 1.75; d_p/D_c , 0.21 to 0.28 and e/100-e in the range of 25 to 66%.



Figure 7.2 Experimental versus predicted (N_u) from Eq. 7.14 for overall heat transfer coefficient (*U*) with multiple particles in fixed axial mode.

7.5.3 Fluid to particle heat transfer coefficient in free and fixed axial mode

As discussed earlier, the initial models for the overall heat transfer coefficients were initially undertaken with forced convection, and the same concept applied when it came to developing the h_{fp} . The Gr/Re² for the fluid to particle heat transfer coefficient (h_{fp}) in free and fixed axial mode ranged from 0.22–13.51 and 0.27-16.79, respectively. The Re, Pr and Fr numbers and ρ_p/ρ_l and e/100-e, were shown to be significant parameters (p<0.05) in stepwise multiple regression analysis of experimental data on h_{fp} for the spherical particles. The following equation shows the best fit h_{fp} correlation obtained when using forced convection, with $R^2 = 0.80$ and SS = 180504:

$$Nu = 0.0723 \times (\text{Re})^{0.69} \times (\text{Pr})^{0.50} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.47} \times \left(\frac{e}{100 - e}\right)^{0.15} (Fr)^{-.20}$$
(7.15)

When $(Gr \times Pr)$ was introduced as an additive term, representing the contribution from natural convection, it resulted in the following relationship where both pure and forced convection are included:

$$Nu = 20(Gr\,\mathrm{Pr})^{0.01} + 0.00955(\mathrm{Re})^{0.72}(\mathrm{Pr})^{0.56} \times (Fr)^{-0.195} \times \left(\frac{\rho_p}{\rho_l}\right)^{1.165} \times \left(\frac{e}{100-e}\right)^{-0.22} \times \left(\frac{d_p}{D_c}\right)^{-1.05} \left(\frac{K_p}{K_l}\right)^{2.26} (7.16)$$

A higher R^2 of 0.90 and lower SS of 99453 were obtained, and with the addition of the other terms in the equation R^2 improved further. Eq. 7.16 suggests that h_{fp} was affected by the particle/liquid thermal conductivity, judging by its inclusion and significance in the equation. These kind of problems are termed as 'conjugate heat transfer' which refers to a heat transfer process involving an interaction of conduction within a solid body and the convection from the solid surface to the fluid moving over the solid surface. A final R^2 of 0.97 with SS of 54049 was observed, which shows the better suitability of the Eq. 7.16 in comparison to Eq. 7.15. The validity of Eq. 7.16 is limited to Re in the range 57 to 2.60× 10³; Pr, 5.76 × 10² to 8.04 × 10³; Fr, 2.0 × 10⁻³ to 7.3 × 10⁻²; Gr, 4.48 × 10⁴ to 7.43 × 10⁶; ρ_p / ρ_l , 0.65 – 1.75; d_p/D_c , 0.21 to 0.28 and e/100-e in the range of 25 to 66 %.

Figure 7.3 shows the relationship between experimental and calculated values of Nu from Eq. 7.16, and it can be clearly observed that a good alignment exists between the experimental and the predicted data. The line obtained has a high correlation of 0.97 which shows that Eq. 7.16 models the presence of a particulate system very well. Using this model, it was calculated that natural convection only contributed to 1.96%, this was lower than the results obtained for the overall heat transfer coefficient, U (3.24%), indicating that the higher force convection will persist in the h_{fp} than that of the U. Therefore, in other words it can be said that the increase in the rotational speed of the can is more effective for h_{fp} than it is for U.

Meng and Ramaswamy (2007a) found that the apparent heat transfer coefficient (h_{ap}) is proportional to the relative density rather than the density simplex, while Sablani

et al. (1997a) found that the density simplex was insignificant to h_{fp} when multiple particles were present in the can and that for only one particle, it was proportional. It was found in this study while investigating both the density simplex and the relative density that the latter resulted in better correlations coefficients. Furthermore, the exponent of $(\rho_p / \rho_l)^{1.165}$, Eq. 7.16, developed for h_{fp} was observed to be higher than the exponent $(\rho_p / \rho_l)^{0.42}$ in Eq. 7.12 developed for U, which indicates that the effect of the relative particle to fluid density was higher in case of h_{fp} than of U. Meng and Ramaswamy (2007a) also reported a similar trend for non-Newtonian fluids with multiple particles where $(\rho_p / \rho_l)^{0.518}$ in the h_{ap} correlation was higher than the $(\rho_p / \rho_l)^{0.286}$ in U_a correlations. Relative density (ρ_p / ρ_l) had a very high significance in the dimensionless correlations for fluid to particle heat transfer coefficient h_{fp} , as well as the density simplex in correlations by Deniston *et al.* (1987).

Following the trend of increasing U with increasing particle concentration, h_{fp} also increased but with a higher exponent of $(e/100-e)^{0.22}$, which demonstrates that the particle concentration has more of an effect on h_{fp} . Because of the combined effect of the initial increase from 20 to 30% particle concentration and then later a decrease when particle concentration rose to 30 to 40%, the exponents for both h_{fp} and U were smaller. Similar results for non-Newtonian fluid were reported by Meng and Ramaswamy (2007a). They found that the U and h_{ap} both increased with the increase in particle concentration but the increase in h_{ap} was higher than in U_a . Sablani *et al.* (1997a) also reported decrease in the h_{fp} with the increase in particle concentration.



Figure 7.3 Experimental versus predicted (N_u) from Eq. 7.16 for fluid to particle heat transfer coefficient (h_{fp}) with multiple particles in free axial mode.

Although Meng and Ramaswamy (2007a) reported that the particle size was insignificant in their study, in this study the Nusselt number decreased with an increase in the diameter of the particle $(d_p/D_c)^{-1.05}$, following the trend found in the correlations of Sablani *et al.* (1997), who discovered that a reduction in the Nusselt number occurred with an increase in equivalent particle diameter. The exponents of Re, Pr of 0.72, 0.56 in the h_{fp} correlation were found to be higher than the *U* correlation, which were 0.66, 0.49 in the current study, whereas the exponent of Fr (-0.165) in *U* correlation was lower than the exponent of Fr (-0.185) in h_{fp} correlation, showing that the Nusselt numbers were more effected for h_{fp} than *U* with these dimensionless numbers. Sablani *et al.* (1997a) and Meng and Ramaswamy (2007a) reported the exponent of Re to be 0.61 and 0.62 respectively in end-over-end rotation, which were lower than the exponent of Re (0.72) in the current study. This shows that the effect of agitation is higher in free axial mode than in end-over-end mode. The exponent of Fr in this study was also found to be negative
which was consistent with the study done by Meng and Ramaswamy (2007a).

The correlation for fluid to particle heat transfer coefficient h_{fp} in fixed axial mode was developed using a procedure similar to the one described above. Initially, when forced convection alone was considered, R^2 and SS were 0.81 and 247587 respectively with the following correlations:

$$Nu = 0.0723 \times (\text{Re})^{0.67} \times (\text{Pr})^{0.57} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.40} \times \left(\frac{e}{100 - e}\right)^{0.00} (Fr)^{-.03} \times \left(\frac{d_p}{D_c}\right)^{-1.1}$$
(7.17)

Later, contributions from natural convection were accounted for by introducing an additive term as $(Gr \times Pr)$ in the model and the following correlation was obtained:

$$Nu = 0.07(Gr \operatorname{Pr})^{0.37} + 0.078(\operatorname{Re})^{0.00}(\operatorname{Pr})^{0.045} \times (Fr)^{-0.06} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.019} \times \left(\frac{e}{100 - e}\right)^{0.09} \times \left(\frac{d_p}{D_c}\right)^{-1.12} \times \left(\frac{K_p}{K_l}\right)^{0.48} (7.18)$$

 R^2 was improved to 0.95 whereas the sum of squares (SS) was reduced to 126434, which signifies a better fit of the latter model. Experimental vs. predicted data from Eq. 7.18 is presented in Figure 7.4, which depicts a good correlation of the values. The contribution of the natural convection to the total heat transfer was calculated from the first term of Eq. 7.18, which was found to be 15.5 %. From this result it can be deduced that natural convection contributes significantly in fixed axial mode. This could be due to the lesser agitation effect in fixed axial mode than in free axial mode, as there is no free rotation on the bottom one third of the retort in the former. Natural convection in case of *U* correlation in fixed axial mode was higher than the h_{fp} correlation. In the case of fixed axial mode, which were 0.72 and 0.56 and thus this further enforces the theory that free-axial rotation provides better agitation to the product than fixed axial mode. The validity of Eq. 7.18 is limited to *Re* in the range 55 to 2.50 × 10³; *Pr*, 5.76 × 10² to 8.04 × 10³; *Fr*, 2.0× 10⁻³ to 7.16 × 10⁻²; *Gr*, 4.24 × 10⁴ to 7.06 × 10⁶; ρ_p / ρ_l , 0.65 – 1.75; d_p/D_c , 0.21 to 0.28 and e/100-e in the range of 25 to 66 %.



Figure 7.4 Experimental versus predicted (N_u) from Eq. 7.18 for fluid to particle heat transfer coefficient (h_{fp}) with multiple particles in fixed axial mode.

7.5.4 Overall heat transfer coefficient in liquid only situation (free axial mode)

The dimensionless correlations for the overall heat transfer coefficient U were developed using the same characteristic length ($RR_s + R_c/2$). Correlations were developed using the general equation Eq. 7.10 but the effect of the particle's physical properties were excluded as can content did not include particles. The following correlation was achieved:

$$Nu = 58.06(Gr \operatorname{Pr})^{0.31} + 0.015(\operatorname{Re})^{0.757}(\operatorname{Pr})^{0.708} \times (Fr)^{.121}$$
(7.19)

Coefficient of correlation, R^2 was 0.96 and sum of squares SS was 39132. Experimental vs. predicted data from Eq. 7.19 is presented in Figure 7.5, which depicts a good correlation of the values.



Figure 7.5 Experimental versus predicted (N_u) from Eq. 7.19 for overall heat transfer coefficient (U) with liquid only situation in free axial mode.

The validity of Eq. 7.19 is limited to Re in the range 183 to 3.3×10^3 ; Pr, 41 to 8.06×10^3 ; Fr, 2.0×10^{-3} to 5.2×10^{-2} and Gr, 4.8×10^4 to 3.23×10^8 .

The contribution of natural convection to the total heat transfer was calculated from the first term of Eq. 7.19, which was found to be 51%. Higher natural convection was achieved in comparison to the overall heat transfer coefficient correlation when used with particles (Eq. 7.12). There could be two main reasons; firstly the particles inside the can could have given secondary agitation to the other contents, and the other reason could be that the range of rpm studied was higher in the later case. In comparison, the U correlations in fixed axial mode with particles, the contribution of natural convection was 21.50%. This shows that the lower natural convection in fixed axial mode above. If the operating parameters were similar in both modes

of agitation, the percentage of natural convection in the case of fixed axial mode without particles will be much higher than 51%. Rao and Anantheswaran (1988) reported that in the canned Newtonian liquid without particles processed in steritort, working between 2 to 8 rpm, the percentage of natural convection varied between 47% and 99%. If the same parameters were set for this experiment, it is feasible that similar results could be achieved.

7.5.5 Overall heat transfer coefficient in liquid only situation (end- over-end mode)

It was important to determine the characteristic length before ever determining the dimensionless correlations in end-over-end mode. Based on the previous literature on the dimensionless correlations developed in end-over-end mode, it was found that Sablani *et al.* (1997) used $D_r + D_c$ as the characteristic length, whereas Meng and Ramaswamy (2007a) used $RR_c + R_c/2$ as the characteristic length in their correlations. Since the cans were placed at the center of the cage in this study, therefore the diameter of the rotation (D_r) was kept at zero. Now since, the D_r was zero the diameter of the can (D_c) was used as the characteristic length in the dimensionless correlation, since his study was subjected to the same restrictions (zero diameter of the rotation).

Overall heat transfer coefficients in end-over-end mode were modeled based on previous literature (Sablani *et al.*, 1997a; Meng and Ramaswamy, 2007a; Fernandez *et al.*, 1988; Anantheswaran and Rao, 1985a, 1985b), while maintaining the pure forced convection situations, and resulted in the following relationship.

$$Nu = 0.437 \times \text{Re}^{0.61} \times \text{Pr}^{0.56} \times Fr^{-0.14}$$
(7.20)

This correlation resulted in a R^2 of 0.81 and the associated sum of squares was 577.57. When the (Gr × Pr) expression was introduced in the correlation as a part of free convection, forming the following equation produced a smaller SS of 224 and a higher R^2 of 0.97. Experimental vs. predicted data from Eq. 7.21 is presented in Figure 7.6, which depicts a good correlation of the values.

$$Nu = 2.17(Gr \operatorname{Pr})^{0.10} + 0.016(\operatorname{Re})^{0.695}(\operatorname{Pr})^{0.66} \times (Fr)^{-.08}$$
(7.21)

Equation 7.21 is valid for Re between $2.13 - 1.18 \times 10^3$; Gr between 320 and 2.1×10^6 ; Pr between 41 and 8.06×10^3 and Fr between 0.00039 and 0.0097.



Figure 7.6 Experimental versus predicted (N_u) from Eq. 7.21 for overall heat transfer coefficient (U) with liquid only situation in end-over-end mode.

The noticeable improvement showed by this model substantiates observations made by Fand and Keswani (1973) on the effect of free convection, even in situations where forced convection is the dominant mechanism of heat transfer. Awuah and Ramaswamy (1996) also reported similar improvement in R^2 and a reduction in associated estimated errors, when contribution from natural convection was included in the correlation of pure forced convection. They included the free convection term by introducing Gr and Gr/Re² while comparing forced and free convection to the finite cylinder. Part of the natural convection from Eq. 7.21 was calculated, which was 47 % under these conditions. While comparing Eqs. 7.21 and 7.19, it can be concluded that, unlike in end-over-end mode, the effects of both natural and forced convection are higher

in free axial mode. Higher forced convection in free axial mode is supported by the higher exponent of $\text{Re}^{0.757}$, $\text{Pr}^{0.708}$ and $\text{Fr}^{0.121}$ in comparison to the end-over-end mode, where exponents were $\text{Re}^{0.0.695}$, $\text{Pr}^{0.66}$ and $\text{Fr}^{-0.08}$.

7.6 Conclusions

Dimensionless correlations for mixed (combination of natural and forced) and pure forced convection were developed with and without particulates in Newtonian fluids during fixed and free axial rotation and end-over-end rotation modes. The developed equations gave higher coefficients of correlations (R^2 ranging from 0.92 to 0.97) and lower SS (175873 to 224) with mixed convection model than with pure forced convection model (R^2 ranging from 0.81 to 0.85 and higher SS ranging from 247587 to 577.57). This means that in all forced convection situations, the natural convection phenomenon continues to operate since buoyant forces resulting from density differences continue to exist. Modeling the dimension correlations on the basis of the heat transferred to canned particulate liquids as a sum of natural and forced convection can help in determining the contribution of each mode of convection. When particulates were present in the liquid, it was found that the natural convection contributed significantly to Nusselt numbers in fixed axial modes. However, the effect in the free axial mode was observed to be lesser. Even though, the effect of natural convection in free axial mode was lower, the improvement in the correlation coefficient of the model was evident. When the particulates were absent, although the heat transfer by natural convection took place in both end-over-end (47 %) and in free axial mode (51 %), the contribution was higher in free axial mode.

PREFACE TO CHAPTER 8

In Chapter 7, dimensionless correlations were developed for the overall heat transfer coefficient, U and fluid to particle heat transfer coefficient, h_{fp} , with canned particulate suspended in Newtonian fluids during axial agitation processing. The developed equations showed a good agreement with the experimental data.

Several studies have demonstrated that artificial neural network (ANN) models can give better predictions of heat transfer coefficients than dimensionless correlations. As a powerful tool, ANN has been successfully used in the many fields of food engineering. The objectives of this paper were therefore to develop ANN models for prediction of the associated heat transfer coefficients, and to compare them with those from the dimensionless correlations under the experimental conditions employed in this study.

Part of this research has also been presented in 2008 IFT Annual meeting, New Orleans, USA and prepared for publications in a scientific journal. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H.S. Ramaswamy.

CHAPTER 8

NEURAL NETWORK MODELLING OF HEAT TRANSFER TO CANNED PARTICULATE FLUIDS UNDER AXIAL ROTATION PROCESSING

8.1 Abstract

Artificial neural network models were developed for the overall heat transfer coefficient (U) and the fluid to particle heat transfer coefficient h_{fp} in canned Newtonian fluids with and without particles, and the model performances were compared with the dimensionless correlations for both free and fixed axial modes of agitation. Part of the experimental data was used for training and testing, and a portion was used for cross validation. The average errors (RMS), associated with predicted h_{fp} and U values in fixed and free axial mode were a function of the ANN variables: number of hidden layers, number of neurons in each hidden layer, learning rule, transfer function and number of learning runs. RMS values were not significantly different with number of hidden layers between one and three, and the associated RMS was minimal with a high R^2 value with one hidden layer and 8 neurons. The combination of the Delta-rule and TanH transfer function also gave the lowest RMS and the highest R^2 . The highest R^2 was achieved for the data set with 85% used for training and testing and 15% for the cross validation in both modes of rotation, and therefore this combination was used for the development of neural network models. Mean relative errors (MRE) for ANN models were much lower compared with MRE associated with dimensionless correlations; 75-78% lower for h_{fp} and 66% lower for U in fixed and free axial mode with particulates in liquid. Without particulates, in comparison with dimensionless correlations, the MRE for ANN models were 37% lower in end-over-end mode and 76% lower for free axial mode. Overall, ANN models yielded much higher R^2 values than dimensionless correlations. The ANN coefficient matrix is included so that the models can be implemented easily in a spreadsheet.

8.2 Introduction

A matter of interest to researchers in thermal process development has been issues related to improving the heat transfer during processing. Adequate thermal processing is the most important means of achieving commercial sterilization of canned foods and ensuring product safety. A balance must be found between achieving the appropriate level of microbial destruction while minimizing the nutrient degradation in the product, in order to obtain a safe process that yields the best quality retention. This has been traditionally achieved by using high temperature short time (HTST) processes for sterilization of canned foods, as these processes ensure quality retention and maintain of safe degree of sterilization (Stoforos, 1988). Agitation of canned liquid foods (with or without particulates) results in good mixing of the contents and higher heat transfer rates, providing a means of uniform heating and rapid heating both contributing to better quality retention. Agitation used in the retorts falls into two categories: end-over-end (E-O-E) processing is where the containers are loaded vertically into a retort crate and rotate around a central horizontal axis, and the second is axial rotation, where the cans are rotated in a horizontal plane. E-O-E rotation is most commonly found in batch retorts, and axial mode of rotation is encountered with continuous systems such as the reel and spiral cooker and cooler. Processors may use convection heating to their advantage, as thermally processed foods heated this way require less processing times, have a higher product efficiency and in some instances are less susceptible to the damaging effects of heat. Soups, sauces, vegetable in brine, meat in gravy and some pet foods are some examples. By agitating the container of food during the process by rotation, forced convection currents mix and heat the food more effectively.

Traditionally the establishment and optimization of the thermal process relies on heat penetration parameters commonly used in combination with process calculation methods like Ball and Stumbo. Theoretical and computational models are useful for the design, optimization and validation of such food systems. Besides the thermo physical properties of the product itself, the overall heat transfer coefficient from the heating medium to the canned liquid (U) and the fluid to particle heat transfer coefficient (h_{fp}) are important parameters (Sablani and Ramaswamy, 1996) in these models.

For U and h_{fp} in free axially rotating cans, few studies have been done to understand the relationships between the various parameters that have a significant influence (Lenz and Lund, 1978; Deniston *et al.* 1987; Fernandez *et al.*, 1988; Hassan, 1984; Stoforos and Reid, 1992). Traditionally, dimensionless correlations have been used for the predictive modeling of U and h_{fp} (Rao and Anantheswaran, 1988). Using the traditional approach of nonlinear multiple regression analysis, the heat transfer coefficient in the form of a Nusselt number is correlated to the other dimensionless numbers involving parameters which influence U and h_{fp} . The selection of appropriate dimensionless groups requires prior knowledge of the phenomenon under investigation.

Artificial neural network (ANN) is an information processing system developed for determining relationships between sets of data. In recent years, ANN has attracted researchers in many disciplines of science and engineering because of its ability to correlate large and complex data-sets. Predicting several output variables at the same time is difficult with the general regression method, but is easily accomplished by this new system. ANN was used to optimize the conduction of heated foods (Sablani et al., 1995) and a correlation was developed among optimal sterilization temperature, corresponding processing time and quality factor retention with the can dimension, food thermal diffusivity and kinetic parameters of the quality factors. The models developed with ANN were able to predict the optimal sterilization temperatures with an accuracy of ±0.5°C and other responses with less than 5% associated errors. Models for the prediction of apparent overall heat transfer coefficient (U_a) and apparent fluid to particle heat transfer coefficient (h_{ap}) associated with the particle liquid mixtures in cans subjected to end-over-end rotation were developed by Meng and Ramaswamy (2008). They found that these models were able to predict responses with mean relative error of 2.9-3.9 % in Newtonian fluids and 4.7 to 5.9 % in non Newtonian fluids. These results were 27-62% lower than those associated with the dimensionless correlations. For U and h_{fp} associated with the low viscosity Newtonian liquids in end-over-end mode, Sablani et al. (1997) developed ANN models and reported that the prediction errors were about 50% better than those associated with dimensionless correlations; less than 3% for U and 5% for h_{fp} . No such models have been developed for U and h_{fp} in axially rotating cans.

The objective of this study was to develop ANN models to predict the overall heat transfer coefficient (U) and fluid to particle heat transfer coefficient h_{fp} for canned Newtonian liquids with and without particulate during free and fixed axial, as well as end-over-end agitation processing, and to compare the results with previously developed dimensionless correlations

8.3 Methodology

8.3.1 Materials, physical properties and experimental range

In order to calculate the dimensionless numbers, the thermo-physical properties of the material were employed at the average bulk temperature. The glycerin used was at 100% concentration, at 38°C (Fischer Scientific Ltd., Montréal, PQ). By changing the concentration of the glycerin solution, the viscosity could be changed to simulate a variety of liquid food products. The densities were determined from the weights of known volumes of the glycerin solution. Propylene, Nylon and Teflon spheres (Small Parts Inc., Miami, FL) were taken as food particulate models, and the thermo-physical properties of the liquid and particles of the simulating solutions were extracted from the available literature (Sablani and Ramaswamy, 1997; Meng and Ramaswamy, 2007b). The different thermo-physical properties are summarized in Table 8.1.

8.3.2 U and h_{fp} in fixed and free axial mode

A single car rotary retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumünster, Germany) was used in the study. The retort basket was retrofitted with a stainless steel enclosure in which test cans could be held in an axial direction. Cans were positioned by using rear and front stainless steel supports, which were fixed to the retort basket. The fabricated enclosures held two free cans on each side of the frame. On one side, end plate facing the retort shell was removed so that the cans could slide down and roll along the retort shell during part of the rotation. These cans rolled on their own axis (in a direction counter to that of retort cage) along the bottom of

the retort shell when the opening was facing downwards (approximately $1/3^{rd}$ of the rotation in facing downward), simulating the action in a Steritort. In the top $2/3^{rd}$ of the

S.No.	Parameters	Symbol	Experimental range
1	Retort temperature	Т	111.6,115,120, 125,128.4°C
2	Rotation speed	R	4,8,14,20,24 rpm
3	Can headspace	Н	5 mm and 10 mm
4	Test liquids	C (Glycerin)	Newtonian: 80,84,90,96,100 %
5	Test particles	M (PP, NYL, TF)	density: 830, 1128, 2210 kg/m ³
6	Particle Size	S	0.019, 0.02225 and 0.254 meters
7	Particle	Р	20 %, 30 % and 40 %
	concentration		

Table 8.1	Range of system and product parameters used in the determination of
	convective heat transfer coefficients (U and h_{fp})

Note: R=rotation speed, T= retort temperature, H = Head space, S = Particle size, C = Glycerin concentration, M = Particle material, P = Particle concentration, PP = Polypropylene, NYL = Nylon, TF = Teflon

cage rotation, the cans were restrained in the enclosure only rotating with the cage. This process caused biaxial rotation of the can in the free axial mode, while only in clockwise direction in the fixed axial mode. The two cans held at the opposite end were held inside in a fixed axial mode and were not allowed to drop on to the retort shell.

In order to develop the ANN models correlations, the heat transfer coefficients data were obtained from previous chapters. To develop the model for U and h_{fp} , data from 148 set of experiments used in both fixed and free axial modes each, with particles in can, whereas 70 set of experiments used for free axial and end-over-end modes each, without particle in the can. The range of parameters related to liquids, particles and retort operating conditions are summarized in the Table 8.1.

8.3.3 Dimensionless correlations

The performance of developed ANN models were compared with the following dimensionless correlations developed earlier using regression analysis (Chapter 7).

8.3.3.1 Liquid with particulate

For U in free axial mode

$$Nu = 29(Gr \operatorname{Pr})^{-0.02} + 0.03306(\operatorname{Re})^{0.66} (\operatorname{Pr})^{0.49} \times (Fr)^{-.1635} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.42} \times \left(\frac{e}{100 - e}\right)^{.009} \times \left(\frac{d_p}{D_c}\right)^{-0.70} (8.1)$$

For U in fixed axial mode

$$Nu = 0.07(Gr \operatorname{Pr})^{0.37} + 0.0379(\operatorname{Re})^{0.50}(\operatorname{Pr})^{0.43} \times (Fr)^{-0.6} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.6342} \times \left(\frac{e}{100 - e}\right)^{0.12} \times \left(\frac{d_p}{D_c}\right)^{-1.27}$$
(8.2)

For h_{fp} in free axial mode

$$Nu = 20(Gr \operatorname{Pr})^{0.01} + 0.00955 (\operatorname{Re})^{0.72} (\operatorname{Pr})^{0.56} \times (Fr)^{-0.195} \times \left(\frac{\rho_p}{\rho_l}\right)^{1.165} \times \left(\frac{e}{100 - e}\right)^{.022} \times \left(\frac{d_p}{D_c}\right)^{-1.05} \left(\frac{K_p}{K_l}\right)^{2.26}$$
(8.3)

For h_{fp} in fixed axial mode

$$Nu = 0.07(Gr \operatorname{Pr})^{0.37} + 0.078(\operatorname{Re})^{0.50}(\operatorname{Pr})^{0.045} \times (Fr)^{-.06} \times \left(\frac{\rho_p}{\rho_l}\right)^{0.619} \times \left(\frac{e}{100 - e}\right)^{.009} \times \left(\frac{d_p}{D_c}\right)^{-1.12} \times \left(\frac{K_p}{K_l}\right)^{0.48}$$
(8.4)

8.3.3.2 Liquid without particulate

For U in free axial mode

$$Nu = 58.06(Gr \operatorname{Pr})^{0.31} + 0.015(\operatorname{Re})^{0.757}(\operatorname{Pr})^{0.708} \times (Fr)^{.121}$$
(8.5)

For U in end-over-end mode

$$Nu = 2.17(Gr \operatorname{Pr})^{0.10} + 0.016(\operatorname{Re})^{0.695}(\operatorname{Pr})^{0.66} \times (Fr)^{-.08}$$
(8.6)

8.3.4 Neural Network

Neural works Professional II/plus (NeuralWare Inc., Pittsburg, PA) was used in the development of neural network models. Six significant variables (glycerin concentration, retort speed, particle density, particle size, particle concentration and retort temperature) corresponded to six neurons which made up the input layer for the test data of cans with multiple particles in free and fixed axial mode. The output layer consisted of a neuron each for U and h_{fp} . Only three neurons were taken for cans of liquid without particles, one for each input parameter (temperature, glycerin concentration and rotation speed), and in the output layer only one neuron representing U was taken. For learning and training the network, the standard back-propagation algorithm was used.

8.3.5 Optimal Configuration

For canned liquids with and without particles, the neural network parameters such as the number of hidden layers, number of neurons in each hidden layer and the learning runs required optimization. Also, the combination of learning rules and transfer function needed to be selected. One to three hidden layers, with the range of 2 to 10 neurons in each hidden layer, and 2000 to 100,000 learning runs were tested to optimize the configuration. In this study, root mean square (RMS) was used to represent the difference between the predicted value by the neural network and the desired output; by minimizing this difference, the optimum configuration was decided.

A full factorial design was created by varying the learning rules and transfer functions in different combinations, all the while keeping two hidden layers with three neurons in each, and 50,000 learning runs. In order to optimize the number of hidden layers and the number of neurons in each of them, a second full factorial set was developed, while the same optimal combination of learning rules and transfer functions was kept. The effect of the learning runs was determined by keeping the parameters selected above, and in the optimization process, the full set of data was used (148 cases involving particles in free axial and fixed axial mode, and 70 cases without particles)

8.4 Results and Discussions

8.4.1 Learning/training of ANN

Neurons are highly interconnected processing elements, which in vast quantities make up a neural network. These neurons are arranged in layers, each layer linked to many others like it, connected by varying connection weights which represent the strength of these connections. In order to generate a result, which will be transmitted by the output path, each neuron receives signals from other neurons in proportion to its connection weight, which it sends to the transfer function. A transfer function is typically non-linear. The connection weights will be altered according to the error between the output of the ANN model and the desired output. A learning rule is a mathematical equation used to determine the increment or decrement by which the weights of the processing elements are changed during the learning phase, describing the way in which connecting weights are adjusted to generate the desired effect. The transfer functions used in this study were sigmoid, hyperbolic tangent (TanH), sine and linear function. The learning rules were Norm Cum Delta, Delta and Ext. DBD. Figure 8.1 shows the schematic of multilayer neural network used in the present study. Table 8.2 represents the root mean square (RMS) and R^2 obtained during the training under different combinations of rules and transfer functions. The combination of Delta as a learning rule and TanH as a transfer function, the smallest RMS and the highest R^2 were found. In fixed axial mode they were 0.0992 and 0.95 whereas in free axial modes the corresponding values were 0.0556 and 0.99, respectively. It was further reported by Rai et al. (2005) and Ochoa-Martinez et al. (2007) that the TanH transfer function usually behaves better than the Sigmoid function. Therefore, in this study the combination of Delta as a learning rule and TanH as a transfer function were selected as the optimal combination for modeling fixed, free and end-over-end mode with and without particulates in the liquid inside the can.



Figure 8.1 General scheme of an ANN

Table 8.2Effects of transfer functions and learning rules on RMS in fixed and free
axial mode

					Learn rule			
			Ext DBD		Norm-Cum-Delta		Delta-Rule	
			RMS	R^2	RMS	R^2	RMS	R^2
	Sigmoid	Fixed Axial	0.1128	0.9461	0.1038	0.9549	0.1018	0.9566
		Free Axial	0.1162	0.9541	0.1104	0.9583	0.0666	0.9851
TT C	Tan H	Fixed Axial	0.1073	0.9522	0.0998	0.9583	0.0992	0.9589
function		Free Axial	0.072	0.9832	0.073	0.9822	0.0556	0.9897
Tunction	Sine	Fixed Axial	0.188	0.8699	0.1009	0.9575	0.1004	0.9579
		Free Axial	0.1249	0.9491	0.0768	0.9802	0.564	0.9894
	Lincor	Fixed Axial	0.7794	0.8579	0.1767	0.8605	0.1915	0.8533
	Linear	Free Axial	0.1537	0.9275	0.1182	0.9522	0.121	0.95

Figures 8.2 and 8.3 present the average error (RMS) associated with experimental and predicted U and h_{fp} values in fixed and free axial mode as a function of the number of hidden layers and the number of neurons in each. It was found that, for both modes of rotation, eight is the optimum number of neurons. The number of hidden layers caused the RMS to vary slightly, but did not cause any significant differences



Figure 8.2.a Effect of hidden layers and number of neurons in each hidden layer on RMS in fixed axial mode





Figure 8.2b Effect of hidden layers and number of neurons in each hidden layer on R^2 in fixed axial mode

when raised from one to three. Eight neurons also gave the highest R^2 values, again not showing market improvement when increased beyond 8. Computation becomes lengthy with too many nodes, or connections. Sometimes, an ANN may 'memorize' the input training sample (Rai *et al.*, 2005). This can happen if there are too many hidden layers and neurons, therefore a single hidden layer was selected with eight neurons. The RMS error decreased for both modes when the learning runs increased, which can be seen in Figures 8.4 and 8.5. No additional benefit was realized when the learning runs were increased beyond 50,000 in either mode, therefore 50,000 runs was used for modeling in both free and fixed axial modes.



Figure 8.3 Effect of hidden layers and number of neurons in each hidden layer on RMS and R^2 in free axial mode



Figure 8.4 Effect of learning runs on RMS and R^2 in fixed axial mode



Figure 8.5 Effect of learning runs on RMS and R^2 in free axial mode

8.4.2 Performance of ANN

The performance of the developed neural network was evaluated after the completion of the learning and training. A full set of data was used to optimize the

parameters. The 148 cases in both fixed and free axial mode were divided into different proportions for training, testing and cross-validation. The combination of data sets included training & testing 75% and cross validation 25%, training & testing 83% and cross validation 17%, training & testing 85% and cross validation 15%, training & testing 90% and cross validation 10%, training & testing 80% and cross validation 20% and training & testing 67% and cross validation 33%.

Figures 8.6-8.9 show the prediction performances of the neural networks for the different set combinations in both modes as plots of neural network predicted values vs. experimental values for both U and h_{fp} . Compared in Table 8.3 are the associated errors with the neural networks output. The excellent agreement between experimental and predicted h_{fp} and U values for the neural networks can be seen by the high R^2 and corresponding low RMS. For both modes of rotation, the highest R^2 was achieved for the data set with 85% used for training and testing and 15% for the cross validation. Therefore this combination was used for the development of neural network models.

	Fixed Axial Mode				Free Axial Mode				
	h_{fp} (W/m ² C) U (V		U (W/m ²	U (W/m ² C) h_{fp} (W/m ²		U(W/r)		n ² C)	
	MRE**								
	(%)	R^2	MRE (%)	R^2	MRE (%)	R^2	MRE (%)	R^2	
Α	8.4	0.91	7.6	0.91	5.6	0.95	3.5	0.97	
В	8.5	0.91	8.3	0.91	5.4	0.95	3.9	0.96	
С	9.0	0.90	7.9	0.90	5.7	0.95	3.8	0.96	
D	9.1	0.90	8.8	0.90	4.4	0.96	3.6	0.97	
Ε	2.5	0.98	3.3	0.97	1.9	0.98	2.3	0.99	
F	2.2	0.98	3.6	0.97	1.8	0.98	2.3	0.99	

Table 8.3Comparison of errors for different combinations of learning and test data
sets for particles in Newtonian and non-Newtonian fluids

A: 67 % for Training and Testing, 33 % for Cross Validation B: 75 % for Training and Testing, 25 % for Cross Validation C: 83 % for Training and Testing, 17 % for Cross Validation D: 80 % for Training and Testing, 20 % for Cross Validation E: 85 % for Training and Testing, 15 % for Cross Validation F: 90 % for Training and Testing, 10 % for Cross Validation

** Mean Relative Error



Figure 8.6 ANN predicted values vs. experimental values for U in fixed axial mode



Figure 8.7 ANN predicted values vs. experimental values for h_{fp} in fixed axial mode



Figure 8.8 ANN predicted values vs. experimental values for U in free axial mode



Figure 8.9 ANN predicted values vs. experimental values for h_{fp} in free axial mode

8.4.3 Comparisons of ANN models with dimensionless number models

The regression models previously obtained with dimensionless analysis were compared with the performances of the neural network models. Summarized in Tables 8.4a, and b are the prediction errors for U and h_{fp} , respectively, for dimensionless correlations and neural network models. Figures 8.10, 8.11 and 8.12 compare the relative distributions of errors associated with the two models, and show them as a plot of experimental versus predicted values. MRE for ANN models were much lower when compared with the MRE for dimensionless correlations; 75% lower than dimensionless correlations for h_{fp} and 66% lower for U under fixed axial mode with particulate in liquid. Under the same conditions the MRE were 78% lower for h_{fp} and 67% lower for U in free axial mode. MRE was again lower for ANN models when computing U in E-O-E and free axial modes; 37% lower than the dimensionless correlations for E-O-E mode and 76% lower for free axial mode. ANN models also had much higher R^2 values than those obtained with dimensionless numbers.

 Table 8.4a
 Comparisons of errors for ANN models vs. Dimensionless correlations for liquid with particulates

	Fixed A	xial Mode	- With p	articles	Free A	xial Mode	e - With p	articles
	$h_{fp}(W)$	m^2C	U(W	$(/m^2C)$	$h_{fp}(W$	V/m^2C)	U(W	$(/m^2C)$
	DC	ANN	DC	ANN	DC	ANN	DC	ANN
MRE								
(%)	10.24	2.6	8.62	2.9	8.3	1.85	7.35	2.5
R^2	0.92	0.98	0.92	0.97	0.95	0.99	0.95	0.98

Table 8.4bComparisons of errors for ANN models vs. Dimensionless correlations for
liquid without particulates

	End-over	-end mode	Free Axial Mode		
	U(W	T/m^2C)	U(W/m ² C)		
	DC	ANN	DC	ANN	
MRE (%)	6.05	3.81	8.34	2.06	
R^2	0.97	0.98	0.95	0.99	



Figure 8.10 Correlation of predicted values (neural network and dimensionless correlation models) vs. experimental values for h_{fp} and U in fixed axial mode with particulate in liquid.



Figure 8.11Correlation of predicted values (neural network and dimensionless
correlation models) vs. experimental values for h_{fp} and U in free axial
mode with particulate in liquid.



Figure 8.12 Correlation of predicted values (neural network and dimensionless correlation models) vs. experimental values for U in End-over-end and free axial mode without particulate in liquid.

8.4.4 ANN output represented in algebraic equations

In reality, a trained neural network consists of input variables, connections weights, biases and transfer functions forming a complex calculation process. Equation 8.7 represents the output neural network with a single hidden layer (Trelea *et al.*, 1997; Hernandez-Perez *et al.*, 2004):

$$Y = f_2 (W_2 f_1 (W_1 X + B_1) + B_2)$$
(8.7)

X is the matrix of input variables and Y is the matrix of output variables. f_1 and f_2 are the transfer functions in the hidden and output layers respectively. W_1 and W_2 are the matrices of connection weights in the hidden and output layers respectively, and B_1 and B_2 are the matrices of biases in the hidden and output layers. Using such an algebraic equation to express the output of neural network makes a trained ANN model easier to access.

A linear transfer function was selected for output layer in the present study in order to simplify the algebraic equation when training the neural network.

For fixed, free axial and end-over-end mod, the following equation was established for the trained neural network output:

$$Y = W_2 TanH(W_1 X + B_1) + B_2$$
(8.8)

In the above equation, X is the input matrix expressed in Eq. 8.9, where X_1 is the particle material density, X_2 is particle concentration, X_3 is rotational speed, X_4 is particle size, X_5 is retort temperature and X_6 is liquid concentration.

$$X = \begin{bmatrix} X_{1} \\ X_{2} \\ X_{3} \\ X_{4} \\ X_{5} \\ X_{6} \end{bmatrix}$$
(8.9)

Y is the output matrix expressed in Eq. 8.10, in which Y_1 is U and Y_2 is h_{fp}

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}$$
(8.10)

It must be mentioned that, in the training process, all the input and output data were normalized according to the following equation (Eq. 8.11) to improve the behavior of the ANN (NeuralWare, 1996).

Normalized _data =
$$\left[\frac{(upper_bound - lower_bound)}{(max - min)}\right] \times [real_data - max] + upper_bond$$
(8.11)

The "upper bound", "lower bound", "max" and "min" for the input and output variables are listed in Tables 5 and 6. Therefore, the output values calculated from Eq. 8.8 have to be denormalized to get the actual values.

For fixed axial mode with particles in liquid in Eq. 8.8,

 W_1 is a 8 × 6 matrix:

$$W_{1} = \begin{bmatrix} +0.1041 & +0.1398 & -0.0843 & +0.3147 & -0.3959 & -0.1901 \\ +0.5723 & -0.1553 & -1.9559 & +1.2752 & -0.0395 & +1.0926 \\ +0.0052 & -0.0078 & +1.6409 & -0.3060 & +0.1191 & -2.2546 \\ +0.0936 & +0.0124 & +0.3202 & +0.1171 & +0.0567 & +1.1715 \\ -0.0510 & -0.0393 & -0.0292 & +0.0268 & +0.0978 & +0.0541 \\ -0.0852 & -0.1452 & -0.0036 & +0.0119 & -0.1452 & -0.2524 \\ +4.4020 & -0.0100 & -0.4674 & +0.0791 & +0.0532 & +0.1151 \\ -0.0360 & -0.0644 & -0.0129 & +0.0447 & -0.1416 & -0.0980 \end{bmatrix}$$
(8.12)

	Max	Min	Upper bound	Lower bound
				· · ·
X 1	2210	830	1	-1
Particle density				
kg/m ³				
\mathbf{X}_2	40	20	1	-1
Particle				
(%) V	24	1	1	1
A3 Dotational anad	24	4	1	-1
(rnm)				
(ipiii) X.	25	10	1	-1
Particle size	25	17	I	-1
(mm)				
Xc	128.4	111.6	1	-1
Retort	120.1	111.0	×	
temperature				
(°C)				
X ₆	100	80	1	-1
Liquid				
(%)				
(70)				
Fixed Axial				
mode				
Y_1	381.0	77.5	0.8	-0.8
$U(W/m^2C)$				
\mathbf{Y}_2	812.9	106.7	0.8	-0.8
$h_{fp} (W/m^2 C)$				
Free Avial mode				
Y.	586.8	136.0	0.8	-0.8
$U(W/m^2C)$	500.0	100.0	0.0	0.0
Y ₂				
$h_{fp} (W/m^2 C)$	1208.0	209.0	0.8	-0.8

Table 8.5

Parameters required to calculate the normalized input and output data for fixed and free axial mode with particulate in the liquid.

	Max	Min	Upper bound	Lower bound
\mathbf{X}_1	128.4	111.6	1	-1
Temperature				
°C				
X_2	100	0	1	-1
Liquid concentration				
(%)				
X_3	20	0	1	-1
Rotational speed				
(rpm)				
\mathbf{Y}_{1}	398	27	0.8	-0.8
$U_{EOE} (W/m^2 C)$	612	36		
Y ₂			0.8	-0.8
$U_{FRA Axial} (W/m^2 C)$				

Table 8.6Parameters required to calculate the normalized input and output data for
end-over-end and free axial mode without particulate in the liquid.

 B_1 is a 8 x 1 matrix:

<i>B</i> ₁ =	+0.0154 +1.9463 +1.5586 -1.4012 -0.0616 +0.2140 +2.8823	(8.13)
	+0.1366	

 W_2 is a 2 x 8 matrix:

$$W_{2} = \begin{bmatrix} +0.1035 & -0.3243 & +0.3110 & -0.3017 & -0.0172 & -0.1042 & +0.3106 & -0.0333 \\ -0.1790 & -0.2491 & +0.2218 & +0.1218 & -0.0163 & +0.0141 & +0.3039 & -0.0160 \end{bmatrix}$$
(8.14)

 B_2 is a 2 × 1 matrix listed in Eq. 8.15

$$B_{2=} \begin{bmatrix} -0.0628\\ -0.0660 \end{bmatrix}$$
(8.15)

U and h_{fp} can also be represented by a simplified algebraic system of equations.

$$U = 0.1035a - 0.3243b + 0.3110c - 0.3017d - 0.0172e - 0.01042f + 0.3106g - 0.0333h - 0.0628$$
 (8.16a)
$$h_{fp} = -0.190a - 0.2491b + 0.2218c + 0.1218d - 0.0163e + 0.0141f + 0.3039g - 0.0160h - 0.0660$$
 (8.16b)

where a-g are the constants:

$$a = \tanh[0.1041X_1 + 0.1398X_2 - 0.0843X_3 + 0.3147X_4 - 0.3959X_5 + 1.1901X_6 + 0.154]$$
(8.17a)

$$b = \tanh[0.5723X_1 - 0.1553X_2 - 1.9559X_3 + 1.2752X_4 - 0.0395X_5 + 1.0923X_6 + 1.9463]$$
(8.17b)

$$c = \tanh[0.0052X_1 - 0.0078X_2 + 1.6409X_3 - 0.3060X_4 + 0.1191X_5 - 2.2546X_6 + 1.5586]$$
(8.17c)

$$d = \tanh[0.936X_1 + 0.0124X_2 + 0.3202X_3 + 0.1171X_4 + 0.567X_5 + 1.1715X_6 - 1.4012]$$
(8.17d)

$$e = \tanh\left[-0.0510X_1 - 0.0393X_2 - 0.0292X_3 + 0.0268X_4 + 0.0978X_5 + 0.0541X_6 - 0.0616\right]$$
(8.17e)

$$f = \tanh[-0.0852X_1 - 0.1452X_2 - 0.0036X_3 + 0.0119X_4 - 0.1452X_5 - 0.2524X_6 + 0.2140]$$
(8.17f)

$$g = \tanh[4.4020X_1 - 0.0100X_2 - 0.4674X_3 + 0.0791X_4 + 0.0532X_5 + 0.1151X_6 + 2.8823]$$
(8.17g)

$$h = \tanh\left[-0.0360X_1 - 0.0644X_2 - 0.0129X_3 + 0.0447X_4 - 0.1416X_5 - 0.0980X_6 + 0.1366\right]$$
(8.17h)

For free axial mode with particles in liquid in Eq. 8.8,

$$W_{1} = \begin{bmatrix} -0.8985 & -0.2482 & -1.0276 & -0.3195 & -0.1569 & +0.6981 \\ -0.0216 & +0.2126 & -1.2319 & +1.2408 & -0.1549 & +0.1875 \\ +3.5283 & -0.1889 & -0.1639 & -1.1130 & +1.0590 & -0.0168 \\ -0.1155 & +0.439 & +0.0980 & +0.5226 & -0.1307 & +1.2359 \\ +0.0668 & -0.1132 & +0.3295 & +0.0458 & -0.1195 & -0.2453 \\ -0.2191 & +0.1217 & +0.2566 & -0.4450 & -0.1066 & +0.3127 \\ +0.2252 & -1.0693 & -0.0950 & -0.1022 & +0.1485 & -0.0415 \\ -0.0740 & +0.4963 & -0.2223 & -0.2070 & -0.0326 & +0.1962 \end{bmatrix}$$
(8.18)

$$B_{1} = \begin{bmatrix} -0.1100 \\ -0.7559 \\ +2.5774 \\ -0.9304 \\ +0.1183 \\ -0.7145 \\ -0.5558 \\ -0.4295 \end{bmatrix}$$

$$W_{2} = \begin{bmatrix} -0.1192 & -0.1659 & +0.2741 & -0.2004 & +0.2129 & -0.1863 & -0.3840 & -0.2793 \\ -0.2055 & -0.2294 & +0.4056 & +0.1151 & +0.0355 & -0.1788 & -0.2268 & -0.2449 \end{bmatrix}$$

$$(8.20)$$

$$B_2 = \begin{bmatrix} -0.3508\\ -0.4326 \end{bmatrix}$$
(8.21)

U and h_{fp} can also be represented by a simplified algebraic system of equations.

$$U = -0.1192a_1 - 0.1659b_1 + 0.2741c_1 - 0.2004d_1 + 0.2129e_1 - 0.1863f_1 - 0.3840g_1 - 0.2793h_1 - 0.3508$$
(8.22a)

$$h_{fp} = -0.2055a_1 - 0.2294b_1 + 0.4056c_1 + 0.1151d_1 + 0.0355e_1 - 0.1788f_1 - 0.2268g_1 - 0.2449h_1$$
(8.22b)

$$-0.4326$$

where

$$a_{1} = \tanh[-0.8985X_{1} - 0.2482X_{2} - 1.0276X_{3} - 0.3915X_{4} - 0.1569X_{5} + 0.6981X_{6} - 0.1100]$$
(8.23a)

$$b_1 = \tanh[-0.0216X_1 + 0.2126X_2 - 1.2319X_3 + 1.2408X_4 - 0.1549X_5 + 0.1875X_6 - 0.7559]$$
(8.23b)

$$c_1 = \tanh[3.5283X_1 - 0.1889X_2 - 0.1636X_3 - 1.1130X_4 + 1.0590X_5 - 0.0168X_6 + 2.5774]$$
(8.23c)

$$d_1 = \tanh\left[-0.1155X_1 + 0.439X_2 + 0.0980X_3 + 0.5226X_4 - 0.1307X_5 + 1.2359X_6 - 0.9304\right]$$
(8.23d)

$$e_1 = \tanh[0.0668X_1 - 0.1132X_2 + 0.3295X_3 + 0.0458X_4 - 0.1195X_5 - 0.2453X_6 + 0.1183]$$
(8.23e)

$$f_1 = \tanh\left[-0.2191X_1 + 0.1217X_2 + 0.2566X_3 - 0.4450X_4 - 0.1066X_5 + 0.3127X_6 - 0.7145\right]$$
(8.23f)

$$g_1 = \tanh[0.2252X_1 - 1.0693X_2 - 0.0950X_3 - 0.1022X_4 + 0.1485X_5 - 0.0415X_6 + 0.5558]$$
(8.23g)

$$h_1 = \tanh[-0.0740X_1 + 0.4963X_2 - 0.2223X_3 - 0.2070X_4 - 0.0326X_5 + 0.1962X_6 - 0.4295]$$
(8.23h)
$$W_{1} = \begin{bmatrix} +0.0498 & +0.1530 & +2.8541 \\ -0.0480 & -1.0626 & -0.9656 \\ +0.1873 & -0.8985 & +0.9576 \\ -0.0117 & -2.9832 & -0.5756 \end{bmatrix}$$
(8.24)

$$B_{1} = \begin{bmatrix} +3.1846 \\ +0.5913 \\ -0.7284 \\ +1.4196 \end{bmatrix}$$
(8.25)

$$W_{2} = \begin{bmatrix} +0.6725 & -0.2599 & +0.3909 & +0.2920 \\ +0.4304 & -0.3770 & +0.5325 & +0.2895 \end{bmatrix}$$
(8.26)

$$B_2 = \begin{bmatrix} -0.3985\\ -0.1344 \end{bmatrix}$$
(8.27)

U can also be represented by a simplified algebraic system of equations:

$$U_{eoe} = 0.6725a - 0.2599b + 0.3909c + 0.2920d - 0.3985$$
(8.28a)

$$U_{freeaxial} = 0.4304a - 0.3770b + 0.5325c + 0.2895d - 0.1344$$
(8.28b)

$$a = \tanh[0.0498X_1 + 0.1530X_2 + 2.8541X_3 + 3.1846]$$
(8.29a)

$$b = \tanh\left[-0.0480X_1 - 1.0626X_2 - 0.9656X_3 + 0.5913\right]$$
(8.29b)

$$c = \tanh[0.1873X_1 - 0.8985X_2 + 0.9576X_3 - 0.7284]$$
(8.29c)

$$d = \tanh\left[-0.0117X_1 - 2.9832X_2 - 0.5756X_3 + 1.4196\right]$$
(8.29d)

The neural network is generally described as the black box regression model, even though it can give very precise predictions. When extrapolated, results can be

unsatisfactory if the variables are selected inappropriately or the represented data was not used for training. Despite habitually yielding better results, ANN models should not be considered complete alternatives to the traditional dimensionless approach. The dimensionless approach can offer useful insight into the physical phenomenon which may benefit scale consideration.

8.5 Conclusions

Artificial neural network models were developed to predict U and h_{fp} associated with canned Newtonian fluids with and without particles during free and fixed axial as well as end-over-end mode. Configuration parameters were optimized by choosing the appropriate combination of hidden layers, learning runs, learning rules, transfer function and number of neurons. The developed ANN models were found to predict the responses with the mean relative error of 2.6 and 2.9% for h_{fp} and U in fixed axial mode, and 1.85 and 2.5% respectively in free axial mode. Similarly, mean relative error associated with the overall heat transfer coefficient in Newtonian liquid without particulates in end-overend mode was 3.8%, and was 2.06 % in the case of free axial mode. ANN models yielded better results than those from the dimensionless correlations reducing the prediction errors from 37-78%. To make the models easy to implement using spreadsheet, algebraic equations were also generated.

CHAPTER 9 GENERAL CONCLUSIONS, CONTRIBUTION TO THE KNOWLEDGE AND RECOMMENDATIONS

GENERAL CONCLUSIONS

1. Mechanical agitation is commonly used to improve the rate of heat transfer in the product being processed. End-over-end, fixed axial and shaking systems (batch operations), and free axial (continuous operation) are the common modes used to impart agitation to cans being processed. This research compared the heat transfer associated with cans filled with particulate and liquid mixtures during the end-over-end, fixed and free axial rotation modes.

2. A pilot scale rotary autoclave (STOCK Rotomat), which could normally be used only for end-over-end and fixed axial rotation was modified to accommodated the free axial mode of rotation as well so that all three modes could be compared simultaneously. The modification with free axial rotation of the cans with an equivalent free rotational angle of 100° also permitted simulating the operation of a laboratory FMC Steritort, the one normally used for establishing processing schedules in the larger turbo cookers.

3. The assumption of reasonably uniform temperatures of liquid inside the cans subjected to rotary agitation processing was verified using temperatures gathered at different locations in the can as well as using the computed heat penetration parameters. It was shown that the heat transfer parameters associated with free axial rotation were uniform and significantly better than in the end-over-end mode, which was better as compared with the fixed axial mode. The overall mean heat transfer coefficient (*U*) in the free axial mode was 340 W/m²C as compared to the mean value of 253 W/m²C in E-O-E mode and the associated ratio C_o/F_o (an indicator of degree of quality loss) was likewise significantly lower in free axial mode than in E-O-E mode. 4. In continuous systems, traditional thermocouples with lead wires is not practical because they cannot be attached to cans going in and out of the helical system. To assist in such scenarios, self-contained wireless sensors are now commercially available. These have replaced conventional thermocouple in recent years in various applications. A study was carried out to compare the performance of such a wireless temperature sensor with a conventional thermocouple. It was found that, statistically, the two sensors were not different (p>0.05) with respect to gathered temperature data or computed f_h , F_O , C_O/F_O values; however, the wireless sensors gave more stable signals and were much easier to use. They are however more expensive.

5. Particle temperature measurement is more complicated in cans going through bi-axial free rotation, like in continuous flow turbo cookers, and this makes the evaluation of U and h_{fp} difficult in these systems. An empirical methodology was developed for the evaluation of convective heat transfer coefficients (U and h_{fp}) in canned liquid/particle mixtures subjected to free axial agitation. The developed method involved correlations between h_{fp} and U using real time-temperature data gathered from test cans in fixed axial mode and then coupling them with experimentally evaluated fluid temperature gathered with wireless sensors in the bi-axially rotating cans to compute both U and h_{fp} . The developed method was responsive to heat transfer evaluation under different rotational speeds, temperatures and product viscosities (glycerin concentrations).

6. The influence of product and system parameters on h_{fp} and U values for canned particulates in Newtonian fluids undergoing free axial agitation were evaluated using methodology developed in this study. An orthogonal L16 experiments and analysis of variance was used to identify the potential product and process dependent variables during the free axial agitation. The heat transfer coefficients were significantly affected (p<0.05) by the rotational speed, glycerin concentration (contributing to fluid viscosity), retort temperature, particle material (contributing to particle density), particle concentration and particle size, while the headspace level was not significant in the range of 5 to 10 mm studied. 7. With the significant factors selected, a response surface methodology and two full factorial experimental designs were used to relate U and h_{fp} to the various process and product variables in each mode of rotation (fixed and free axial modes). Results showed that with an increase in rotational speed, particle density and retort temperature, there was an increase in the associated h_{fp} and U values; however, an increase in glycerin concentration resulted in the opposite. An increase in particle concentration showed an initial increasing trend in h_{fp} and U values which subsequently decreased with a further increase in particle concentration. T-tests revealed that both U and h_{fp} were significantly higher (p < .01) in free axial mode as compared to fixed axial mode.

8. Dimensionless correlations for heat transfer coefficients in canned Newtonian liquids in all three modes of rotation, both with and without particles, under mixed and pure forced convection heat transfer were developed using multiple non-linear regressions of statistically significant dimensionless groups. The combination of reel radius, can radius and particle radius was used as the characteristic length for the correlation. The developed equations gave higher coefficients of correlations (R^2 ranging from 0.92 to 0.97) and lower SS (175873 to 224) with mixed convection model than with pure forced convection model (R^2 ranging from 0.81 to 0.85 and higher SS ranging from 247587 to 577.57). This means that in all forced convection situations, the natural convection phenomenon continued to operate since buoyant forces resulting from density differences continue to exist.

9. In mixed convection mode, and with the presence of particulates, Nusselt number (Nu) was correlated to Reynolds (Re), Prandtl (Pr), Grashof (Gr) and Froude (Fr) numbers, relative density of particle to liquid (ρ_p/ρ_l) , particle concentration (e/100-e), diameter of particle to can (d_p/D_c) and particle/liquid thermal conductivity ratio (k_p/k_l) . For particulate fluids, an excellent correlation of $(R^2>0.93)$ was obtained between the Nu and other groups: $Nu = A_l(GrPr)^A_{2+}A_3(Re)^A_4 (Pr)^A_5 Fr^A_6 (\rho_p/\rho_l)^A_7 (e/100-e)^A_8 (d_p/D_c)^A_9 (K_p/K_l)^A_{10}$. Even in the absence of particles, and with the end-over-end mode of agitation where forced convection dominates, introducing natural convection term (Gr×Pr), improved R^2

from 0.81 to 0.97 which indicates the presence of some natural convection even with forced convection systems.

10. Artificial neural network models were successfully developed for U and h_{fp} associated with canned Newtonian fluids with and without particles during free and fixed axial rotation as well as end-over-end mode. Parameters were optimized by choosing the appropriate combination of hidden layers, learning runs, learning rules, transfer function and number of neurons. The developed ANN models were found to predict the responses with the mean relative error of 2.6 and 2.9% for h_{fp} and U in fixed axial mode, and 1.85 and 2.5% respectively in free axial mode. Similarly, mean relative errors associated with the overall heat transfer coefficient in Newtonian liquid without particulates in end-overend mode were 3.8%, and 2.06 % in the case of free axial mode. ANN models yielded better results than those from the dimensionless correlations, reducing the prediction errors by 37% to 78%. Algebraic equations were also generated to make the models easily implemented using a spreadsheet.

CONTRIBUTIONS TO KNOWLEDGE

1. In previous literature, no distinction was made between fixed and free axial mode, and both were lumped under the term axial rotation. When it was claimed that end-over-end mode was superior to the axial mode, comparison often included fixed axial modes. This research revisited previous studies with the new knowledge that the axial rotation falls under two separate categories. It can now be said with certainty that while end-over-end is better than fixed axial mode as described in the previous literature, the free axial mode is better than both.

2. Modifications were made to a pilot rotary cage autoclave (Stock Rotomat) to simulate free axial mode of heat transfer so that all three modes could be compared in the same retort equipment.

3. Traditional wired thermocouples are unsuitable for heat penetration data gathering in continuous free axially rotating cans; and even in the process simulators the use of two slip rings one at the retort level and one at the can level the process often results in considerable noise and variability in gathered temperature data. The wires used also often tend to entangle making the system more unreliable. Under limited carefully controlled experiments the performance of wired thermocouples and wireless temperature sensors were compared. The results showed no statistically significant differences (p>0.05) between the two sensors. For ease of data gathering, wireless sensors were employed for the rest of the study in free axial cans.

4. A new empirical methodology was developed to study the heat transfer coefficients (U and h_{fp}) to canned particulate – Newtonian fluids subjected to free axial agitation processing. The method was responsive to heat transfer evaluation under different levels of system and product parameters such as rotational speed, head space, retort temperature, liquid concentration, particle density, particle concentration and particle size.

5. A comprehensive study was carried out to understand the effects of system parameters on associated heat transfer coefficients (U and h_{fp}) for canned particulates Newtonian fluids subjected to free axial agitation processing. The significance of system and product parameters such as rotational speed, headspace, retort temperature, liquid concentration, particle density, particle concentration and particle size on U and h_{fp} were evaluated.

6. Dimensionless correlations were established to predict heat transfer coefficients U and h_{fp} for canned particulates in Newtonian fluid subjected to free axial agitation processing, demonstrating the continued contribution of natural convection to heat transfer even when forced convection conditions existed.

7. Artificial neural networks models were developed for the prediction of heat transfer coefficients U and h_{fp} for canned particulates in Newtonian fluids subjected to free axial

agitation processing and were found to perform better than the dimensionless correlations.

RECOMMENDATIONS FOR FUTURE RESEARCH

This research work has demonstrated several important findings. Meanwhile it also showed some areas of interests for future research and development, which could be summarized as follows:

- 1. Extending this study to quantifying the heat transfer coefficient U and h_{fp} in non-Newtonian fluids in free axially rotating cans will add significantly to process developments in axially rotating cans since most foods involve non-Newtonian fluids. These studies often are a more complex than with Newtonian fluids.
- 2. Quantifying the influence of can sizes, can materials, particle shape and different retort heating medium (water vs. steam) on U and h_{fp} in free axial agitation of can.
- 3. Visualization of particle/liquid moments in Newtonian fluids during the free axial agitation processing
- 4. Quantifying the particle motion/mixing in the container and relating it to heat transfer coefficient.
- 5. Conducting biological validations of thermal process using predicted heat transfer coefficients
- 6. Relating the evaluated heat transfer coefficients to the conventional thermal processing heat penetration parameters, heat rate index and lag factor.

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