HEATING BEHAVIOR AND QUALITY CHANGES IN CANNED POTATOES SUBJECTED TO AGITATION PROCESSING

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By

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ABSTRACT

Thermal processing is based on the application of heat to destroy pathogenic microorganisms of public health concern and to reduce the activity of enzymes and microorganisms that are responsible for spoilage of food to a low level. Often, thermal processing also results in degradation of color, texture and other quality attributes. In this study, quality changes in potatoes subjected thermal processing in agitation retorts were evaluated as related to process variables for the purpose of elucidating conditions for the maximum retention of color and textural qualities of canned potatoes.

Heating behavior of canned potatoes suspended in non-Newtonian fluid (CMC) was studied under different modes of retort processing (free axial, end-over-end, fixed axial and still mode). Heating rate index (f_h), lethality (F_o), cook value (C_o) and degree of cooking (C_o/F_o) associated with CMC fluid and potatoes in different processes were compared. Simultaneously the impact of thermal treatments on color and texture parameters was evaluated. Under the different processing conditions, better heat transfer was found to accumulate the process lethality faster and quality changes were well related to the degree of lethality accumulated.

Using heat transfer data obtained process times were adjusted to provide equivalent lethality of 10 min at center of potato particles. While processing under all agitation modes at higher temperatures, the process times were considerably lowered and hence resulted in better retention of quality. Overall, high temperature short time processes and more rapidly heating conditions demonstrated lesser damage to the quality of canned potatoes. Thermal processing under free bi-axial mode processing provided the best processing conditions for canned potatoes.

RESUMÉ

Le traitement thermique utilise la chaleur, pour détruire les microorganismes pathogéniques représentants un risque pour la santé ainsi que pour réduire l'activité enzymatique des microorganismes causant le pourrissement prématuré des aliments. Le traitement thermique des aliments peut entrainer une dégradation de la couleur, de la texture ainsi que d'autres traits de qualités des aliments. Dans cette étude, les changements en qualité des pommes de terres sujet a différent traitements thermiques agités ont été évalués dans le but de trouver les conditions permettant la meilleur conservation possible de la couleur et de la texture des pommes de terres en conserves.

Le comportement des pommes de terres en conserves suspendues dans un fluide non-Newtonian (CMC) ont été étudié couplé à différent type de toucheau d'agitation (Axe libre, Axe fixé ainsi que sans mouvement et 'end-over-end'). L'index de chaleur (f_b), la létalité (F_o), l'indice de cuisson (C_0) et le niveau de cuisson (C_0/F_o) associés avec le fluide CMC et les pommes de terre lors des différents scenarios ont été comparés. Simultanément, l'impact des traitements thermiques sur la couleur et la texture a aussi été évalué. Sous les différent traitements de cuisson, un meilleur transfère d'énergie a eu tendance a augmenté le niveau de létalité plus rapidement. Les changements dans la qualité générale de l'aliment sont fortement reliés avec le niveau de létalité accumulé.

Utilisant les données obtenues lors du transfert de chaleur, les temps de cuisson ont été ajustés pour produire un niveau de létalité de 10 min au centre des particules de pomme de terre. Le temps des traitements selon les différentes méthodes d'agitation sous un régime plus élevé de température ont permit d'être réduite. Cela a permit d'augmenter la qualité des pommes de terre produite. En conclusion, une température plus élevée, un temps de cuisson plus court ainsi qu'une augmentation en température plus rapide ont résulté en une meilleure conservation des qualités des aliments. L'utilisation du traitement thermique sous un mode axe libre est la meilleurs combinaison technique pour obtenir les conserves de pomme de terre de plus grande qualitée.

CONTRIBUTIONS OF AUTHORS

Several presentations have been made based on the thesis research and three manuscripts have been planned for publication. Hence the thesis is written in the manuscript style so that the three chapters highlighting the thesis research could be suitably modified for publication. Two authors have been involved in the thesis work and their contributions to the various articles are as follows:

Navneet Singh Rattan is the MSc candidate who planned and conducted all the experiments, in consultation with his supervisor, gathered and analyzed the results and drafted the thesis and the manuscripts for scientific presentations and publications.

Dr. Hosahalli S. Ramaswamy is the thesis supervisor, under whose guidance the research was carried out, and who guided and supervised the candidate in planning and conducting the research, as well as in correcting, reviewing and editing of the thesis and the manuscript drafts for publication.

LIST OF PUBLICATIONS AND PRESENTATIONS

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

Rattan, N. S. and Ramaswamy, H. S., 2012. Evaluation of the influence of process variables on the heating behavior of potatoes canned in a non-Newtonian fluid subjected to different modes of retort processing (to be submitted).

Rattan, N. S. and Ramaswamy, H. S., 2012. Evaluation of the influence of process variables on color and texture of potatoes canned in a non-Newtonian fluid subjected to different modes of retort processing (to be submitted).

Rattan, N. S. and Ramaswamy, H. S., 2012.Optimization of processing conditions for maximum retention of color and textural attributes of canned potatoes (to be submitted).

Part of this thesis has been presented/ prepared for presentation at the following scientific conferences:

Rattan, N. S., Hassan, H. and Ramaswamy, H. S., 2011**.**Comparative study of Quality Characteristics of vegetables subjected to various modes of Novel and Conventional Canning Operations. Northeast Agricultural and Biological Engineering Conference (NABEC), Burlington, Vermont, USA, July 2011.

Rattan, N. S. and Ramaswamy, H. S., 2012.Evaluating the impact of thermal treatments in preserving textural and color attributes of canned potatoes. Institute of Food Technologists (IFT) Annual Meeting, Las Vegas, Nevada, USA, June 2012.

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Chapter I

INTRODUCTION

Food is intimately woven into all aspects of life of a man, whether it is economic, social, or cultural. The perishable nature of the food has compelled the concerns of mankind towards its preservation, so the vast food processing industry is engaged in this purpose. The agricultural produce like cereals, pulses, fruits and vegetables as well as the reared animals for slaughter, milk, eggs etc. that act as food or food raw materials are exposed to physical, chemical, microbial or parasitic factors that render them unsuitable for consumption. Need for three meals a day, across the three hundred and sixty five days in a year has propelled the need for proper planning and preservation so as to get unvarying supply of healthy food. Time restrictions for meal preparation, is acting as the buoyant force which, at all the times is soaring the food industry to greater heights.

Today`s demand is to obtain safe, properly labeled, high quality, value added food products (Ramaswamy and Marcotte, 2006). The canning technology has come to the forefront amongst all the other processing or preservation technologies. Statistics Canada reveals that consumption of fruits and vegetables occupy a considerable portion of Canadian diet. Food pyramid issued by USDA and FDA also indicates fruits and vegetables to occupy significant share in diet of Americans. Hence it becomes imperative to process and preserve fruits and vegetables. Although the thermal processing tackles safety issues pertaining to food, but they often result in some degradation of nutrients and other likeable attributes as well (Stumbo, 1973; David *et al*., 1996). So the need is to have such a thermal process that provides a safe product and at the same time retains good quality after the processing. There are National/International legislatures that

enforce regulatory requirements on the canning process so as to ensure that the methods are efficient to achieve a high level of safety and without unduly affecting the product quality.

The optimization of thermal processing is bound by many constraints as every process has different quality attributes, which further have different criterion and each constraint added, tends to give different results (Silva *et al*., 1992). For example, optimization of a thermal process can be done to maximize the quality retention after processing (Lund *et al*., 1982) and/or to minimize the costs incurred and/or energy consumed (Barreiro *et al*., 1984) etc.

The quality retention after processing depends on consistency of food, thermal processing conditions which are basically decided on basis of food, container size, shape etc. Foods from consistency and their heating point of view can be classified as convection, conduction or mixed mode heating foods. The convection heating foods exhibit thinner consistency and their heating is quite uniform as well. Whereas, the conduction heated foods which are mainly the solid foods, heat slowly, while semi-solid food products that are purees heat in mixed or intermediate modes. Former can be heated efficiently by high temperature short time (HTST) processes with improved quality retention but, latter ones cannot be heated by HTST processes due to their slow heating behavior and diverse temperature profiles. Hence to achieve the required degree of lethality, the conduction heating foods often gets over cooked which are characterized by their lower quality. This has led to more inclination towards reducing the severity of processing conditions by employing higher temperature short time processes (Holdsworth, 1985; Koutchma, 2006).

Fortunately, the destruction of microorganisms and quality factors does not proceed at the same rate (Stumbo, 1973; Holdsworth, 1985). Studies have shown that thermal destruction rate of

microorganisms is considerably faster than quality destruction, and the difference between their rates increase with an increase in temperature. Hence, when the process is carried out at higher temperatures, relatively there is lower destruction of quality factors while fixing the microbial destruction such as the one required for achieving commercial sterility. In addition when the heat transfer rate is enhanced then the process will be shorter which eventually results in lesser destruction in quality factors and this forms the basis of HTST processes. The three main approaches used in industries to enhance the heat transfer in order to achieve benefits of HTST processing are 1) Thin profile packaging, 2) Aseptic processing and 3) Agitation processing. In thin profile processing the food is processed in semi rigid plastic containers and/or in retort pouches; and by increasing the surface area of container the processing time is shortened which eventually results in better quality retention. Food products in these containers heat rapidly in order to gain the advantage of HTST concept. Even conduction heating foods can benefit from processing under thin profiles because the heat transfer path to the cold spot is considerably reduced and the heat transfer is achieved more rapidly and uniformly because of the large surface area. In aseptic processing, the food and the packaging material are subjected to thermal treatments separately and post process packaging takes place in aseptic environment. This permits the use of optimal heating conditions for both product (mostly liquid) and the package, and hence high quality can be ensured. High viscosity foods and foods with particulates often pose problems when they are processed in rotary autoclaves. It was proposed by Clifcorn (1950) that by rotating the cans during processing, the rate of heat transfer can be enhanced and the processing times can be reduced considerably to achieve desired lethal effects. In canning, mainly three modes of rotation are employed: 1) End-over-end rotation, 2) Fixed axial rotation and 3) Bi/Free-axial rotation. End over end mode of rotation has proven to be quite good in

quality retention (Abbatemarco and Ramaswamy, 1994; Garrote *et al*., 2008). Due to comparatively lower heat transfer rates associated with fixed axial mode, it has been used scarcely in industries. Naveh and Kopelman (1980) in their study measured the heat transfer rates in canned foods under varying configurations: rotational speed, headspace. Their results demonstrated that better heat transfer rates were achieved in foods subjected to free axial mode of rotation as compared to end-over-end mode. Dwivedi and Ramaswamy (2010) also reported higher heat transfer rates in free axial mode as compared to end-over-end and fixed axial mode of rotations. Most of the heat transfer and quality optimization studies have been performed on vegetables subjected to end-over-end agitation mode and there is a very limited data available on the similar studies in axial modes (fixed, free axial) of rotation. Generally industrial systems based on end-over-end agitations are batch mode operations while those in the axial rotations are employed in continuous turbo cookers. More recently, another system based on horizontal shaking of retort cages as in pneumatic shakers is employed and it is called "Shaka" system. They provide the same advantage as other agitation systems.

It is hypothesized that by processing under agitating modes of rotation better heat transfer will be observed, especially under free axial mode of rotation. It is also expected that shorter processing times due to better mixing conditions under agitating modes will also result in better quality retention.

Based on available knowledge and recognizing the need for quality optimization studies in free axial rotation involving canned particulate foods, the following general objectives were formulated for this study:

1. Evaluation of the influence of process variables on the heating behavior of potatoes canned in a non-Newtonian fluid subjected to different modes of retort processing.

2. Evaluation of the influence of process variables on color and texture of potatoes canned in a non-Newtonian fluid subjected to different modes of retort processing

3. Optimization of processing conditions for maximum retention of color and textural attributes of canned potatoes.

Chapter II

LITERATURE REVIEW

2.1 Historical perspective

Thermal Processing is widely employed technique in food processing industry. It is the oldest and widely studied technology, which made it very successful throughout the years and will keep it going for years to come. In thermal processing heat is employed to food product so as to kill spoilage causing microorganisms and to make it shelf stable. The first instance of application of heat to make product shelf stable was in 1809, when Nicholas Appert heated food kept in glass jars so as to feed French Troops in battle. The results were very promising but the reason for extended shelf stability was not clear at that time. This process was named as Appertization after the name of Nicholas Appert. Years later, in 1864 Louis Pasteur explained that the pasteurization was the basis of Appert's canning. The microbiological safety of food was obtained by heat treatment that killed the spoilage microorganisms and this enhanced shelf life of products.

Till the end of nineteenth century and in the beginning of twentieth century the procedure laid down by Pasteur was followed extensively. The autoclave was used for cooking of foods. During mid 1800`s Chevallier patented commercial autoclave, which heated foods under pressure. Later in 1880`s the kettle in which heating medium was steam or hot water came into use. As mentioned by Ball (1938) that the autoclave was capable of achieving temperatures of up to 115˚C and it marked start of commercial autoclave manufacturing in United States. Then soon after this Still Retort was developed that had more controls over keeping high temperatures and high pressures for longer times and they were capable of achieving temperatures more than 120˚C (Ball, 1938). Ball (1923) proposed a graphical method of achieving safe sterilization

processes and his contribution was amazing as it triggered the spark of extensive improvements in safe sterilization processes. The disease outbreaks that used to occur due to food spoilage plummeted considerably because the processes were developed correctly by following methods developed by Ball. This graphical method was a bit cumbersome and had many limitations although it is now basis for most of the versatile and advanced methods of calculating safe sterilization process times (Stumbo, 1973).

It was also realized at nearly the same time that food quality attributes (texture, color etc.) are better retained if the processing is done at higher temperatures as compared to the conventional processing (Ball, 1938). The batch processing carried out in these still retorts was very widely followed by food processing industries especially in United States. During mid of last century the Food Machinery and Chemical Corporation, commonly known as FMC corporation launched the Sterilmatic system which was developed after Clifcorn (1950) proved the benefits of agitation during processing of foods. The Serilmatic device offered agitation and in commercial setups this improved outputs of cannery Industries.

The development in the equipments for the thermal processing kept booming and it will keep on expanding for the years to come. Efficient, user friendly, accurate and robust equipments came in to the market with the time. The latest ones being Rotomat, FMC`s continuous turbo cooker, Malo`s crate-less car and others.

2.2 Principles of thermal processing

2.2.1 Overview

The thermal processing is performed to impart commercial sterility to a food product. According to United States Food and Drugs Administration, *Commercial Sterility* refers to conditions achieved in product by the application of heat to render the product free of microorganisms that are capable of reproducing in the food under normal non-refrigerated conditions of storage and distribution (Awuah *et al*., 2007).

Depending on the food product undergoing thermal processing and the severity of the process, the processing regime can be either pasteurization or sterilization (Lund, 1975). The Classification of foods on the basis of pH, which forms the basis of selection of the required thermal processing and its adequate lethality, is Tabulated in 2.1.

Table 2.1: Classification of foods based on pH (Ramaswamy and Marcotte, 2006)

Name	pH	Examples
Low Acid Foods	>4.6	Meat & Fish, Vegetables and Soups etc.
Medium Acid Foods	3.7-4.6	Fruit jams, Tomato and Fruits etc.
High Acid Foods	<3.7	Fruits Juices, Berries and Pickles etc.

The high acid and medium acid foods are considered to be in one single category, i.e. acid foods and hence the simplified classification becomes acid foods and low acid foods. The demarcating

line between acid and low acid foods is pH 4.6. The choice of this pH of 4.6 is based on the microbiological concerns in canning, which are explained later.

The acid foods like fruit juices, fruit jams, tomatoes, milk etc. are mainly spoiled due to presence of vegetative microorganisms. The vegetative microorganisms are very heat sensitive and they get easily killed by mild heat treatments. Hence, acid foods are subjected to pasteurization, which is intended to inactivate undesirable enzymes and to kill vegetative microorganisms. Pasteurization process is performed at mild temperature conditions which are below 100˚C. On the other hand, low acid foods require severe thermal treatments, because of the concerns due to presence of bacterial spores and microbes capable of causing spoilage and that are of public health concern. The schematic listing the principles involved in thermal processing of foods is presented in Figure 2.1 (Ramaswamy and Abbatemarco, 1996).
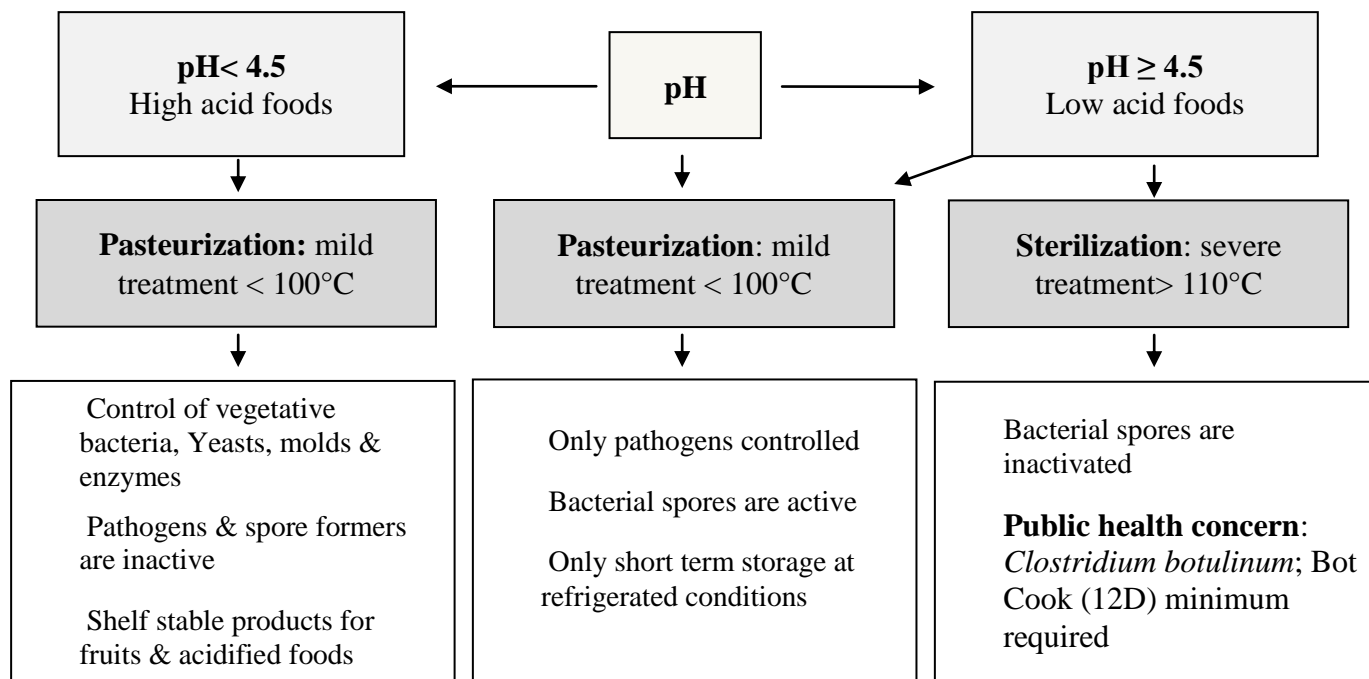
Figure 2.1: A schematic illustrating the principles involved in thermal processing applications (Source: Ramaswamy and Abbatemarco, 1996)

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The microorganism of public health concern which is known for its thermal stability in anaerobic conditions is *Clostridium botulinum*. This microorganism cannot grow in food if the pH is less than 4.6; hence the pH 4.6 acts as a separating line to differentiate foods on the basis of pH.*C. botulinum* is a spore forming, obligatory anaerobic, mesophilic and spoilage causing microbe which is capable of causing a diseased condition called, botulism. Botulism is detrimental as the neurotoxin produced by this organism can prove to be fatal. This organism is ubiquitous, as it can grow at room conditions (as it is a mesophile), and it can grow sometimes in presence of mild pH conditions as well.

2.2.2 Characteristics of microorganisms

The main steps for establishing a thermal process for commercial sterilization of food product involves identifying most heat resistant bacteria in food and its destruction mechanism and additionally the heat flow behavior in the food product (Hallstrom *et al.*, 1988). The identification of most heat resistant bacteria depends on the food`s intrinsic properties. The main influencing factor is the pH and the classification of foods based on the pH has been shown in Table 2.1.

The spore bearing bacteria are of chief concern in thermal processing due to their high heat resistance (Stumbo, 1973). The canning operation involves sterilizing food product inside a can, i.e. in oxygen free environment; this condition excludes those organisms which require oxygen for their growth. Hence the spore bearing organisms are even classified according to their oxygen requirements. Obligate aerobes are those microorganisms that require significant levels of oxygen for their growth. These are of least concern as they are heat sensitive, and can be destroyed in fraction of a second at 121.1˚C. There are certain organisms that can grow in lesser

quantities of oxygen and most of them cause "flat sour", they are called Facultative Anaerobes. Some of the facultative anaerobic thermophiles like few *Bacillus spp.* sometimes can grow at room conditions and they are of huge concern. *Bacillus macerans* and *Bacillus polymyxa* have been known to spoil food and food products at room temperature (Vaughn *et al,*. 1952).

The microorganisms of chief concern in thermal canning operations are *Clostridium* species, which belongs to group of obligate anaerobes, which are capable of growing in absence of oxygen. Thermophillic obligate aerobes are not much prevalent in cans; whereas, obligate mesophiles are found inside the can frequently. *Clostridium botulinum* is a mesophile which produces toxin and can grow in absence of oxygen by forming spores. *C. botulinum* types A and B are very heat resistant with D_{250} of 0.10 and 0.20 minutes respectively. *Clostridium sporogenes* (P.A. 3679) is much more heat resistant than *C. botulinum* but it is not of public health concern hence it is not considered in thermal processing except it is used as model organism in thermal process research because of its non toxic nature and easy cultivation. (Stumbo, 1973; Holdsworth, 2008)

The non-sporulating bacteria are capable of growing in high acid canned foods, but if they gain entrance in to cans of low acid food then they are of concern. *Lactobacillus spp.* and *Leuconostoc spp.* are widely found in high acid foods and they can be of concern if a can with low acid food is having any leaks.

2.2.3 Microbial destruction

Survivor curve and D- value

Once the organism of concern is identified then, its destruction needs to be studied i.e. kinetics of destruction of microorganism needs to be evaluated. Rahn (1945) hypothesized that, the heat treatment to the microbe causes the loss of reproduction power due to denaturation of particular gene which is essential for reproduction. Previous studies cite enough evidence that, inactivation of microorganisms follow first order reaction kinetics. First order degradation means that destruction rate with respect to time is directly proportional to amount or concentration of the quantity, whose degradation is being studied. It can be mathematically expressed as follows.

$$-dn/dt = kN^n \qquad (2.1)$$

In case of Survival curve, the N corresponds to number of spores of target microbe surviving after time of t min, k is proportionality constant which is reaction rate constant and n is order of reaction (for first order reaction n equals unity). If the Equation 2.1 is integrated under limits N_o to N from time zero to time t respectively, with n=1 then, result is:

$$\ln (N/N_o)= -kt \qquad (2.2)$$

Alternatively it can be expressed as

$$\ln (N/N_o)= -kt / 2.303 \quad \text{or} \quad N=N_o (10)^{-kt} \qquad (2.3)$$

Graphical representation of above equation is presented in Figure 2.2. The logarithmic plot of the number of number of survivors vs time is called *Survivor Curve*, which has log scale on ordinate axis and linear time scale on abscissa. That is why some times it is called semi-logarithmic survivor curve.

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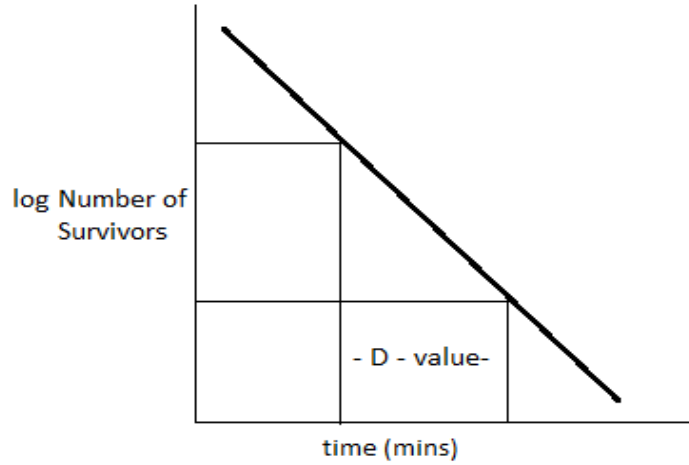
Figure 2.2: A typical survivor curve

From the survivor curve, a term of interest, "D-value" is deduced which represents the time required to destroy 90% of the surviving population or alternatively it is time required by straight line semi-log survivor curve to traverse one log cycle. Katzin *et al.* (1943) termed it as "D-value" or "decimal reduction value" or "decimal reduction time". So, in Equation 2.1 when N equals 90% of N_o then, t equals D-value. This can be mathematically related to reaction rate constant as:

$$D = 2.303 / k \tag{2.4}$$

The D-value can be computed from any time interval in semi-log survivor curve. The general equation to calculate D value from any time interval t_1 and t_2 is:

$$D = \frac{t2 - t1}{\log(N1/N2)} \tag{2.5}$$

Where, N_1 and N_2 are the number of microbes surviving at times t_1 and t_2 respectively.

The complete destruction of any microbial population is impossible because of the logarithmic nature of the surviving spore population. Hence there is always reduction in the population, not

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the complete destruction. Often, in food microbiology a term called thermal death time (TDT) is used, which refers to heating time required for destruction of microbial populations so that, there is no growth on the culture media after thermal treatment. So TDT can be any multiple of D-value. Mathematically:

$$TDT = nD \qquad (2.6)$$

n represents number of decimal reductions (Ramaswamy and Marcotte, 2006). For *C. botulinum* the thermal death time value corresponds to 12 decimal reductions. Specifically, 12D thermal treatment to food is intended for destruction of *C. botulinum* and it is called *"Bot Cook"*.

The semi log plot of the survivor curve is not always a straight line, because the microbes are always experiencing different environments in the different foods so, often there is deviation from straight line which can be attributed to many reasons like, 1) Heat activation for spore germination 2) Nature of subculture medium 3) Flocculation or De-flocculation during heating 4) Clumping of microbial cells 5) Presence of mixed flora 6) Anaerobiosis (Stumbo, 1973)

Thermal destruction time and z-value

The survivor curve is an isothermal plot of log of surviving microbial population vs time. But the thermal destruction is temperature dependent; hence a temperature sensitivity indicator called *"z-value"* was postulated. z-value is temperature range through which the decimal reduction of 90% is accomplished, in other words it is temperature range by which D-value passes through one log cycle. z-value reflects relative resistance of bacteria to different lethal temperatures (Stumbo, 1973). Mathematically

$$z = \frac{T2 - T1}{\log(D1/D2)} \qquad (2.7)$$

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Where (T_2-T_1) is temperature range and D_1 and D_2 corresponds to decimal reduction times at temperatures T_1 and T_2 respectively. Typical thermal resistance curve is presented below.
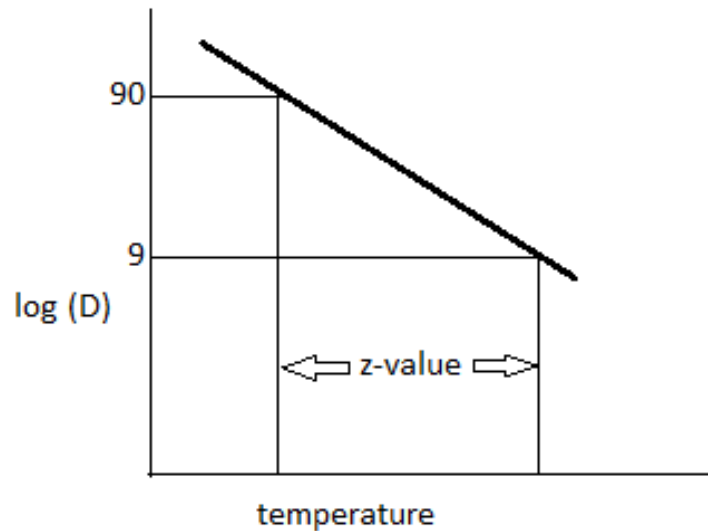
Figure 2.3: A typical thermal resistance curve

2.2.4 Thermal process evaluation

Process lethality

In food processing industries, in real time scenarios during thermal treatment, food undergoes varying temperature treatments for varying time intervals. Each temperature-time contributes to specific lethality. Hence for the whole process the lethality contributions need to be summated, when it is done, the integrated lethality over all the temperature-time combinations throughout the process is referred to *Process Lethality (*F_o*)*. In order to make comparisons between different thermal treatments a unit of lethality has been established (Stumbo, 1973), that is defined as equivalent heating time at reference temperature of 250 ^{o}F or 121.1 ^{o}C. The mathematical expression to calculate lethality is:

$$F_o = \int 10^{(T-121.1)/10} dt \qquad (2.8)$$

If we know the lethality at any temperature T, then its corresponding lethality at reference can be calculated from following mathematical relationship:

$$F_o = F \, (10^{[(T-T_o)/z]}) \qquad (2.9)$$

For example, if F value of a process at 110^oC with z value as 10 ^{o}C is 10 minutes. Then equivalently the F_o value will be 1 minute. For target organism in low acid foods, *C. botulinum*, the D-value is 0.21 min at 121.1 ^{o}C, and we know that, for bot cook 12D is needed, which is the complete sterilization process and hence F_o in this case will be 12x0.21, i.e. 2.52 min. For non spoilage concern microbes that are more heat resistant (say D-value of 1 min) the F_o value of 5 min is very commonly employed, which will impart 5D process lethality for the heat resistant microbes. Hence, initial load of such microorganisms must be controlled with efficient practices so as to keep spoilage rate below one spoiled can per thousand cans (Meng, 2006).

Cook value concept

Cook value (C_o) is used for estimating the quality losses that occur due to processing. In optimizing a thermal process from quality standpoint the cook value serves as basis. The cooking and microbial inactivations are the pillars that serve as basis for establishing a thermal process. The traditional canning used to be two step process in which cooking was followed by sterilization. Now-a-days the canning accomplishes adequate cooking with the microbial inactivation.

There can be many processes which are termed equivalent processes having same F value but different temperature-time combinations. Similarly, there can be processes with same C_o value

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and different processing conditions. A cook value of the process is basically taken as equivalent minutes of heating at 100 ˚C with z value of 33 ˚C (Eisner, 1988). Cook value can also be calculated by using numerical integration technique (Ohlsson, 1988).

$$C_o = \int 10^{(T-100)/33} dt \qquad (2.10)$$

The C_o/F_o ratio more than only cook value is commonly used parameter to estimate quality changes. C_o/F_o ratio gives indication of degree of cooking that takes place in product especially when the processing conditions are varying (Abbatemarco and Ramaswamy, 1994).

Fortunately, the z values for quality factors are much more in magnitude than the ones for microorganisms. z values for cooking and nutrient degradation are in range 25-45 ^{o}C, whereas for microbial inactivation z values are in range 7-12 ^{o}C. So for every 10 ^{o}C rise in temperature cooking rate doubles but microbial inactivation rate becomes ten times (Holdsworth, 2008). The above expression was for cook value at a single point in the can. In some studies, the process evaluation is done by calculating cook value for whole mass of product. So, mass average cook value (C_s) is used as objective function.

$$C_s = D_{ref} \log(C_o/C) \qquad (2.11)$$

Where, C_o/C is volume average quality retention and this concept for optimization has also been used by many researchers Thijssen *et al.* (1978); Martens *et al.* (1982); Banga *et al.* (1991).

2.2.5 Heat penetration in to the food

Heat penetration measurements

To obtain heat penetration profile of food, temperature measuring devices are used. Most commonly copper-constantan thermocouples are used to record temperature at different times. From literature, it was noticed that in liquid foods under rotary processing a needle thermocouple is used at geometrical center of the can (Abbatemarco and Ramaswamy, 1994), later on a thin flexible wire thermocouple was used for temperature measurements inside the moving particles in agitating cans (Sablani, 1996; Meng, 2006; Dwivedi, 2008).

Heat penetration profile

The thermocouples are placed in the appropriate cold spot location in can in order to gather temperature-time profile for the liquid and particulates in the can. The heat transferred from the heating medium to the canned food particle has to cross various sequential barriers. The first barrier is heat transfer through the can surface which is mainly, convection at the outside and inside surface of the can and conduction through the can wall. Second obstacle is convective heat transfer that takes place in can`s liquid up to the particle surface, and then the liquid to particle heat transfer and finally the transfer of heat from particle surface to the center of particle which mainly takes place via conduction. The typical temperature profile in a canned particulate liquid food during the process is shown in Figure 2.4 (Ramaswamy and Marcotte, 2006). The temperature profile shows that the retort heats much faster than the liquid and the particle in the can. This difference is attributes to the fact that particle heats by conduction which is the slowest mechanism, and liquid heats up by convection hence its heating is faster than particle.
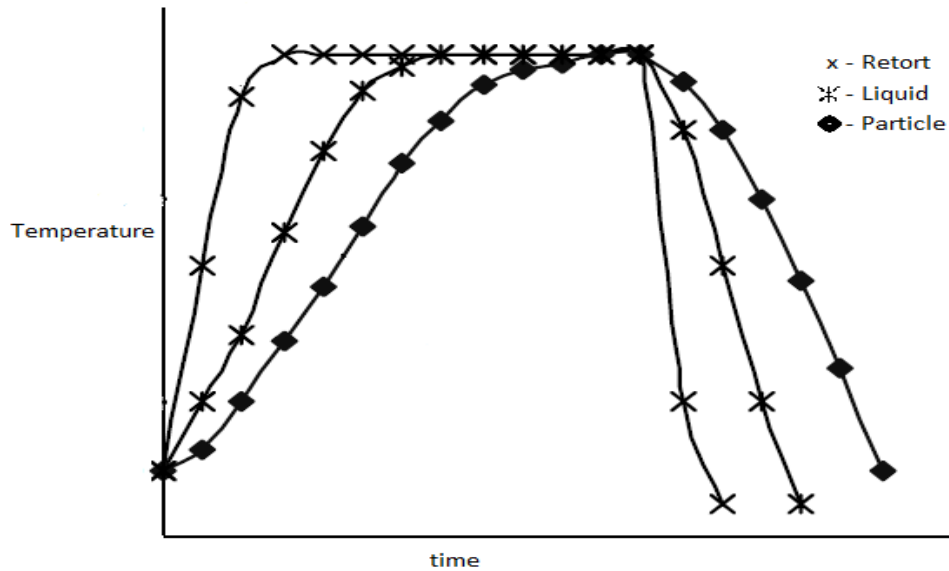
Figure 2.4: Typical temperature-time profiles of retort, can liquid and particle

From the above profile we can establish a thermal process and calculate the process time by using graphical methods i.e. the General (Bigelow *et al.*, 1920) and Improved General method (Ball, 1938; Schultz and Olson, 1940). These methods are very accurate as they involve use of original temperature-time profile. There are other methods which are quite conservative and henceforth are safe to use, they are based on first evaluating the heat penetration parameters and then calculation of process time is done. There are many formula methods developed for thermal processing these were reviewed by Smith *et al.* (1982) and he evaluated performance of Ball formula method , Stumbo formula method (1966), Hayakawa formula method (1970) and some modification of these methods was done by Jen *et al.* (1971). Later Pham (1990) developed a formula for calculating process times in conduction heated foods.

The temperature profile of food product undergoing thermal processing depends on various factors like, heating process (still vs agitated; in container vs aseptic), heating medium (steam, hot water, steam-air mixture), heating conditions (retort temperature, initial temperature of food),

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product type (solid, semi-solid, liquid, particulate liquid, thermo-physical properties of product) and container`s shape size and type (Holdsworth, 2008).

Characterization of heat penetration data

The formula methods make use of heat penetration parameters which are calculated by plotting semi-logarithmic heating and cooling curves. The heating curve (or heat penetration curve) is constructed by plotting logarithm of difference of retort temperature and the product temperature versus heating time (Figure 2.5). From the heat penetration graph heating rate index (f_h) and heating lag factor (j_{ch}) are obtained.
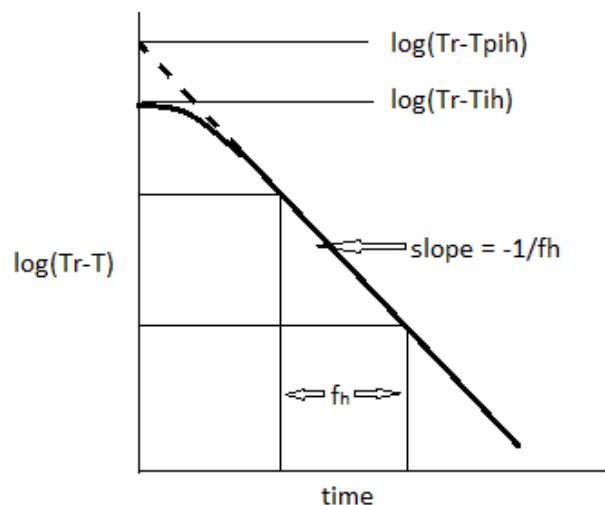
Figure 2.5: A typical heating curve

Heat penetration parameters

The heating rate index (f_h) is defined as time taken by straight line portion of heating curve to traverse one log cycle. It is equal to negative reciprocal of the curve. It indicates the rate of

heating. If f_h is higher it implies product takes longer time to heat, when it is small, it means product heats up rapidly.

The heating lag factor (j_{ch}) when multiplied with I_h ($I_h = T_r - T_{ih}$) gives the intersection of straight line portion of heat penetration curve and vertical line which marks effective beginning of the process. It measures the delay in beginning of uniform heating in the product. Mathematically it is expressed as:

$$j_{ch} = (T_r - T_{pih})/(T_r - T_{ih}) \qquad (2.12)$$

T_r is the retort temperature, T_{pih} is pseudo initial temperature of products which is obtained by extrapolating the intersection of straight line portion of the heat penetration curve and vertical line which marks effective beginning of the process. T_{ih} is the initial product temperature. The lag in heating is due to slow come up time (CUT) of the retort. It was found experimentally by Ball and Olson (1957) that the 42% of the CUT is actually effective and it can be considered as part of actual process.

Similarly, the cooling portion of the temperature time profile is analyzed by plotting logarithmic difference of product temperature and temperature of cooling water (T_w) versus time (Figure 2.6). Correspondingly, the cooling rate index (f_c) and cooling lag factor (j_{cc}) are obtained from cooling curve.

Mathematically a cooling lag factor can be obtained from following equation:

$$j_{cc} = (T_{pic} - T_w)/(T_{ic} - T_w) \qquad (2.13)$$
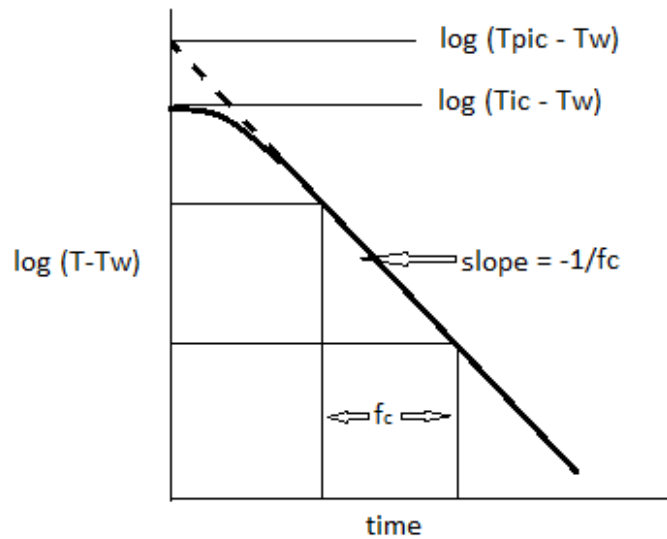
Figure 2.6: A typical cooling curve

Temperature conversion

In commercial operations the retorts are always running at variable conditions, such as different initial product temperature or retort temperature. So if we have particular process established for the heat penetration behavior and process times and we seek to establish it at different conditions then it is quite possible to use the established process (Stumbo, 1973).

If the retort temperature is run at new temperature and we need to find the corresponding can temperature keeping initial food temperature same then following temperature conversion can be used (Schultz and Olson, 1940):

$$T'_c = T'_r - \frac{T'r - Ti}{Tr - Ti}(T_r - T_c) \tag{2.14}$$

T_r is original retort temperature, T'_r is the new retort temperature, T_i is the initial food temperature, T_c is the can temperature of original set and T'_c is can temperature of new set.

Similarly if the retort remains the same and initial product temperature is changed then following equation is used (Schultz and Olson, 1940):

$$T'_c = T_r - \frac{Tr - T'i}{Tr - Ti}(T_r - T_c) \qquad (2.15)$$

2.2.6 Factors influencing heat transfer

In agitating retorts, the heat transfer to liquid as well as particles should be fast so as to retain better quality and lesser processing times. There can be many factors affecting the heat transfer like rotational speed, Liquid viscosity, Particle concentration, particle size, particle density, particle shape, headspace and type of agitation.

Conley *et al.* (1951); Lenz and Lund (1978), studied the effects of rotational speed on heat transfer rates. It was found that increasing rotational speed results in increased heat transfer coefficients. In all cases the overall heat transfer coefficient was found to increase with increasing rotational speed. Stoforos and Merson (1992) found that liquid to particle surface heat transfer coefficient decreased if the rotational speed is increased too much, this was attributed to decline in relative particle to liquid velocity.

Liquid viscosity also influences the heat transfer coefficients during rotational thermal processing. Higher viscosity results in lesser turbulence and hence poor heat transfer (Lenz and Lund, 1978). Particle concentration may or may not affect the heat transfer rates. It was found that up to certain level of increasing particle concentration liquid to particle heat transfer enhanced but after particular concentration it started dipping (Deniston *et al.*, 1987). Similar trends were observed with particle size and particle shape. It was observed by Sablani (1996) that by increasing can headspace, there was considerable increase in the heat transfer coefficients.

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Agitation in the cans can be accomplished in mainly four ways, End over end, fixed axial, free axial and Shaka system. The details about the movement of cans in each of these modes are described later.

2.3 Food quality

The term quality is very elusive term because there are no dimensions and constraints in defining it. Term quality is a relative term and it is referred to be those characteristics of food that makes food agreeable to person (Ramaswamy and Marcotte, 2006). Kramer and Twigg (1966) defined quality as "the composite of those characteristics that differentiate individual units of a product and have significance in determining the degree of acceptability by the buyer". Thermal processing`s primary focus is destroying the spoilage causing microorganisms and quality concerns were not give importance until recently when consumers desire for good quality increased. Hence, the required processing with maximum quality retention is the main focus of food processing industries. Food quality can be evaluated by sensory evaluations or by using various analytical instruments.

2.3.1 Quality factor degradation

Enough literature proves that thermal processing is ought to degrade food product from quality stand point (Stumbo, 1973; Ohlsson, 1980; Holdsworth, 1985; Leonard *et al*., 1986). Fortunately, the susceptibility of microorganisms to thermal destruction is much greater than that of enzymes and various quality factors. This difference in susceptibility led to development of optimal thermal processes that result in maximum quality retention with commercial sterility (Leonard *et al*., 1986).

Quality factor degradation follows first order degradation kinetics just similar to microbial destruction. The quality factor determination is needed so as to model the quality factor changes that are obtained from analytical methods.

2.3.2 Effect of heat on quality attributes

Color

First and the foremost thing by which, a consumer is influenced with while buying food is its appearance. The appearance is characterized primarily by the color that fruit or vegetable bears and it influences the purchase (Gnanasekharan *et al*., 1992). Heating treatment often results in the leaching of the cooked food products as the pigments are destroyed by application of heat. Significant color changes are seen in the heat treatment of green vegetables in which chlorophyll is converted to pheophytin and the green color becomes dull olive brown (Schwartz and Elbe, 1983) . The other food stuffs in which the color is due to pigments such as carotenoids and anthocyanins, it is observed that color degradation by thermal treatments is less as compared to green colored foods (Clydesdale and Ahmed, 1978). The reason for this is, carotenoids are dispersed in the food and they rely on the association with lipids or proteins hence they have protective effect. In case of anthocyanins it is found they break down by pH and oxygen changes and it is found that in anaerobic conditions the pH effect also becomes very small hence the color changes are less (Clydesdale and Ahmed, 1978).

Color is a three dimensional parameter that is analyzed by human eye`s three receptors red, green and blue (Francis, 1995). The subjective nature of color makes tough to reproduce the same analysis of the food every time, hence an instrumental method is appropriate for analysis. Such instrumental methods are based on the fact that color is a mathematical combination of three

primary colors (red, green and blue) (Clydesdale and Ahmed, 1978). Tristimulus colorimeters, Hunter L*a*b and CIE L*a*b are some of the methods to express the color in mathematical form. Hunter L*a*b model is very widely used in food industries for analyzing color changes. "L value" depicts the lightness and it is expressed on the scale 0 to 100 corresponds to light (0) to dark (100) spectrum. "a value" is measure of greenness and redness and it is expressed on scale -60 (Green) to +60 (Red); similarly "b value" depicts blueness(-60) and yellowness(+60). The total color change can be estimated by using parameter ΔE which is mathematically evaluated from the equation:

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{-1/2} \quad\quad\quad (2.21)$$

Texture

Texture of the food substance also determines overall quality and consumer acceptance of a particular food product (Hutchings, 1988). It is often observed that with application of heat the texture of the food becomes soft; this phenomenon is termed as "thermal softening". Lund (1982) explained that thermal softening can be attributed to two main reasons. First is, it can be due to changes in cell wall matrix polysaccharides (celluloses, hemicelluloses, pectins etc.) which depend on many factors like pH, types and amounts of various salts present in the plant cell wall, per se presence of calcium chloride can result in harder texture of the food. Water uptake by polysaccharides results in reduction of cohesiveness of cell wall matrix thereby resulting in lower adhesion. Other reason for softening is due to loss of turgor pressure which is pressure of cell components against the cell wall and it is due to the water content inside the cell. The thermal treatments can result in plasmolysis which reduces the turgor pressure and eventually it is responsible for softening of food (Rao and Lund, 1986). Previous studies show

that the extent of softening varies for different foods if they are subjected to similar treatments due to difference in their compositions (Rao and Lund, 1986).

The textural changes can be analyzed by using sensory evaluation or by instrumental methods. The instrumental texture profile analysis method developed by Szczesniak and Hall (1975) has become very common with advent of computer assisted texturometers (like TA-XT 2, Stable Microsystems Ltd., Surrey, England). The texture analyzer generates "texture profile" by compressing bite sized food particles, which basically simulates the mastication process of humans to give force time curves. The TPA graph is a force versus time graph (Figure 2.7) as a function of deformation and hence it provides 3D product analysis.
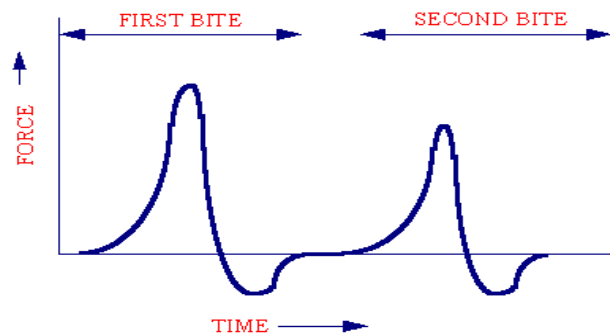
Figure 2.7: A typical texture profile

Parameters such as hardness (maximum force needed to compress the sample); springiness (how well food recovers after second compression); and other parameters such as gumminess, adhesiveness, chewiness etc can be evaluated from texture profile generated by using the computer assisted texturometers.

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2.4 Quality optimization

Traditionally, the primary objective of canning industry was to obtain a commercially sterile food product whereas, now a days the inclination towards obtaining a good quality and commercially sterile food product has increased. Thermal and non thermal techniques are employed currently on large scale in industries so as to achieve good quality and safely processed foods. Improvement in traditional thermal techniques such as agitation processing (end over end, fixed axial, bi/free axial, Shaka system) in which heat transfer rate is enhanced and the quality of processed products is found to be high. Other type of thermal technique can be processing in retort pouches where heat has lesser distance to travel so as to process the food, as a result of which shorter processing times are required which ensures better quality. The newest of the thermal techniques which ensures better quality is aseptic processing in which the food products and the containers are separately sterilized and then packed aseptically. This technique is suited to liquid foods or liquids with very small particulates. The current research is based on quality optimization of canned vegetables through agitation processing.

2.4.1 Agitation processing

Agitation in the cans can be achieved by either rotation (end over end, free axial, fixed axial) or by rocking action (shaka system). Agitating retorts have many advantages than the still retorts most important of all is that, they offer better and fast heat transfer to the food products which ensures better quality retention during the processing as the time required in processing assisted with agitation is lesser than time required for processing in still mode. The types of agitation that are used commonly in industries are:

<p align="center">(a)   (b)   (c)</p>
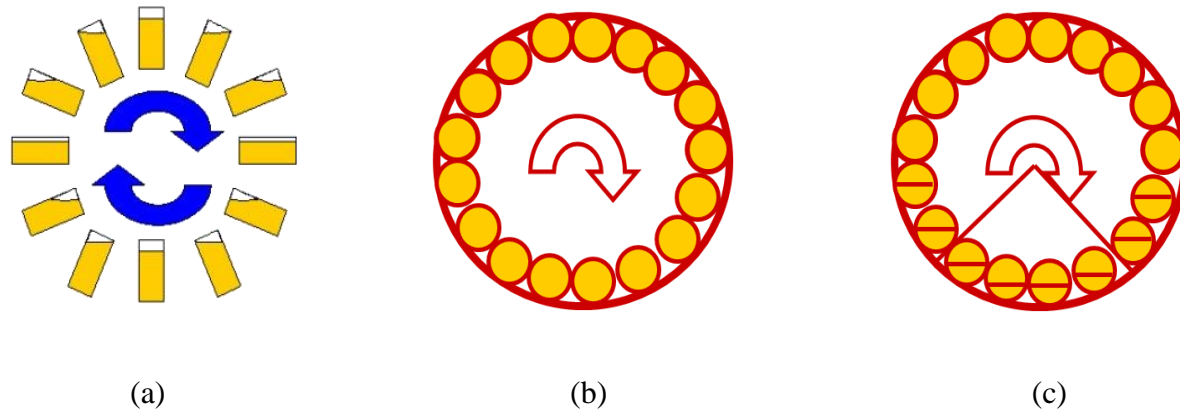
Figure 2.8: Different modes of agitation in a retort

End-over-end rotation

In this mode of rotation the cans held in vertical position in the cage and rotated in such a way that the head space bubble moves in longitudinal direction and causes mixing of can contents, Figure (2.7a). This type of agitation was first used by Clifcorn *et al*. (1950) in order to sort methods to improve heat transfer to canned food products.

Fixed axial rotation

In fixed axial mode, the cans are held horizontally in the cage and rotated as it can be seen in, Figure (2.7b). This mode of rotation is not common in the industries because of its minimal advantages compared to other modes of agitation.

Free axial/ bi-axial rotation

The bi-axial mode of rotation consists of two phases of rotation of the cans which are mutually in opposite directions hence this type of rotation is termed as bi-axial rotation; and a third phase of transition. The FMC's continuous turbo cookers, the Sterilmatic (JBT Corporation/ FMC Corporation) involves agitation in bi-axial mode of rotation. The cans move in helical path and

this ensures continuity in the processing and cans are subjected for appropriate residence time in the cylindrical shells to ensure effective sterilization on contents. For the upper 220° of the cycle of rotation the cans move in fixed axial mode along with the cage and for the lower 100° of the rotation the cans move freely along the cage wall and the transitional phase of 30° is on either side of free rotation (Figure 2.7c).

Shaka system

In Shaka system cans are agitated in rocking action mode. The cans are held in such a way that they are rigorously shaken in back and forth direction thereby producing a lot of turbulence. Shaka system offers better heat transfer rates than the rotational modes but it lacks continuity of process which can be achieved in free axial modes (Dwivedi, 2008).

2.5 Origin and importance of potato

Potato belongs to *Solanaceae* family and it is a tuberous, starchy food crop which originated from Andes region in South America. From there it spread throughout the world and it is fourth largest food crop in the world after wheat, rice and maize. Europe is the higher per capita producer of potato, whereas maximum cultivation of potato is done in China.

Potato is a good source of nourishment to humans. According to Food and Agriculture Organization, on an average it was found that a global citizen consumed about 33 kg potatoes in first decade of 21st century. Potato is a good energy source that can provide approximately 322 kJ per 100 gram potato. Mainly potato composes of water (~80%), carbohydrate, fiber etc. Apart from presence of carbohydrates, potato is a good source of several vitamins and minerals such as calcium, potassium and phosphorus. During storage, transportation, processing many of the important nutrient components are affected. Cold storage conditions are often recommended for

longer storage stability of potatoes. Careful transportation can again result in better quality potatoes. The processing of potato is done in many ways such as frying, dehydrating, cooking and canning etc. During canning many quality attributes are modified thereby rendering processed potatoes poor in quality. Hence this study was aimed at reducing the quality deterioration that takes place during canning.

White potatoes are extensively canned in many parts of world. Also, due to uniformity of potato it is very widely used in research areas. Due to easy availability and economical feasibility, potato was selected for this research.

PREFACE TO CHAPTER III

Although commercially successful, novel and continuous flow cookers as the FMC continuous turbo cookers have not been fully explored to their full potential, because of lack of full length scientific work capable of demonstrating and validating their usefulness for processing particulate fluids. Currently they are mostly used for soups and other liquid products or liquid products with some amount of suspended solids of small size. Most heat transfer studies have been carried out under end-over-end mode of processing. In recent years, only our lab has carried out detailed experimental studies on thermal processing of particulate fluids in end-over-end and bi-axially rotating cans under commercial processing conditions especially focusing on heat transfer issues. This study is aimed at evaluating and comparing the influence of such processing systems on quality changes in foods.

Based on previous heat transfer studies performed by using Nylon spheres by Hassan (2011); preliminary processing conditions were established by matching heating behavior of potato cubes with that of Nylon spheres. Processing times were selected to provide three lethality levels at three different temperatures under different processing modes. Prior to embarking on optimization of thermal process by maximizing quality retention during processing, it was considered important to study heating behavior in terms of parameters such as heating rate index, lethality and cook values. Chapter III is focused on these issues.

Part of this research was presented in 2011 in Northeast Agricultural and Biological Engineering Conference, NABEC (Vermont, USA). Manuscript for publication in scientific journal has been prepared. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H. S. Ramaswamy.

Chapter III

EVALUATION OF THE INFLUENCE OF PROCESS VARIABLES ON THE HEATING BEHAVIOR OF POTATOES CANNED IN A NON-NEWTONIAN FLUID SUBJECTED TO DIFFERENT MODES OF RETORT PROCESSING

3.1 Abstract

The study was aimed at evaluating heat transfer behavior of potato particles subjected to thermal processing in a pilot scale full water immersion retort. The potato particles suspended in a non-Newtonian fluid (1% CMC) were subjected to thermal treatments under varying processing conditions (retort temperature 115–125˚C; rotation speed 10, 20 rpm; modes: still and agitating). Potatoes were prepared as cubes of different sizes and evaluated for their heating patterns. Based on the results, 1.6x1.6x1.6 cm cubes were selected for further study since they provided heating patterns similar to those employed in earlier heat transfer studies. Nominal processing times were determined to provide three lethality levels at each temperature. A retrofitted, single basket rotary retort was used to simultaneously accommodate end-over-end and axial modes of rotation. The effects of thermal treatments were evaluated in terms of lethality values achieved at particle centre and at geometrical center of can. Under same processing conditions, free axial mode processing demonstrated better heat transfer than other agitating modes, which were characterized by higher lethality values achieved in cans. All the process parameters were found to have significant impact $(p<0.05)$ on the heat transfer. Overall, processing at higher rotational speeds for longer times under agitating modes demonstrated better delivery of lethality to the product.

3.2 Introduction

Heat transfer to the food product forms the basis for the thermal processing. The mechanisms of heat transfer are important considerations in order to design and optimize a thermal process. Conduction and convection heat transfer are the two principal mechanisms by which heat travels in to the food. Conduction prevails as the predominant mechanism in the heating of solid foods whereas the convection takes place in the liquid foods. The canned foods comprising the mixture of liquid and particle mixtures such as sauces and soups containing meat chunks or vegetables heat by combination of both conduction and convection mechanisms.

In search of better quality thermally processed products, the food industry is seeking alternative approaches to the conventional heating methods. The trend is towards incorporation of high temperature short time processes (HTST) because at higher temperatures the rate of microbial destruction is significantly higher than the quality destruction (Holdsworth, 1985). In order to exploit HTST benefits, there is a need of systems that can provide rapid heating conditions. Mechanical agitation of the container during processing serves this purpose well. Research has shown that container agitation results in rapid heat transfer even in particulate or viscous foods. Commercial sterilization of food calls for the adequate and predetermined amount of heat to be delivered at the slowest heating point to obtain a microbiologically safe product. In particulate foods, while achieving this requirement, often the product gets over heated at the surface as compared to the centre. The particulate liquid products that normally heat via conduction in conventional retorts can be heated at accelerated rate via forced convection in rotating retorts. Moreover the agitation processing promises to be an energy efficient process which again is very important scenario in food processing industries.

There are several methods being employed in industries for agitating the cans during processing, amongst them end-over-end and axial modes are most common. In end-over-end mode the sealed can rotates in a vertical plane in such a fashion that headspace bubble moves along the length of can and causes the mixing of contents (Clifcorn *et al*., 1950). The end-over-end mode is commonly employed in batch retorts and by comparison the axial rotation is achieved in continuous retorts in which agitation takes place when cans roll freely across bottom of the shell. These continuous retorts are designed with two or more cylindrical shells through which the cans are carried and advanced further on a revolving reel. These continuous retorts offer several advantages over their batch counterparts such as, high productivity, reduced consumption of heating medium (steam, water) and lower labor requirements.

In order to establish a successful thermal process schedule, the main requirement is to ensure that adequate heat is delivered at the coldest spot in can. In cans with liquid and particulates, the geometrical centre of the largest particle is considered to be the coldest spot. To predetermine the process lethality at the particle center several approaches have been studied extensively in previous years. The most reliable and the traditional approach is to gather time-temperature data and the other approaches are based on theoretical models or computerized simulations.

Several Berry and coworkers have extensively studied the heating characteristics of foods in rotary retorts (Berry *et al*., 1979; Berry and Bradshaw, 1980,1982; Berry and Dickerson, 1981; Berry and Kohnhorst, 1985). Many studies have been conducted to study the influence of processing variables that influence heat transfer coefficients (Anantheswaran and Rao, 1985a,b; Lekwauwa and Hayakawa, 1986; Sablani and Ramaswamy, 1995, 1996; Garrote *et al*., 2006; Meng and Ramaswamy, 2006, 2007a,b; Dwivedi and Ramaswamy, 2008, 2010a,b). These studies were conducted on food systems in end-over-end mode and the results of these studies

suggested that the retort temperature, rotational speed, head space, liquid viscosity, particle size, particle center density are the main factors that influence heat transfer to the foods.

Fewer studies have been conducted in food systems processed in free axially rotating cans. Lenz and Lund (1978); Deniston *et al.* (1987); Fernandez *et al.* (1988); Dwivedi and Ramaswamy (2008, 2010a,b) reported effects of processing variables on heat transfer rates in axially rotating cans. Most of the heat transfer studies performed earlier involved fixed particles in the can, in which the particles were mounted in fixed wire thermocouple. Stoforos and Merson (1992) conducted a study using liquid crystal coated particles so that actual movement of particles can be realized during agitation. This study was performed at lower temperatures hence its applicability at sterilization temperatures was doubtable. Various biological based indicators have also been used for deducing heat transfer coefficients: Weng *et al.* (1992); Haentjens *et al.* (1998); Guiavarc'h *et al.* (2002a,b) used time temperature integrators (TTIs) in which they used microorganisms, enzymes and some chemicals in combination with mathematical models to compute the heat transfer coefficients. Since the time when the technique developed by Sablani and Ramaswamy (1996) where the flexible wired thermocouple could be attached to particle center, several heat transfer studies have been done at McGill University (Sablani and Ramaswamy, 1995, 1996; Meng and Ramaswamy, 2006, 2007a,b; Dwivedi and Ramaswamy, 2008, 2010a,b). In a recent study by Dwivedi and Ramaswamy (2010), the heat transfer rates were compared between end-over-end and axial modes in particles suspended in Newtonian fluid (glycerin). Hassan (2011) extended the above work for biological validation by carrying out detailed studies on microbial destruction kinetics in spore immobilized particles. However, in most of the canned liquid particulate food systems, the liquid shows non Newtonian nature; hence this study was performed to compare the heating behavior of the particles suspended in

non Newtonian fluids subjected to different modes of canning (free axial, end-over-end, fixed axial and still mode). Furthermore, the effect of the thermal treatments will be related to quality changes that will take place in potato particles.

3.3 Materials and methods

3.3.1 Water bath experiments

Heat transfer studies conducted previously by Hassan (2011), employed Nylon spheres (diameter 1.9 cm) which are assumed to be good simulating particles for matching the heating behavior of foods. In order to predict the processing times for this study, firstly the potato cubes of different sizes were prepared. Copper-constantan thermocouple wires (diameter = 0.0762 mm, Omega Engineering Corp, Stamford, CT, USA) were introduced into the centre of the cubes such that the thermocouple junction is placed at the geometrical centre of the cube (Figure 3.2). Thermocouples were connected to a data acquisition switch unit (HP34970A, Hewlett Packard, Loveland, CO, USA) which in turn was connected to a computer to record the temperature readings at regular intervals of 1 second. A water bath (Thermo Electron Corporation, HAAKE C10, MA, USA) set at three different temperatures (60, 80 and 100°C) was used (one condition at a time). Heating profiles of Nylon and different potato cubes were used to further evaluate heating rate index (f_h) which was used as an index to compare and match the heating behavior of potato particles with those of Nylon.

3.3.2 Liquid and particulate system

The test material, potato samples *(Solanum tuberosum)* of Goldrush variety stored under refrigerated conditions (4°C) were used in this study. Using a sharp knife, samples were prepared as cubes of the size obtained from the water bath experiments. After blanching the potato cubes

for 1 min at 100˚C in boiling water, by using aqueous solution of carboxy methyl cellulose (1%) as the covering liquid and by keeping 10 mm headspace, the contents were sealed in 307x409 sized cans in ratio 30% v/v with help of manually operated seaming machine (Home Canning Co., Montreal, QC, Canada).

3.3.3 Processing experimental setup

For the processing experiments, a pilot scale rotary, single cage, full water immersion retort (Stock Rotomat PR900, Hermann Stock Maschinenfabrik GmbH, Neumŭnster, Germany) was used. Dummy cans were filled with water and placed in retort along with actual experimental cans to provide ballast. The cans undergoing agitation in End-over-end, fixed axial mode were held inside the cage and the cans undergoing the free (bi) axial rotation were positioned along the frame of the cage (Figure 3.1). Stainless steel supports attached to retort basket were used to hold the cans which ensured movement cans along the inside wall of retort shell in free axial mode. For the experiments in still mode, the cage was kept stationary and the cans were held inside the retort cage.

Figure 3.1: Stock Rotomat – PR900 and experimental set up

3.3.4 Temperature measurements

Temperature data gathering was done during processing on real time basis. The cans for EOE and Fixed axial modes were fitted with CNS 24 gauge Teflon coated copper-constantan needle (T-type) thermocouples (Ecklund Harrison, Miami, FL, USA) so as to record temperature of can liquid. In order to gather particle center temperature a technique developed by Sablani and Ramaswamy (1996) was used (Figure 3.2). Flexible copper-constantan thermocouple wires (diameter = 0.0762 mm, Omega Engineering Corp, Stamford, CT, USA) whose junction was placed at the particle center (Figure 3.2) were used to record temperature data. Thermocouple signals were recorded at 10 second intervals by using data acquisition switch unit (HP34970A, Hewlett Packard, Loveland, CO, USA). The wires from these cans positioned in the cage were passed through 32 slip ring assembly using 24 AWG copper-constantan thermocouple wires (Omega Engineering Corp. Stamford, CT, USA). Tracksense[®] Pro, a FDA compliant wireless logger (Ellab Inc., Centennial, CO, USA) was attached to the can in free axial mode, in such a manner that its tip is placed in close proximity of geometrical center of the can so as to gather temperature of can liquid (Figure 3.2). The recorded data from the wireless logger was obtained in computer by using a USB connected four port TrackSense[®] Pro Master Reader Station (Ellab Inc., Centennial, CO, USA).

3.3.5 Lethality and cook value calculations

The improved general method was used to calculate the accumulated lethality value (F_o) at particle centre and at geometrical centre of can. The following numerical integration was performed to calculate lethality:

$$F_o = \int 10^{(T-121.1)/10} dt \qquad\qquad (3.1)$$
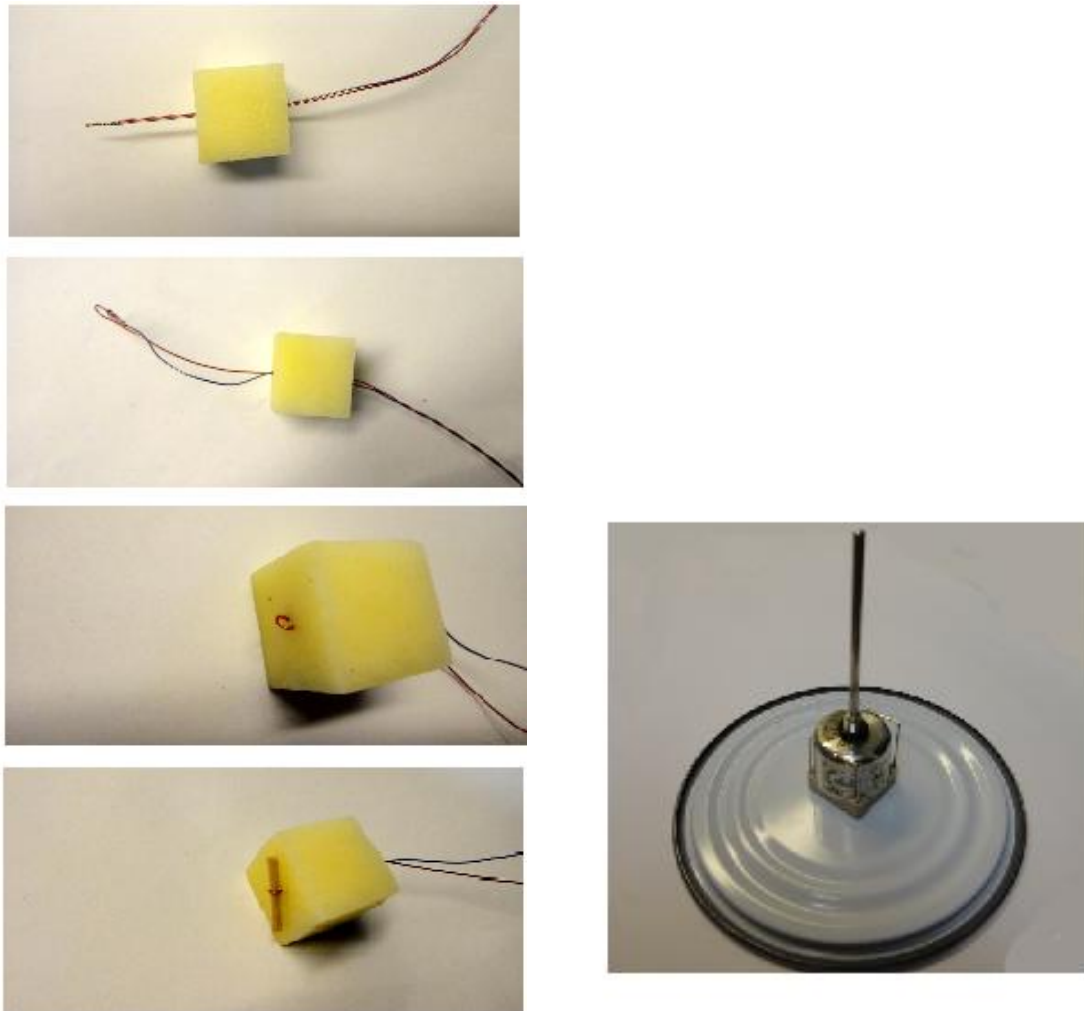
Figure 3.2: Thermocouple and wireless sensor attachment

A cook value of the process C_o was computed as equivalent minutes of heating at 100 °C with z value of 33 °C (Eisner, 1988). Cook value was also computed by using numerical integration technique.

$$C_o = \int 10^{(T-100)/33} dt \qquad (3.2)$$

For these values deduced for each processing condition corresponding to time-temperature data at particle center and geometrical center of can, the ratio C_o/F_o was also computed. The C_o/F_o

ratio gives indication of degree of cooking that takes place in product especially when the processing conditions are varying (Abbatemarco and Ramaswamy, 1994).

3.3.6 Statistical analysis

Statistical analysis of data was performed by using IBM$^{®}$SPSS$^{®}$ statistical package and student t-test in Microsoft excel. Analysis of variance (ANOVA) was conducted and the significant differences were computed between the means with Least Square Difference (LSD) range test *(p < 0.05).*

3.4 Results and Discussions

3.4.1 Heating patterns of Nylon and potato particles

In order to compute the processing conditions for the retort experiments; firstly, studies involving matching of heating rate indices of nylon with that of potatoes was performed in a water bath for simplicity. From the previous studies, mean f_h value for Nylon (diameter 1.9cm) was obtained to be 139s at three different temperatures, 60, 80, 100˚C. Logarithm of ($T_{water \, bath}$ − $T_{particle \, center}$) was plotted versus time and heat penetration curve was obtained. Heating rate index was calculated as negative reciprocal of the slope of straight line portion of the heat penetration curve and it represents the time taken by straight line portion of curve to traverse one log cycle of heating. Similarly to the data available for Nylon spheres, the heating rate indices for potato cubes were evaluated at 60, 80 and 100˚C. The f_h value for potatoes was found to be ranging between 124 and 230s for the 1.4 to 2.0cm cubes. Statistical analysis of variance (Table 3.1), revealed that there was no significant difference *(p>0.05)* between f_h values at different temperatures for the particles of same size and this result was in consensus with the previous studies. Whereas significant differences *(p<0.05)*, were observed in f_h values when the particle

sizes employed were different. For instance, by increasing the particle size from 1.5 to 1.6 cm, and from 1.8 to 1.9 cm, f_h values were found to increase by 7% and 9%, respectively. This finding was also in accordance with the previously reported results (Heldman & Hartel, 1997; Hassan, 2011) and this is attributed to the fact that, larger particles heat at a slower rate than the smaller particles.

Table 3.1: Analysis of variance for f_h of potato cubes in water bath studies

Tests of Between-Subjects Effects

Dependent Variable: f_h

Source	Type III Sum of Squares	Mean Square	F	Sig.
Temp	633.409	316.705	1.336	.275
Size	29014.021	4835.670	20.400	.000

Potato cubes cut to 1.6cm size cube depicted similar heating behavior to that of Nylon spheres of 1.9 cm in diameter (Figure 3.3). Based on the heat transfer studies performed previously on nylon spheres, the nominal processing times for providing three different lethality values at each temperature were selected (Table 3.2).
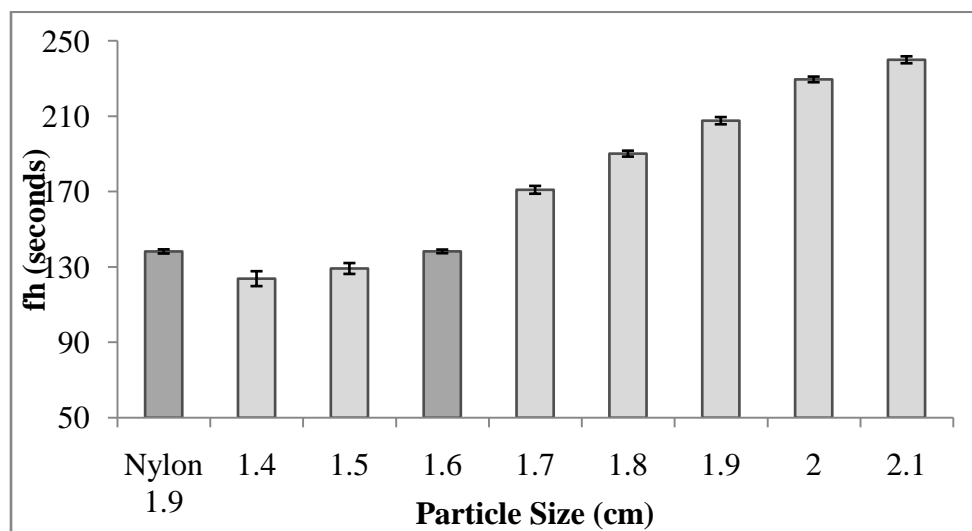
Figure 3.3: Heating rate index of nylon and potato cubes in water bath studies

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Table 3.2: Processing conditions evaluated from water bath studies

| PROCESSING CONDITIONS | | | MODES |
Temperature (˚C)	Rotation Speed (rpm)	Time (min)	OF ROTATION
115	0	70, 85, 100	Still
120	10	25, 30, 35	EOE, Axial
125	20	10, 12, 14	EOE, Axial

3.4.2 Heating behavior during thermal processing in the retort

Thermocouples attached at particle center, can's geometrical center and at retort shell were used to record the respective heating profiles. Retort (T_R) temperature profile, liquid temperature (T_L) profile and particle center temperature (T_{pc}) profiles were recorded by T type thermocouples and Figure 3.4 shows the heating profiles recorded at 120˚C, 10 rpm in end-over-end mode. These profiles are also the representation of typical heating profiles achieved in the different experiments carried in this study.

The heat flow during the canning process takes place in a sequential manner. Initially, the heat transfer takes place from water (retort heating medium) to can liquid through the can wall. Then, the heat traverses through the can liquid to the particle surface and furthermore, the heat travels to the center of the particle. This can also be seen from the experimental data gathered that, the temperature profiles of can liquid and particle center lags behind the time-temperature profile of heating medium.
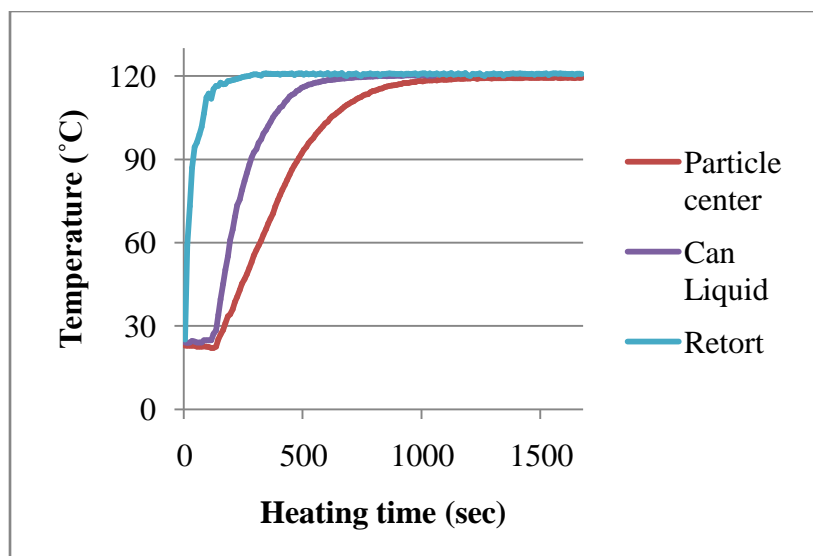
Figure 3.4: Heating profiles of retort, can liquid and particle center at 120°C, 10rpm in EOE mode

Similar types of trends were observed in the heating profiles for all other experimental runs as well. The retort come up time was found to be approximately 4.5 min, which was similar to the results reported by Sablani and Ramaswamy (1996); Meng and Ramaswamy (2006); Dwivedi and Ramaswamy (2008).

The particle center and can liquid data gathered by thermocouples attached to the cans rotating in different modes (end-over-end, fixed and free axial) were also compared. Figure 3.5 shows the liquid heating profiles recorded during processing at 120°C, 10 rpm.

From Figure 3.5, it can be inferred that heating profiles of can liquid (CMC) demonstrate different trends in different modes. The liquid profile in fixed axial mode lags behind the liquid heating profiles in EOE and free axial modes. The liquid in free axial mode is found to heat most rapidly than all other modes of processing. Under still mode (0 rpm) of processing, the prevailing heat transfer mode is mainly natural convection as compared to forced convection mode that prevails when cans are processed under agitating conditions. Therefore, the temperature-time
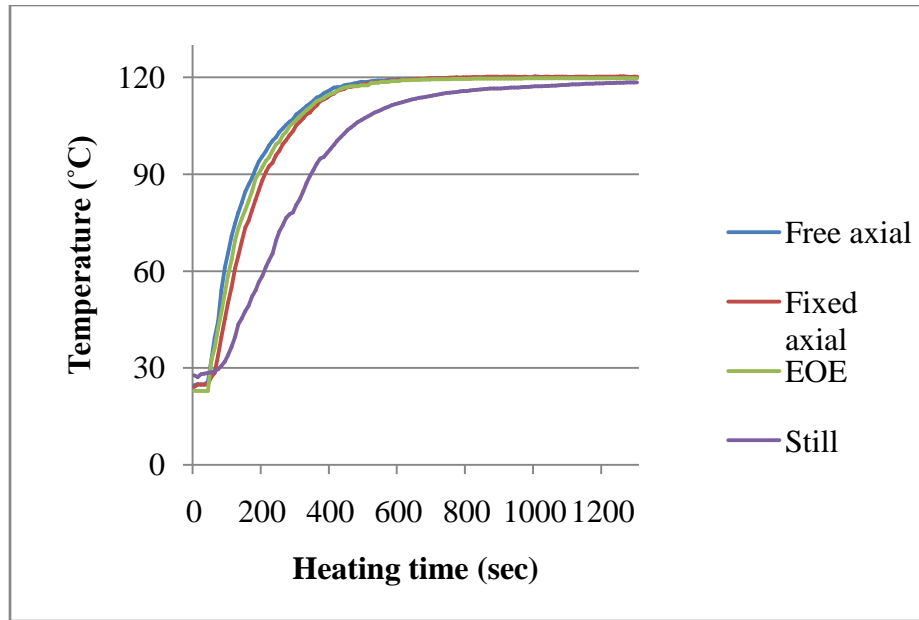
Figure 3.5: Liquid heating profiles at 120˚C, 10rpm in EOE mode

profile of can liquid under still mode lags behind that of agitating modes by a considerable

margin. Similar results were also reported by Dwivedi and Ramaswamy (2010) in their study

which was based on comparison of the heating behavior in cans rotating in end-over-end and

both axial modes of rotation. The lags between the heating profiles in different modes can be

attributed to the heat transfer rates associated with respective modes. Due to dual mode of

rotation prevailing in free axial mode the associated heat transfer coefficients are greater than in

end-over-end and fixed axial mode (Dwivedi and Ramaswamy, 2010). Naveh and Kopelman

(1980) also studied heat transfer rates in variety of rotational configurations and found that the

heat transfer in end-over-end mode is approximately 2 - 3 times faster than in fixed axial mode.

The temperature data gathered at the particle center under EOE, fixed axial and still modes of

processing at 120˚C, 10 rpm are presented in Figure 3.6. Trends similar to that of liquid heating

were observed in heating profiles of particle centers. Due to the difficulty in attaching

thermocouples at particle centers in free axial mode, the data was only obtained for the other two agitating modes processing.
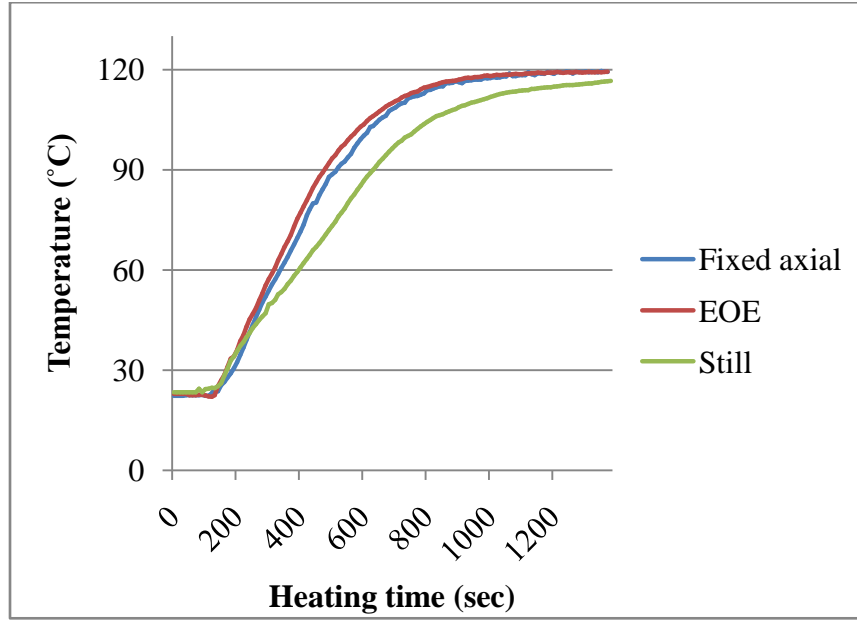
Figure 3.6: Particle heating profiles at 120˚C, 10rpm in EOE mode

3.4.3 Effect of processing variables on heating rate index f_h

The logarithm of (T_R-T_L) and (T_R-T_{pc}) were plotted against time on linear scale to obtain the values of heating rate indices (f_h) for liquid and particle respectively. f_h values give estimate of how fast the heat transfer takes place; faster heat transfer is characterized by lower f_h values and vice versa. The lag in heating curves as observed in results described in 3.4.2 can also be explained on the basis of relative values of heating rate indices.

The three processing times were selected at each temperature in order to achieve three lethality levels. Student t-test was performed for both liquid and particle f_h values obtained at different processing times corresponding to each temperature. The results suggested that there were no significant differences $(p>0.05)$ observed in f_h values when the processing time was varied.

Analysis of variance for liquid heating (Table 3.3), suggests that all the processing variables (temperature, mode and rpm) were found to be significantly *(p<0.05)* influencing the heating rate index. Rotational speed was found to have highest significance (highest mean square/ total, value) followed by mode of rotation and the temperature was found to have least significant effect on f_h in comparison to the other two processing variables.

Figure 3.7 shows the graphical representation of the f_h values of can liquid (CMC) which were obtained from the time-temperature data gathered at geometrical center of 307x409 can. Overall the heating rate index of liquid in still mode (0 rpm) ranged between 7 and 8 min as compared to that of 4 and 6 min in agitating modes (fixed, free axial and EOE). Previous heat transfer studies reported lower heating rate index values at higher rotational speeds and the results found in this study are in consensus with literature studies. The lower f_h values at higher rotational speeds are result of better mixing and rapid heat transfer in the cans. For instance, processing at 120˚C in 20 rpm under free axial, end-over-end and fixed axial modes, the f_h values obtained were approximately 18%, 9% and 12% lower than at 10 rpm, thereby proving the usefulness of rapid heat transfer conditions.

Table 3.3: Analysis of variance for f_h of can liquid (CMC)

Tests of Between-Subjects Effects

Dependent Variable : f_h liquid

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	5.808	5.808	182.755	.000
Temp	1.000	.500	15.733	.000
Mode	5.206	2.603	81.907	.000
RPM * Temp	.064	.032	.999	.378
RPM * Mode	.243	.122	3.830	.031
Temp * Mode	.008	.002	.061	.993
RPM * Temp * Mode	.138	.035	1.087	.377

In the heat transfer study in Newtonian fluid, Dwivedi and Ramaswamy (2010) reported better heat transfer and correspondingly lower f_h values in free axial mode followed by EOE and fixed axial mode. In current study, at 120°C and 20 rpm, f_h values in free axial mode were found to be nearly 14%, 17% and 42% lower than those of liquids subjected to end-over-end, fixed axial and still mode of processing respectively. Similar trends were observed in f_h values at 10 rpm and all these results are in tune with results of previous studies. As the f_h values were found to be increasing in order: free axial, end-over-end, fixed axial and still mode, so this explains the heating behavior depicted in Figures 3.5.
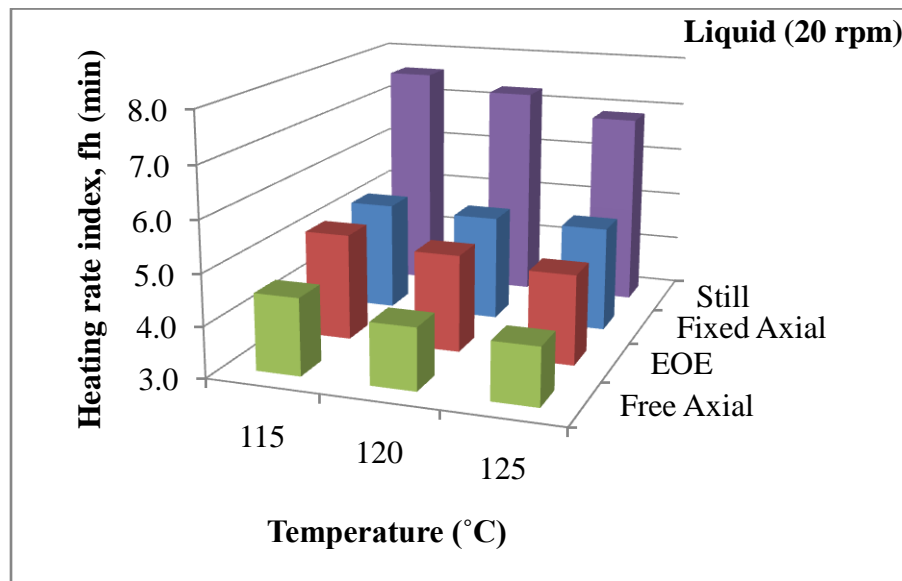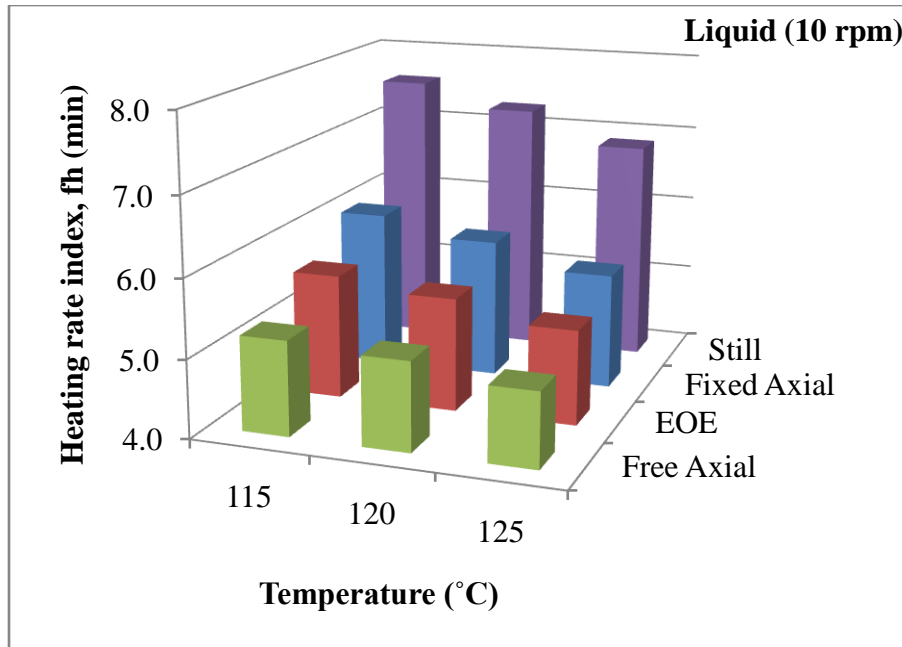
Figure 3.7: Effect of temperature, mode and rpm on heating rate index of liquid

Effect of temperature on heating rate index of liquid is not that prominent as compared to effects of rpm and mode of rotation. But still, the effect of temperature on liquid f_h was found to be significant $(p<0.05)$. With increase in temperature the heating rate index was found to decrease in all the modes of processing both at 10 and 20 rpm. For example, at 10 rpm, liquid in free axial mode depicted mean f_h values to be nearly 4.9% lower at 125˚C than mean f_h values at 115˚C. However these findings with reference to temperature are opposite to the findings of Abbatemarco and Ramaswamy (1994). This could be a result of using different test fluids CMC solution in current studies as compared to starch preparations in Abbatemarco and Ramaswamy (1994).

The interactive effects of the processing variables correspond that, out of all the different two way combinations, only the (rpm*mode) combination was found to be significantly influencing $(p<0.05)$ the heating rate index of liquid. This result can be attributed to the findings that rotational speed and mode of processing are the major factors influencing the heating behavior of can liquid.

Analysis of variance for particle heating (Table 3.4) showed that all the processing variables studied had significant influence $(p<0.05)$ on the heating rate index. Although, the heating rate index decreased with increasing temperature but the reduction was not that significant as compared to the other processing parameters. The interactive effects of all the processing variables studied were found to be insignificant $(p>0.05)$.

Table 3.4: Analysis of variance for f_h of potato cubes

Tests of Between-Subjects Effects

Dependent Variable : f_h particle

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	5.244	5.244	121.869	.000
Temp	.694	.347	8.060	.002
Mode	5.808	5.808	134.976	.000
RPM * Temp	.110	.055	1.279	.297
RPM * Mode	.090	.090	2.092	.161
Temp * Mode	.022	.011	.258	.775
RPM * Temp * Mode	.027	.014	.319	.730

The f_h values for particle heating as influenced by temperature, mode of processing and rotational speed are presented as bar graphs in Figure 3.8. Similar trends to that of liquid heating rate index were observed in particle heat rate indices as well. Owing to better and faster heat transfer at higher rotational speed, particle's f_h values in still mode (0 rpm) were found to be approximately 43% and 31% higher than the corresponding values in EOE and fixed axial modes at 20 rpm respectively. At all processing conditions employed particle f_h in EOE mode were found to be lower than particle f_h in fixed axial and still mode.
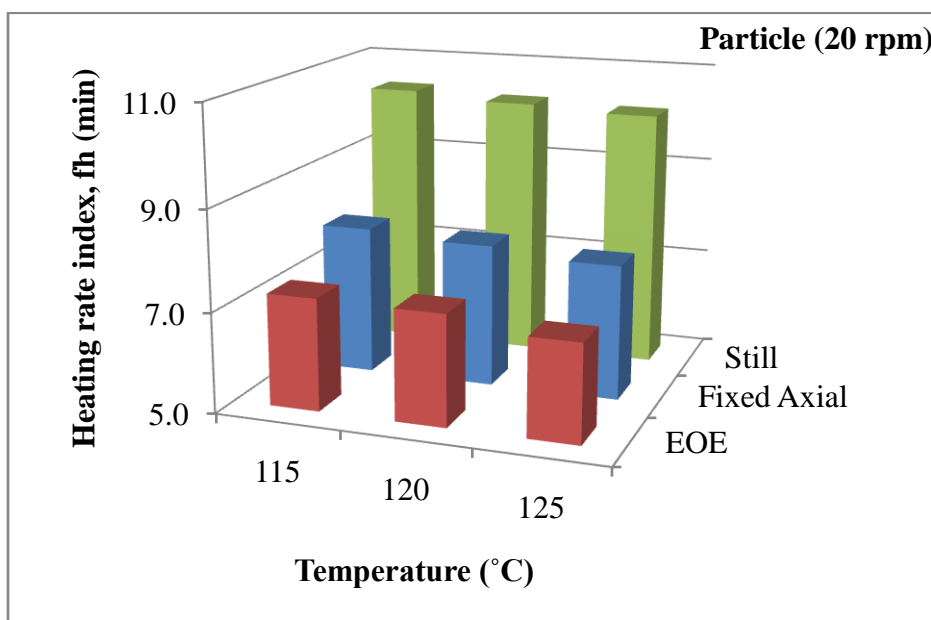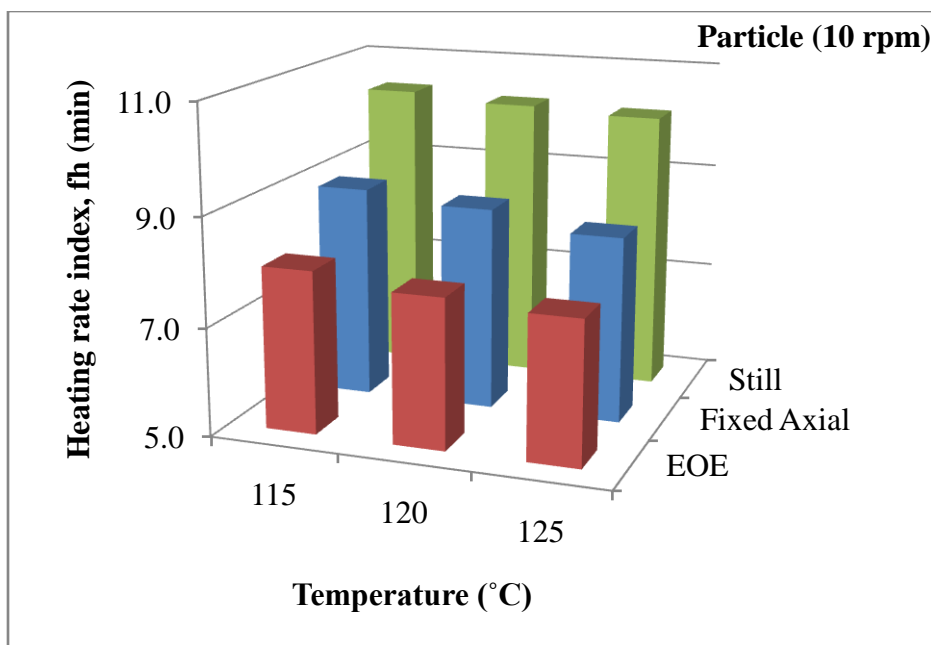
Figure 3.8: Effect of temperature, mode and rpm on heating rate index of particle

As the particle center data for free axial mode was not available, the f_h values in free axial modes could not be calculated. However, as the liquid f_h values are lower in free axial mode as compared to all other modes of processing, so it can be safely concluded that better heat transfer rates exists in free axial mode; therefore, the particles in free axially rotating cans will also be heating at faster rate than the particles subjected to other modes of processing. Compared with heating rate indices of particles, the f_h values for liquid were found to be approximately 27–36% lower in magnitude. These results followed the expected trends as the convective heat transfer associated with liquid heating is always faster than the conduction heat transfer associated with potato particles; as a result the heating rate index for liquid is lower than the particles.

3.4.4 Effect of processing variables on process lethality (F_o), cook value (C_o) and C_o/F_o values

A valid thermal process is based on the fact that adequate amount of heat has been delivered at the most critical point in the food. Process lethality (F_o value) is the most commonly used parameter that is used in thermal processing industry in order to define adequacy of thermal process. In rotational processing the main objective is to deliver appropriate amount of heat in short period of time so as to have minimal damage to food quality. Another parameter, cook value (C_o) that indicates equivalent amount of heating minutes at 100 ˚C is also very useful parameter, that can be further used to calculate C_o/F_o ratio, which is a measure of degree of cooking. The parameter C_o/F_o ratio gives indication of relative degree of cooking taking place in the product when the processing conditions are varying (Abbatemarco and Ramaswamy, 1994). The processing factors that promote better heat transfer eventually results in increase in F_o and C_o values but, they are marked by corresponding decrease in C_o/F_o values.

T-test was performed to evaluate effect of time on lethality, cook value and C_o/F_o ratio. Keeping temperature and rotational speed constant, F_o and C_o were found to be significantly increasing $(p<0.05)$ with increase in processing time at particle center and in liquid in all the modes of processing (fixed axial, end-over-end, free axial and still) whereas, the C_o/F_o ratio was found to be invariable $(p>0.05)$ under these conditions. For example, for particles at 115 °C and 10 rpm, F_o value increased from 13.6 min to 20.8 min when processing time was increased from 70 min to 100min in fixed axial mode of processing. Similar trends were observed with respect to effect of time in other processing modes. This increase is because more amount of heat is delivered when the heating time is increased that consequently results in higher lethality and cook values. In all the experimental runs, F_o and C_o for liquid heating were found to be higher in Free axial mode, followed by end-over-end, fixed axial and still modes. Similar trends were observed for particle heating as well. These trends can be justified based on the fact that better heat transfer exists in free axial mode of rotation than other three modes of processing.

Analysis of variance of C_o/F_o values achieved under different experimental conditions suggested significant effect of the processing variables on the degree of cooking (Table 3.5, 3.6). From Table 3.5 it can be inferred that in liquid heating the influence of temperature was most prominent and effect of mode of processing was found to be comparatively less significant $(p<0.05)$. Rotation speed was found have to have no significant $(p>0.05)$ effect on degree of cooking (C_o/F_o) in liquid. Similarly Table 3.6 elucidates that temperature has the most significant effect on C_o/F_o in potato particles followed by mode of rotation and speed of rotation. Contrary to the liquid heating, in case of particle heating the effect of rpm on degree of cooking was found to be significant $(p<0.05)$. The interactive effects of rpm, temperature and mode were found to be statistically insignificant $(p>0.05)$ for both liquid and particle heating.

Table 3.5: Analysis of variance for C_o/F_o ratio of can liquid

Tests of Between-Subjects Effects

Dependent Variable : Co/Fo Liquid

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	.213	.213	1.909	.170
Temp	1230.271	615.136	5.505E3	.000
Mode	15.201	7.601	68.018	.000
RPM * Temp	.218	.109	.977	.380
RPM * Mode	.097	.048	.432	.650
Temp * Mode	.932	.233	2.085	.089
RPM * Temp * Mode	.107	.027	.239	.916

Table 3.6: Analysis of variance for C_o/F_o ratio of potato cubes

Tests of Between-Subjects Effects

Dependent Variable: Co/Fo particle

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	5.769	5.769	11.173	.001
Temp	558.859	279.429	541.226	.000
Mode	7.258	7.258	14.058	.000
RPM * Temp	1.434	.717	1.389	.257
RPM * Mode	.026	.026	.050	.824
Temp * Mode	.038	.019	.037	.964
RPM * Temp * Mode	.129	.064	.125	.883

Figures 3.9 and 3.10, shows the bar graphs representing C_o/F_o values of liquid and particle heating respectively. The mean C_o/F_o value decreased dramatically by 70% in liquid and by 58% in particle when temperature was raised from 115 to 125°C under fixed axial mode of processing. For both liquid and particle increase in temperature from 115°C to 120°C and further to 125°C resulted in significant reduction in degree of cooking *(p<0.05)* demonstrating high temperature short time processes' usefulness. The better heat transfer in biaxial mode was marked by considerably lower degree of cooking as compared to other modes of processing. At 120 °C, C_o/F_o value of liquid for free axially rotating can was found to be approximately 56%, 14% and 8% lower than corresponding C_o/F_o values in still, fixed axial and end-over-end modes of processing respectively.

The overall results indicate that lower temperature and lower rotational speeds results in increase in C_o/F_o ratio and vice versa. Lowest C_o/F_o values were observed in free axial mode followed by end-over-end, fixed axial and still mode of processing. These results were obtained because in free axial mode of processing cans rotate in two axes thereby resulting in rapid heat transfer as compared to other three modes of processing.
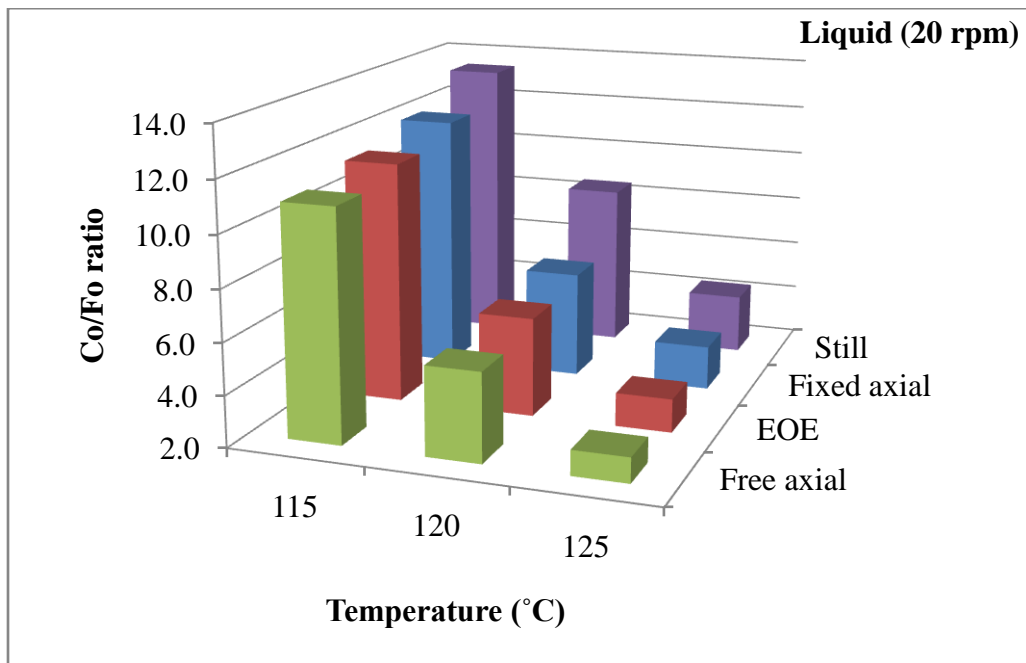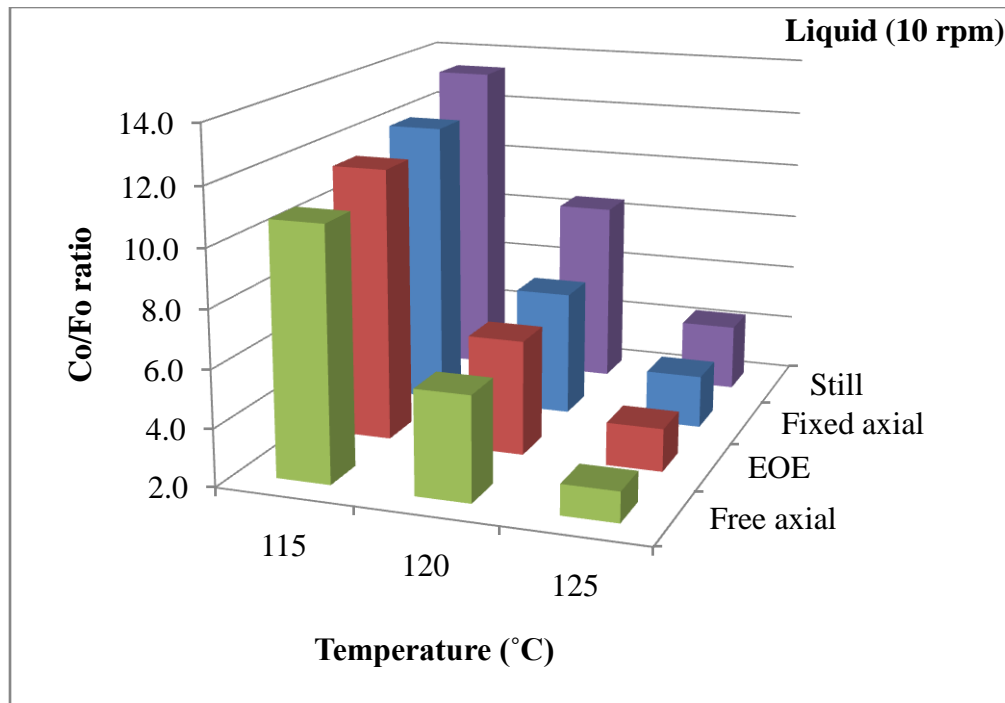
Figure 3.9: Effect of temperature, mode and rpm on C_o/F_o ratio of liquid
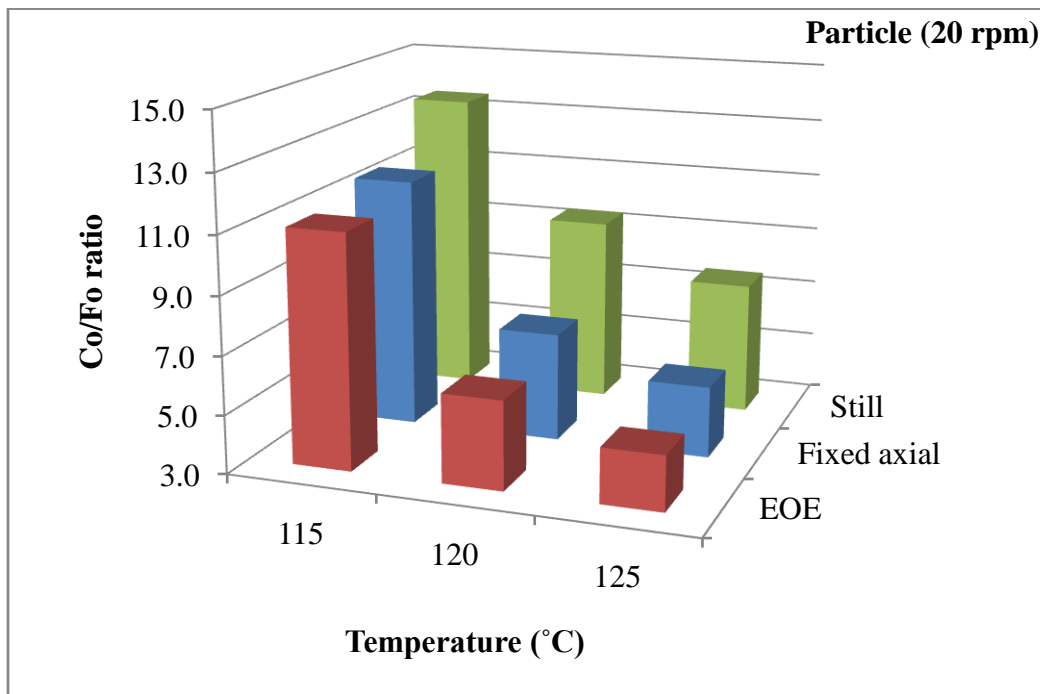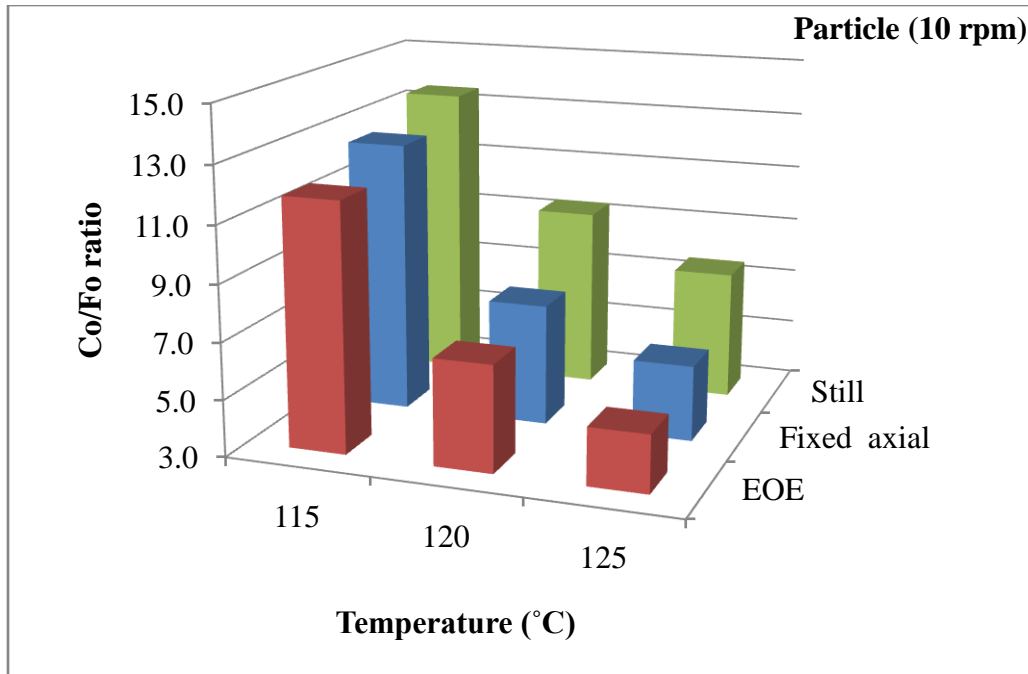
Figure 3.10: Effect of temperature, mode and rpm on C_o/F_o ratio of particles

3.5 Conclusions

The heating behavior of Nylon particles matched to that of 1.6x1.6x1.6 cm potato cubes. Processing conditions were selected based on the previous studies conducted on Nylon particles. In non-Newtonian liquid medium (1% CMC), rotational speed and mode of rotation showed greater effects on heating behavior and heating rate index, followed by temperature. Results indicated that higher rotational speed resulted in considerably lower lag times in heating which were also characterized by lower f_h values. Lowest f_h values for liquid and particles were found in free axially rotating cans followed by cans in end-over-end, fixed axial and still mode of processing. These findings corresponds that better heat transfer takes place in free axially rotating cans. Apart from these, all the factors that improve heat transfer rate were found to result lower C_o/F_o values which is a clear indication of better quality retention. The corresponding effects of these processing conditions on quality attributes of particles are discussed in Chapter 4.

PREFACE TO CHAPTER IV

The previous chapter was focused on heat transfer issues related to processing of potato cubes suspended in CMC solutions under various modes of rotation. For optimization of thermal processing, maximizing quality retention during processing has been the main basis for many studies. Most of the optimization studies under agitation processing have been focused on end-over-end mode of. Many products available commercially such as vegetable soups, vegetable pieces and meat chunks suspended in gravy etc. are best characterized by particulate canned foods in non-Newtonian fluids and in continuous flow systems. Hence, it was of prime importance to evaluate the associated quality changes due to thermal processing in similar food systems.

The quality of processed food can be best described by its appearance and mouth feel. Therefore, important color (L, b, ΔE values) and texture (hardness, chewiness, gumminess) parameters were studied during processing of 1.6 cm x 1.6 cm x 1.6 cm potato cubes suspended in 1% carboxy methyl cellulose solution, which were subjected to different modes of processing. Furthermore, the extent of changes in these quality parameters was correlated with corresponding heat treatments imparted. These form the basis for the next chapter.

Part of this research was presented in 2011 in Northeast Agricultural and Biological Engineering Conference, NABEC (Vermont, USA). Manuscript for publication in scientific journal has been prepared. The experimental work and data analysis were carried out by the candidate under the supervision of Dr. H. S. Ramaswamy.

Chapter IV

EVALUATION OF THE INFLUENCE OF PROCESS VARIABLES ON COLOR AND TEXTURE OF POTATOES CANNED IN A NON-NEWTONIAN FLUID SUBJECTED TO DIFFERENT MODES OF RETORT PROCESSING

4.1 Abstract

Color and texture changes in potatoes as a result of thermal treatments in retort processing were evaluated. Potato cubes were cut into sizes of 1.6x1.6x1.6 cm, filled in 307x409 cans, covered with 1% aqueous solution of carboxy methyl cellulose (CMC). The processing was done in a pilot scale full immersion rotary retort as described in previous chapter. Color indicators L, b and ΔE values and texture parameters hardness, chewiness and gumminess were evaluated for the particles processed under each condition. After processing at the same temperature, significant differences *(p<0.05)* were observed in color and texture parameters of particles as a result of all processing variables (time, rpm and type of mode). Due to more heat penetration in biaxial mode the processed particles were dark (lower L and higher b values) as compared to other modes of rotation. Hardness, gumminess and adhesiveness were found to be lowest in biaxial mode while processing at 115 ˚C as compared to 120 ˚C and 125 ˚C. Lowest quality destruction was observed in still mode of processing as a result of lesser heat transfer taking place than the agitating modes under same processing conditions.

4.2 Introduction

The low acid vegetables are usually preserved in canned form so as to ensure their availability throughout the year. The thermal treatments imparted during the canning of vegetables have to meet the criterion of commercial sterility. Desired lethal effect can be provided in wide range of temperature-time combinations; if the temperature is small then the processing time has to be longer and vice versa. During the processing of vegetables, physical, chemical and various organoleptic modifications take place which are inevitable to a certain extent. But the rapid heating mechanisms promise to cause lesser modifications in the quality parameters during processing of the vegetables. The rapid and uniform heating helps to achieve target lethality in less amount of time which consequently results in lesser degradation of texture, color and nutrients in foods. Moreover, rapid heating results in efficient processing outputs and reduced energy consumption as well.

Although, the thermal processing is considered to impart negative influence to the quality of processed foods but, apart from providing microbiological safety there are few beneficial effects of thermal processing as well. The cooking effect during the thermal processing is quite beneficial at times as it can significantly reduce the cooking time required by the consumers; hence the texture softening that takes place during processing is acceptable to a certain extent. Moreover, few studies have demonstrated the positive influence of thermal treatments on nutritional attributes of few vegetables as well. Roy *et al*. (2007) reported an increase in antioxidant activity due to thermal processing of selected vegetables. In another study, Dewanto *et al*. (2002) found that thermal processing enhanced the nutritional value of tomatoes by increasing lycopene content and the antioxidant activity as well. Hence such findings encourage

consumers towards thermally processed vegetables and fruits, which as such have been considered to be of poor quality (Dewanto *et al*., 2002).

The food processing industry should aim to achieve balance between the conducive and harmful effects of the thermal processing (Balsa-Canto *et al*., 2002). Hence the basis for optimization of thermal process should be to impart required lethal effect to ensure microbiological safety and to simultaneously reduce the extent of thermal damage on color, texture and nutritional attributes. As a very important external quality attributes, color and texture have been receiving great deal of attention from various researchers.

Visual appearance of the food is the first thing that influences buying behavior of customers. Color is an important component of the visual appearance that can be represented in three dimensions that represents responses of three different (red, green and blue) receptors in human eye (Francis, 1995). Color changes as a result of thermal treatments have been studied by many researchers (Rao *et al*., 1981; Gnanasekharan *et al*., 1992; Abbatemarco and Ramaswamy, 1994; Shin and Bhowmik, 1995; Ahmed *et al*., 2002a, b; Nourian and Ramaswamy, 2003; Smout *et al*., 2003; Garrote *et al*., 2008).

The texture of vegetables is mainly due to the properties of pectic substances that provides adhesion and keeps the cells together (Loh and Breene, 1982). During thermal processing, these pectic substances undergo chemical changes; the native protopectin breaks down in the interlamellar layer mainly via β – elimination or β-dealkoxyation reactions (Loh and Breene, 1982). These complex chemical changes results in dispersal of the plant cells thereby causing the softening of the vegetable tissue (Huang and Bourne, 1983). The extent of softening influences the acceptance of the processed product and hence it is very important to study the textural

changes that take place during thermal processing of vegetables. Thermal softening of potato tissue has been studied by many researchers (Alvarez and Canet, 2002; Solomon and Jindal, 2003; Lebovka *et al*., 2004). The two mechanisms that are responsible for the softening of potato tissue are mainly due to changes in pectic substances in cell wall in inter-lamella and due to gelatinization of potato starch (Alvarez *et al*., 2001). Moyano *et al*. (2007) have also studied the textural changes in potato products as influenced by different types of thermal treatments.

Most of the quality studies in vegetables have been performed on the rotary processing in end-over-end mode or in fixed axial mode of processing. No literature on the quality evaluation studies was found when the processing in bi/free axial mode was done. Hence the objective of this study was to evaluate the quality changes taking place in potato particles suspended in non Newtonian fluid and subjected to different modes of canning (free axial, end-over-end, fixed axial and still mode).

4.3 Materials and methods

4.3.1 Preparation of cans and thermal treatments

Test cans were prepared by following the same methodology as described in Chapter 3. Processing conditions deduced in Chapter 3 were employed and after processing the potato particles were recovered from cans for quality analysis.

4.3.2 Color analysis

Analysis of color was performed by using Tristimulus Minolta Colorimeter (Minolta Corp., Ramsey, NJ, USA). Hunter's color parameters for the processed particles were recorded in computer by software (SpectraMagic, Minolta Corp., Ramsey, NJ, USA). The total color difference, ΔE was obtained using equation (2.21).

4.3.3 Texture analysis

The texture analysis was done by using TA-XT Plus Texture Analyzer (Texture Technologies Corp., Scarsdale, NY/ Stable Micro Systems, Godalming, Surrey, UK). A 2 kg load cell and circular aluminum probe was used to perform double mode compression test. The texture profile was generated by keeping pre-test, test and post test speeds of 1.0, 1.5 and 1.5 mm/s respectively. Various texture parameters were obtained from texture profiles by using Texture Exponent 32 software (Texture Technologies Corp.).

4.3.4 Statistical analysis

Statistical analysis of data was performed by using IBM$^{®}$SPSS$^{®}$ statistical package. Analysis of variance (ANOVA) was conducted and the significant differences were computed between the means with Least Square Difference (LSD) range test *(p < 0.05)*.

4.4 Results and discussions

4.4.1 Lethality

The extent of quality degradation can be related to the lethality values achieved in food during processing if the processing times are not adjusted to result in equivalent lethality. The lethality values (Fo) were calculated by using numerical integration method (Equation 3.1) and the lethality values achieved at particle center are summarized in Table 4.1.

According to the heat transfer results reported in Chapter 3, it is clear that under same processing conditions better heat transfer is achieved in free axial mode followed by end-over-end, fixed axial and still mode of processing. These trends are visible from F_o values achieved at particle center that are presented in Table 4.1. Although, the F_o values at particle centers under free axialmode of processing could not be computed but from data gathered for liquid heating it was

Table 4.1: Lethality values achieved at particle center

Temp. (˚C)	Time (min)	Fixed(10rpm)	EOE(10rpm)	Fixed(20rpm)	EOE(20rpm)	Still (0rpm)
	70.0	13.62 ± 0.59	15.21 ± 0.94	16.67 ± 0.49	17.93 ± 0.55	11.66 ± 0.63
115 C	85.0	17.38 ± 0.41	18.98 ± 1.07	20.47 ± 0.57	21.84 ± 0.39	15.18 ± 1.16
	100.0	20.77 ± 0.52	23.08 ± 0.42	24.06 ± 0.37	25.19 ± 0.44	18.94 ± 1.03
	25.0	7.75 ± 0.76	9.51 ± 0.57	10.57 ± 0.57	11.72 ± 0.49	4.11 ± 0.62
120C	30.0	12.06 ± 0.52	13.23 ± 0.78	14.64 ± 0.64	16.99 ± 0.54	7.03 ± 1.20
	35.0	15.76 ± 0.44	16.37 ± 0.22	18.39 ± 0.60	20.66 ± 0.66	10.09 ± 0.45
	10.0	2.14 ± 0.30	3.05 ± 0.87	2.71 ± 0.25	3.25 ± 0.46	1.17 ± 0.08
125C	12.0	3.97 ± 0.35	6.06 ± 0.40	5.65 ± 0.62	6.75 ± 0.51	2.31 ± 0.14
	14.0	9.30 ± 0.27	10.80 ± 0.81	10.94 ± 0.60	11.99 ± 0.28	3.44 ± 0.18

observed that cans in free axial mode receives more heat than other modes when processed under similar conditions. Hence it can be safely assumed that the F_o values achieved at particle center were highest in free axial mode of rotation.

From Table 4.1 it can be seen that in all the modes of processing, F_o values increased with increase in time at all the three temperatures (115, 120, 125 ˚C) employed in this study. Also with increase in rotational speed, better mixing of the can contents is achieved and consequently higher F_o values were obtained. Higher F_o values were observed at 20rpm than 10rpm in all the modes of rotational processing and overall the rotational modes of processing were characterized by higher lethality values as compared to still mode of processing.

4.4.2 Effect of processing variables on visual appearance

The external appearance of any food greatly influences its acceptability by customer. During handling, storage, processing, packaging and transporting the color of food products change due to many influencing factors. In current study the visual appearance changes taking place in potato cubes during processing were studied and they were quantified in terms of lightness (L-value), yellowness (b-value) and total color difference (ΔE) values.

Lightness or L-value is an indicator of brightness of food. It is quite useful parameter for investigating effects of processing parameters (rpm, temperature, time, and mode) on visual appearance of potato cubes. Effect of time did not show any consistent trend in L-values of potato cubes. Although at few instances processing for longer time at a temperature resulted in dark (low L-value) products. But due to lack of consistency in the trend with reference to time, the L-values at different times while keeping all other conditions constant were taken as single values and their mean values were compared further.

Analysis of variance of L-values of potato cubes are Tabulated in 4.2. From Table 4.2 it can be concluded that all the parameters studied except speed of rotation had significant effect on lightness values *(p<0.05)*. Influence of temperature on lightness values of potato cubes is more remarkable than the mode of processing. For example, by increasing the temperature from 115 to 125˚C in free axial mode at 20rpm, approximately 14% increase in lightness was observed.

The lightness values of the processed potatoes were found to be inversely proportional to lethality values achieved in the potato cubes. Higher values of lethality achieved in particles were characterized by lower L-values (i.e. dull and darker products) which further indicate that, the extent of quality loss was directly proportional to lethality values achieved. Figure 4.1 shows

the graphs of L-values of processed potatoes. Rotational processing demonstrated higher lethality values as compared to still processing hence, the potato cubes in end-over-end and both axial modes of rotation were found to be dark (lower L-values) than the potato cubes in still mode of processing. Similar results were reported by Abbatemarco and Ramaswamy (1994) and Jobe (2003). Based on the results presented in Figure 4.1, under same rotational processing conditions, darker products (lower L-values) were obtained from processing in free axial mode, followed by lighter products in end-over-end and then in fixed axial mode. For instance, at 115°C, 20rpm mean L-value of potato cubes processed in free axial mode were found to be approximately 5% and 7% lower than potato cubes in end-over-end and fixed axial modes respectively. Out of all the interactive effects studied, only the two way effects of rpm and mode with temperature were found to be significant in influencing the L-values *(p<0.05)*.

Table 4.2: Analysis of variance for Lightness values of potato cubes

Tests of Between-Subjects Effects				
Dependent Variable: LIGHTNESS				
Source	**Type III Sum of Squares**	**Mean Square**	**F**	**Sig.**
RPM	.970	.970	.761	.384
TEMPERATURE	1214.817	607.409	476.787	.000
MODE	153.468	76.734	60.233	.000
RPM * TEMPERATURE	25.848	12.924	10.145	.000
TEMPERATURE * MODE	40.804	10.201	8.007	.000
RPM * MODE	2.680	1.340	1.052	.351
RPM * TEMPERATURE * MODE	9.884	2.471	1.940	.104

Yellowness (b-value) values investigated in this study were found to be significantly influenced *(p<0.05)* by all the processing parameters. Likewise lightness values, b-values were also most influenced by temperature, followed by mode of rotation and rotational speed (Table 4.3).

Comparison of the mean effects showed that yellowness of potato cubes is also directly proportional to the accumulated lethality achieved in the potato particles. As color of untreated potato samples ranged from white to slightly yellow and the mean b-value for raw unprocessed sample was found to be 1.74. So after processing the b-values of potato cubes were found to increase significantly *(p<0.05)*. Figures 4.2(a); (b) show the mean b-values of potato cubes as influenced by processing variables.

The potatoes in free axial mode demonstrated 27% and 30% more yellowness (b-values) respectively than the particles processed under end-over-end and fixed axial mode of processing at 120˚C, 10rpm. When the speed of rotation was increased from 0 to 10rpm and then from 10 to 20rpm in free axial mode, the mean b-values were also found to enhance by 61% and 36% respectively. Similar trends in b-values of potato cubes were observed in end-over-end and fixed axial modes of processing.
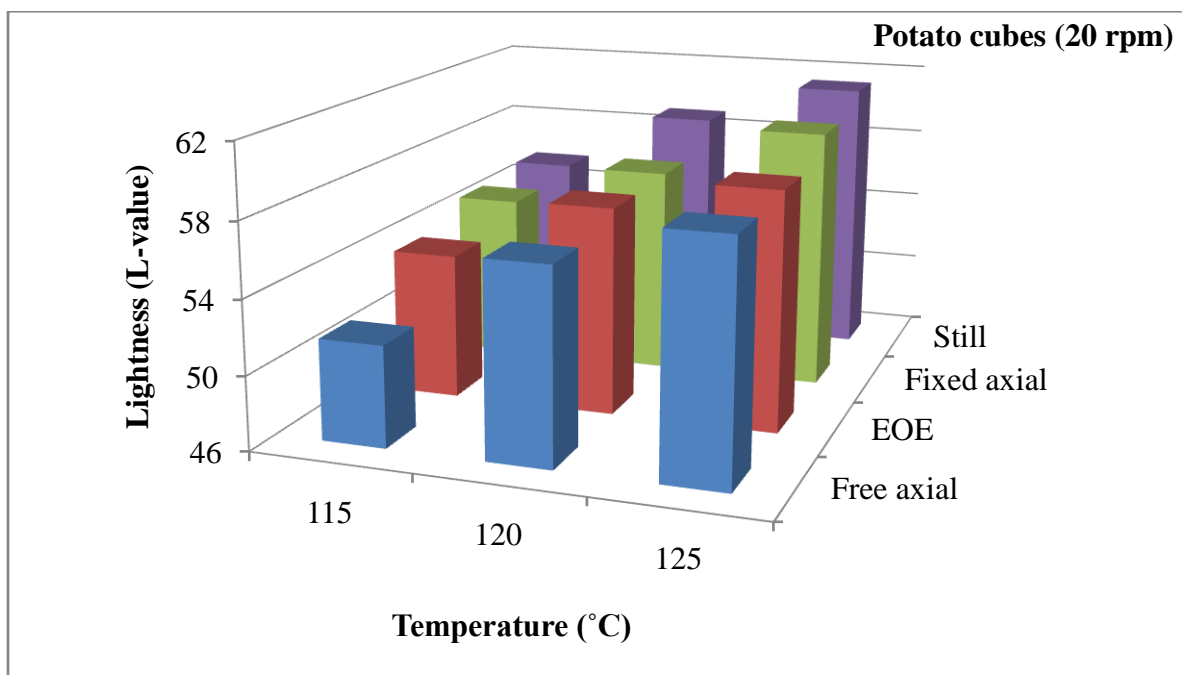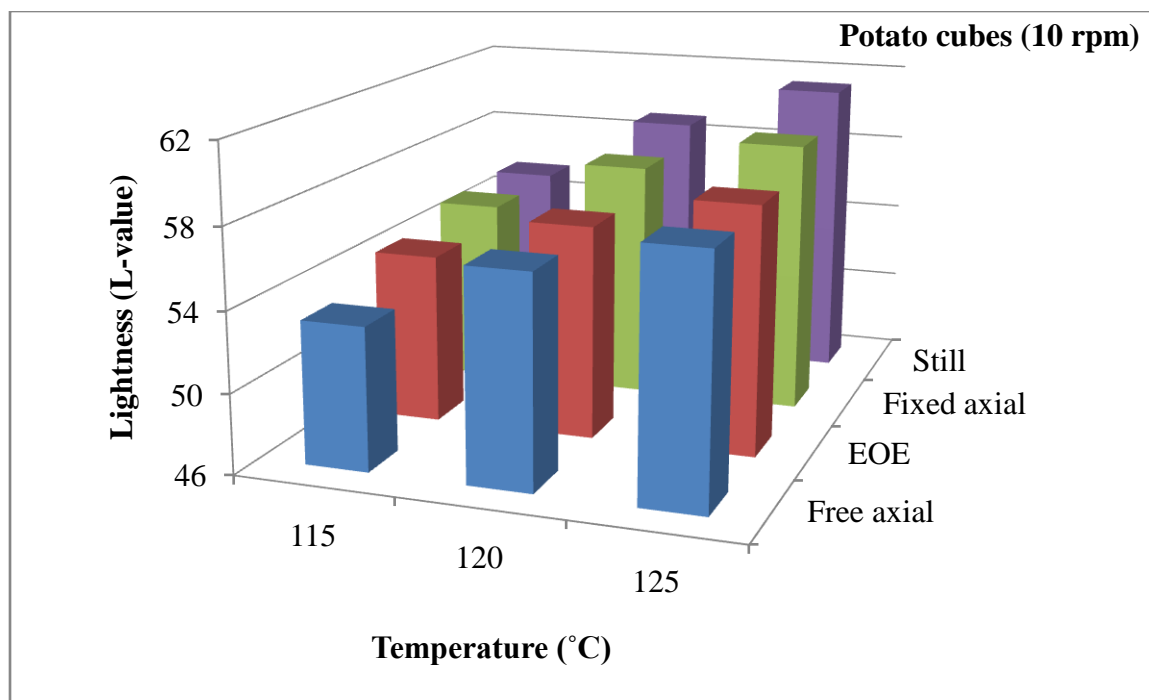
Figure 4.1 Effect of processing variables on lightness of potato cubes

Table 4.3: Analysis of variance for yellowness (b-value) of potato cubes

Tests of Between-Subjects Effects

Dependent Variable : Yellowness

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	37.933	37.933	30.049	.000
Temp	1853.153	926.577	733.988	.000
Mode	358.528	119.509	94.669	.000
RPM * Temp	21.081	10.541	8.350	.000
RPM * Mode	13.780	4.593	3.638	.013
Temp * Mode	92.452	15.409	12.206	.000
RPM * Temp * Mode	9.451	1.575	1.248	.281
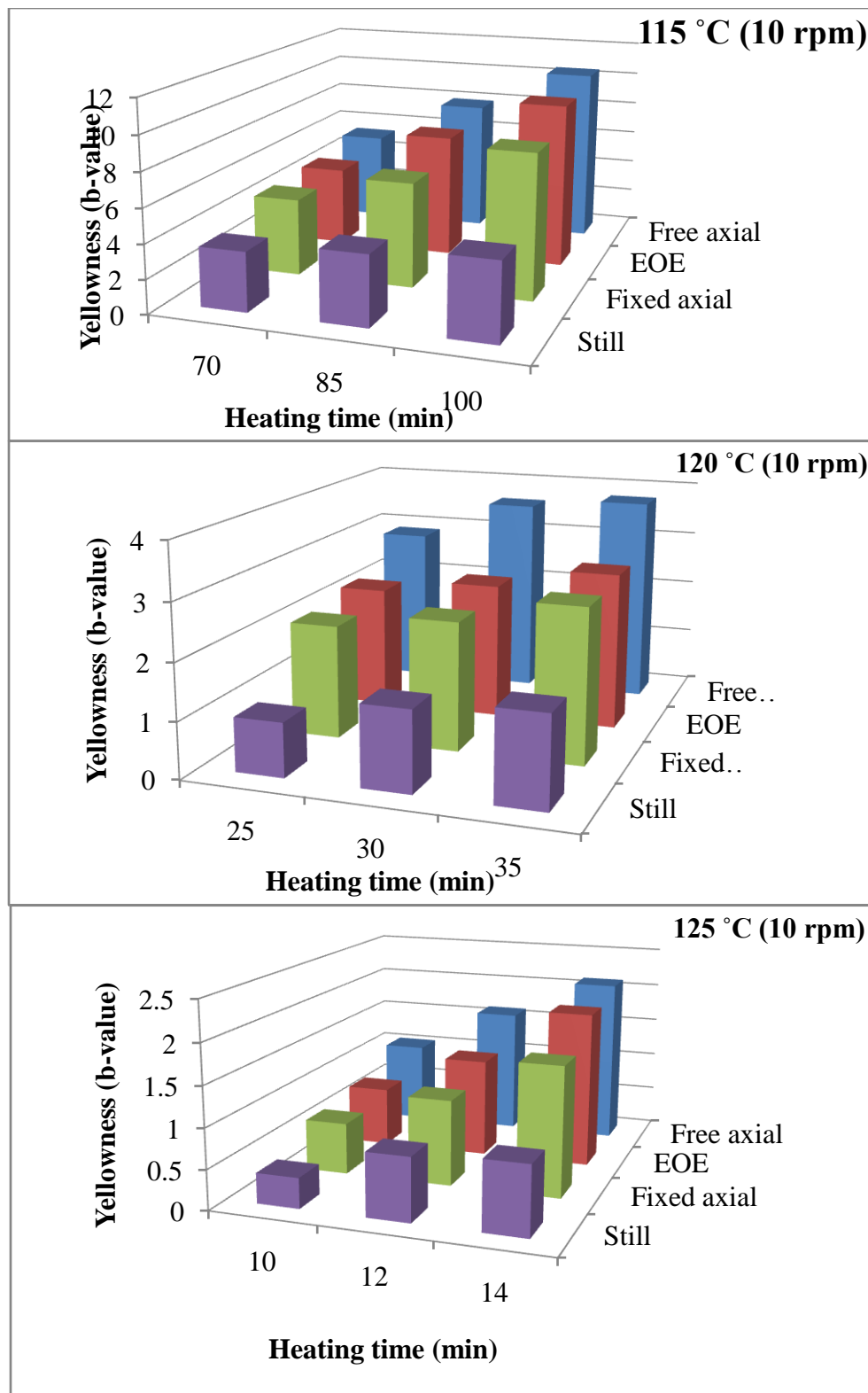
Figure 4.2 (a) Effect of processing variables on yellowness of potato cubes
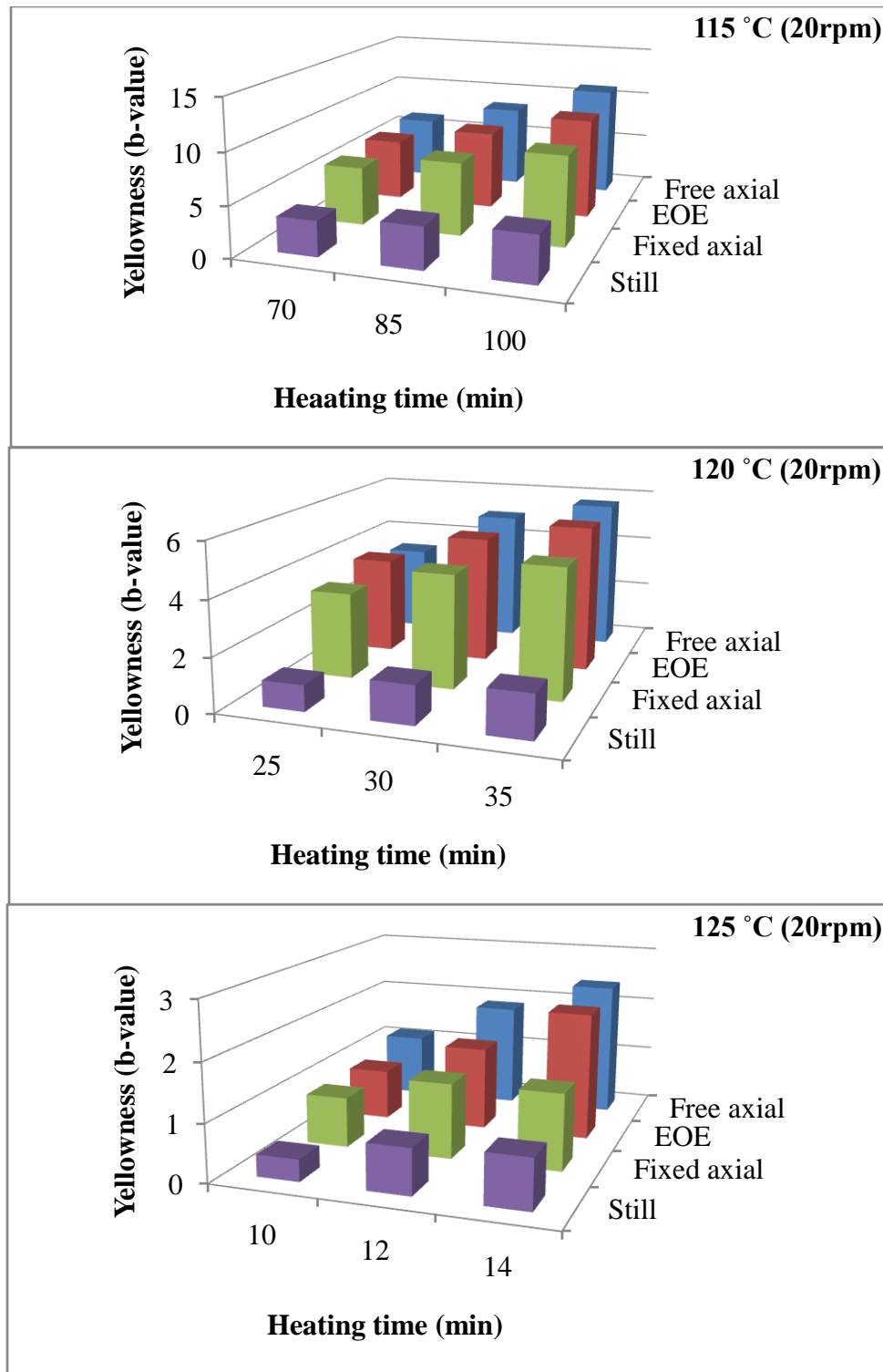
Figure 4.2 (b) Effect of processing variables on yellowness of potato cubes

Total color difference/change (ΔE) was also evaluated for all the processing conditions. Trends similar to L and b-values were observed in total color difference values evaluated by using Equation 4.1. The mean values of hunter L, a and b parameters for raw sample used for calculating ΔE were 63.82, -1.98 and 1.74 respectively. Overall effect of time at each of the three temperatures was analyzed by using T-test and the results showed the effect of time to be insignificant *(p>0.05)* on ΔE values.

Analysis of variance (Table 4.4) suggests that effect of temperature was more prominent on ΔE as compared to mode of processing. Effect of rotational speed on total color difference was found to be insignificant *(p<0.05)*.

Bar graphs presented in Figure 4.3 elucidate the trends observed in ΔE values of potato cubes. Lowest ΔE values were associated with still mode of processing at all three temperatures because the associated lethality values were also lowest (refer to Table 4.1) and consequently lowest quality loss took place in still mode. Due to better mixing of can contents as more lethality was achieved in free axial mode, hence the ΔE values in free axial modes were highest than all other processing modes. Also due to considerably lower lethality values achieved at 125˚C, the corresponding total color change values were also found to be very low.

Table 4.4: Analysis of variance for total color difference (ΔE) of potato cubes

Tests of Between-Subjects Effects

Dependent Variable: DELTA E

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	1.647	1.647	1.392	.244
TEMP	505.470	252.735	213.519	.000
MODE	106.453	35.484	29.978	.000
RPM * TEMP	5.440	2.720	2.298	.111
RPM * MODE	1.121	.374	.316	.814
TEMP * MODE	14.384	2.397	2.025	.080
RPM * TEMP * MODE	2.606	.434	.367	.896
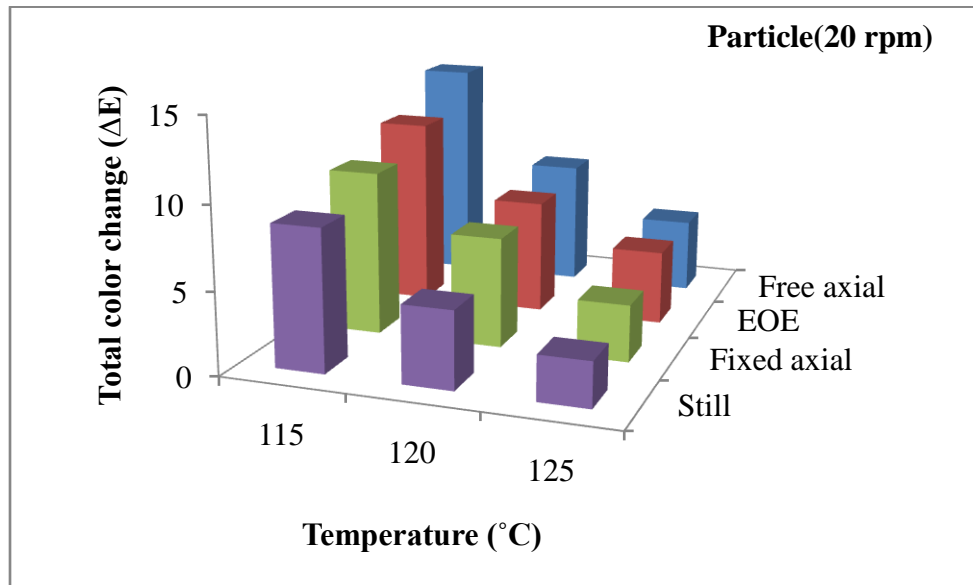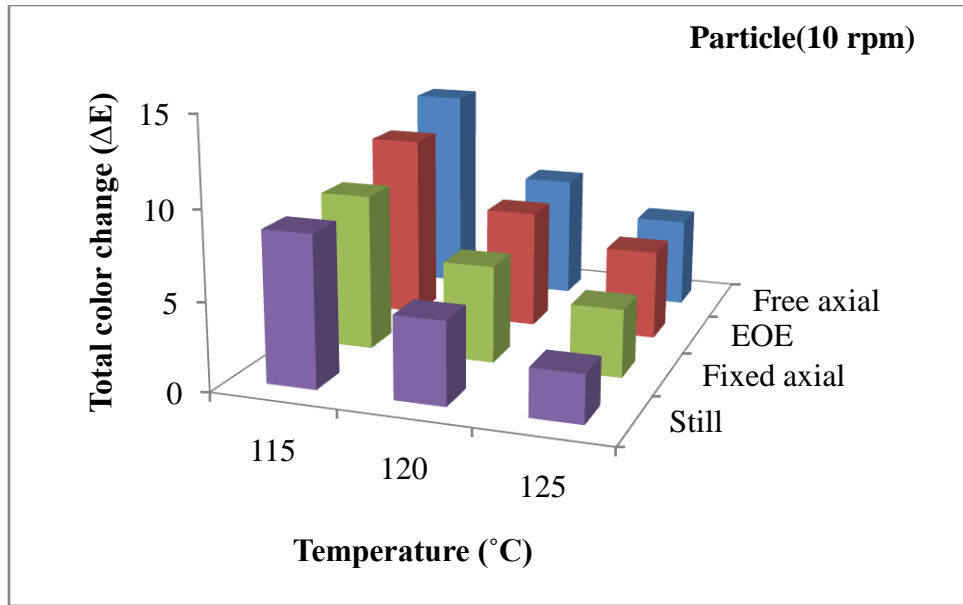
Figure 4.3 Effect of processing variables on total color change of potato cube

4.4.3 Effect of processing variables on textural characteristics

Palatability of food is greatly influenced by its texture. Texture is often modified during processing of food which is done in order to enhance the storage life of foods (Huang and Bourne, 1983). Textural changes as a result of thermal processing in this study were quantified by using parameters that were evaluated by texture profile analysis.

Hardness of a food is defined as the maximum force that is required to compress the food material. With heating of potato particles, the pectin substances degrade and gelatinization of potato starch takes place which ultimately softens the potato tissue (Alvarez *et al*., 2001). Therefore, as the potato particles are heated, reduction in their hardness values are expected and also with increasing amount of heating the hardness values are expected to be even lower. In this study, similar trends were observed which are found to be in consensus with literature studies. Figure 4.4(a) and 4.4(b) show the bars of the mean hardness values of potato cubes as influenced by different processing variables.

Due to highest heat transfer associated in free axial mode, the potato cubes received maximum heat in free axial mode and eventually the potatoes were found to be softer than other modes of processing. For instance, at 120 ˚C and 10rpm the potato particles processed in free axial mode had mean hardness value of 6.61N, which in comparison to mean hardness values in end-over-end, fixed axial and still mode of processing respectively were found to be approximately 29%, 36% and 45% lower. As higher lethality values were achieved at 115˚C as compared to 120 and 125˚C so potato cubes processed at 115 ˚C were found to show lesser hardness than those processed at 120 and 125 ˚C. Also with increase in rotational speed from 10 to 20rpm, due to better mixing of contents, more heat was received at 20 rpm; so the particles at 20rpm were

characterized by lower hardness values. For example, in free axial mode of rotation, 9% reduction in hardness was observed when rotational speed was increased from 10 to 20rpm at 125 ˚C. Similar trends in hardness values were observed in other modes of processing as well.

Analysis of variance of hardness values of potato cubes shows that mode of rotation has maximum influence followed by temperature and speed of rotation (Table 4.5). All three processing variables were found to show highly significant effect on hardness values *(p<0.05)* of potatoes. Out of all the interactive effects studied, the two way interactive effects of rpm and temperature with mode of rotation were found to significantly influence *(p<0.05)* the hardness of potatoes.

Table 4.5: Analysis of variance for Hardness of potato cubes

Tests of Between-Subjects Effects

Dependent Variable: Hardness

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	37.487	37.487	54.955	.000
Temp	721.576	360.788	528.904	.000
Mode	1886.926	628.975	922.060	.000
RPM * Temp	.301	.150	.221	.802
RPM * Mode	15.440	5.147	7.545	.000
Temp * Mode	40.577	6.763	9.914	.000
RPM * Temp * Mode	2.316	.386	.566	.758

Chewiness and gumminess are other important texture parameters that were evaluated in this study. Both these factors are directly related to hardness values, so any effect on hardness values is seen as similar effect on chewiness and gumminess. Likewise hardness values, the chewiness and gumminess values depicted decreasing trend with increasing severity of heat treatment (i.e. increasing F_o values). Effects of processing variables on chewiness are presented as bar graphs in Figures 4.5(a), (b) and the effects of processing variables on gumminess are presented in Figures 4.6 (a), (b).

Analysis of variance for chewiness and gumminess values of potato cubes are presented in Table 4.6 and 4.7 respectively. Although, to different extent, but all the processing variables studied were found to significantly influence *(p<0.05)* the chewiness and gumminess values of processed potato particles.

Other texture parameters such as springiness, cohesiveness and resilience values for original raw samples were found to be 0.79, 0.70 and 0.47 respectively. Whereas for the processed potato cubes the mean springiness values were ranging between (0.78 - 0.93); mean cohesiveness values were found to be in range (0.60 - 0.72) and the mean values of resilience were in (0.25 - 0.35) range for all the processed potato cubes. So it is clearly visible that apart from resilience other two parameters were not much modified. Resilience of the potato cubes was found to decrease by 25-46% during processing.

115 °C (10rpm)

120 °C (10rpm)

125 °C (10rpm)

Figure 4.4 (a) Effect of processing variables on hardness of potato cubes
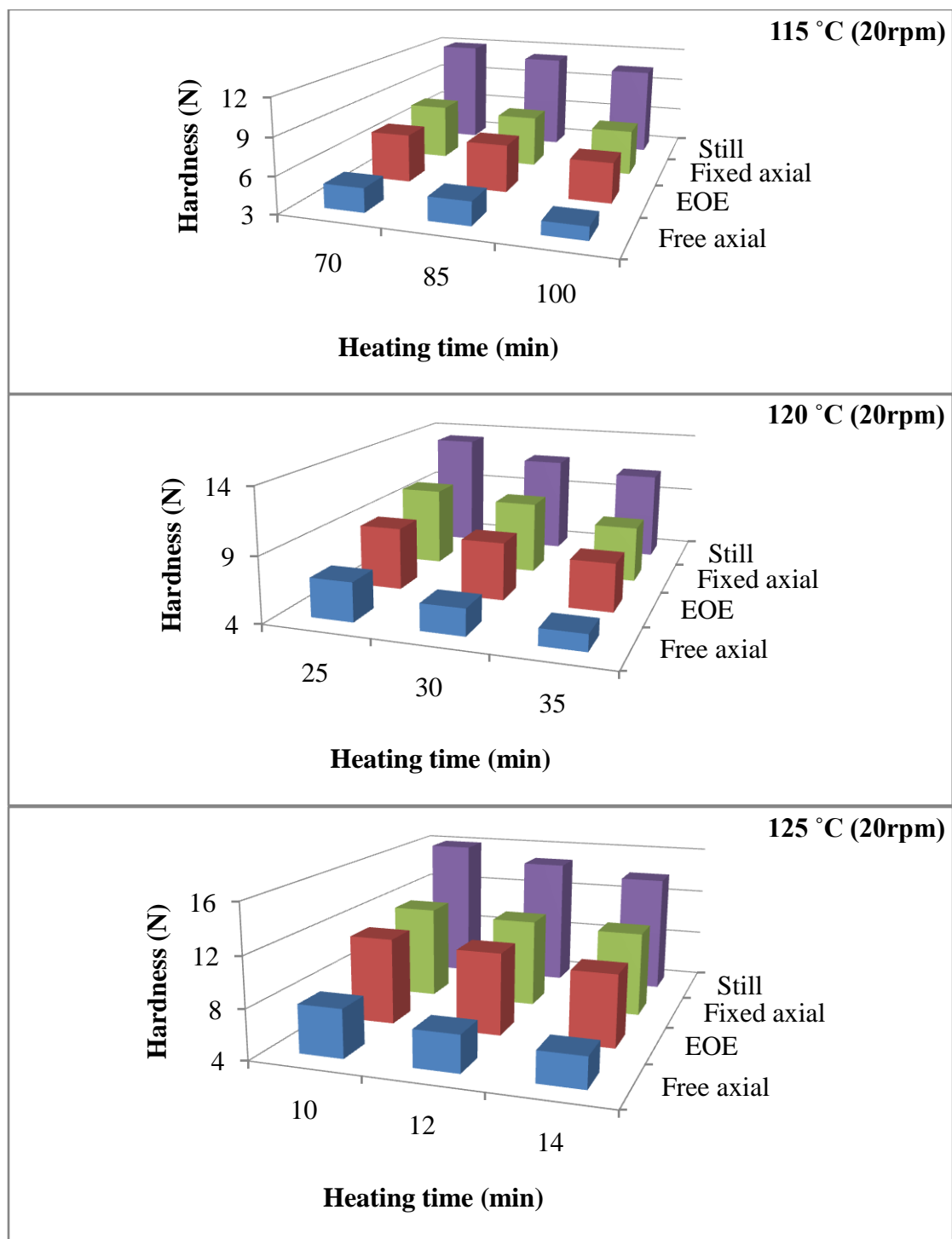
Figure 4.4 (b) Effect of processing variables on hardness of potato cubes

Table 4.6: Analysis of variance for chewiness of potato cubes

Tests of Between-Subjects Effects

Dependent Variable: Chewiness

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	12.063	12.063	17.520	.000
Temp	225.742	112.871	163.928	.000
Mode	603.515	201.172	292.170	.000
RPM * Temp	.615	.308	.447	.640
RPM * Mode	8.749	2.916	4.236	.006
Temp * Mode	24.627	4.105	5.961	.000
RPM * Temp * Mode	4.587	.765	1.110	.356

Table 4.7: Analysis of variance for gumminess of potato cubes

Tests of Between-Subjects Effects

Dependent Variable: Gumminess

Source	Type III Sum of Squares	Mean Square	F	Sig.
RPM	16.581	16.581	26.117	.000
Temp	331.026	165.513	260.706	.000
Mode	822.177	274.059	431.681	.000
RPM * Temp	.350	.175	.275	.759
RPM * Mode	9.019	3.006	4.735	.003
Temp * Mode	29.382	4.897	7.713	.000
RPM * Temp * Mode	2.057	.343	.540	.778
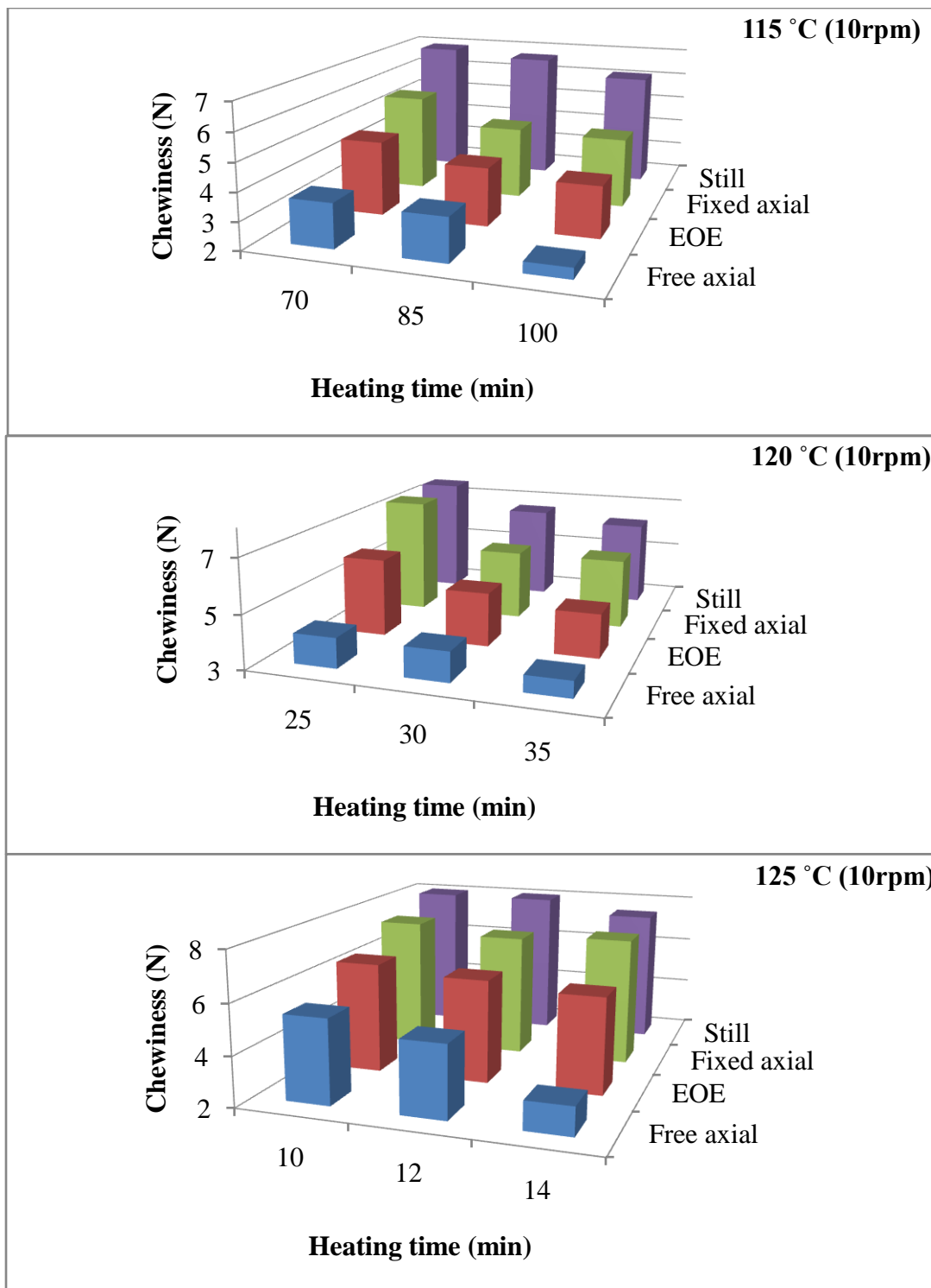
Figure 4.5 (a) Effect of processing variables on chewiness of potato cubes

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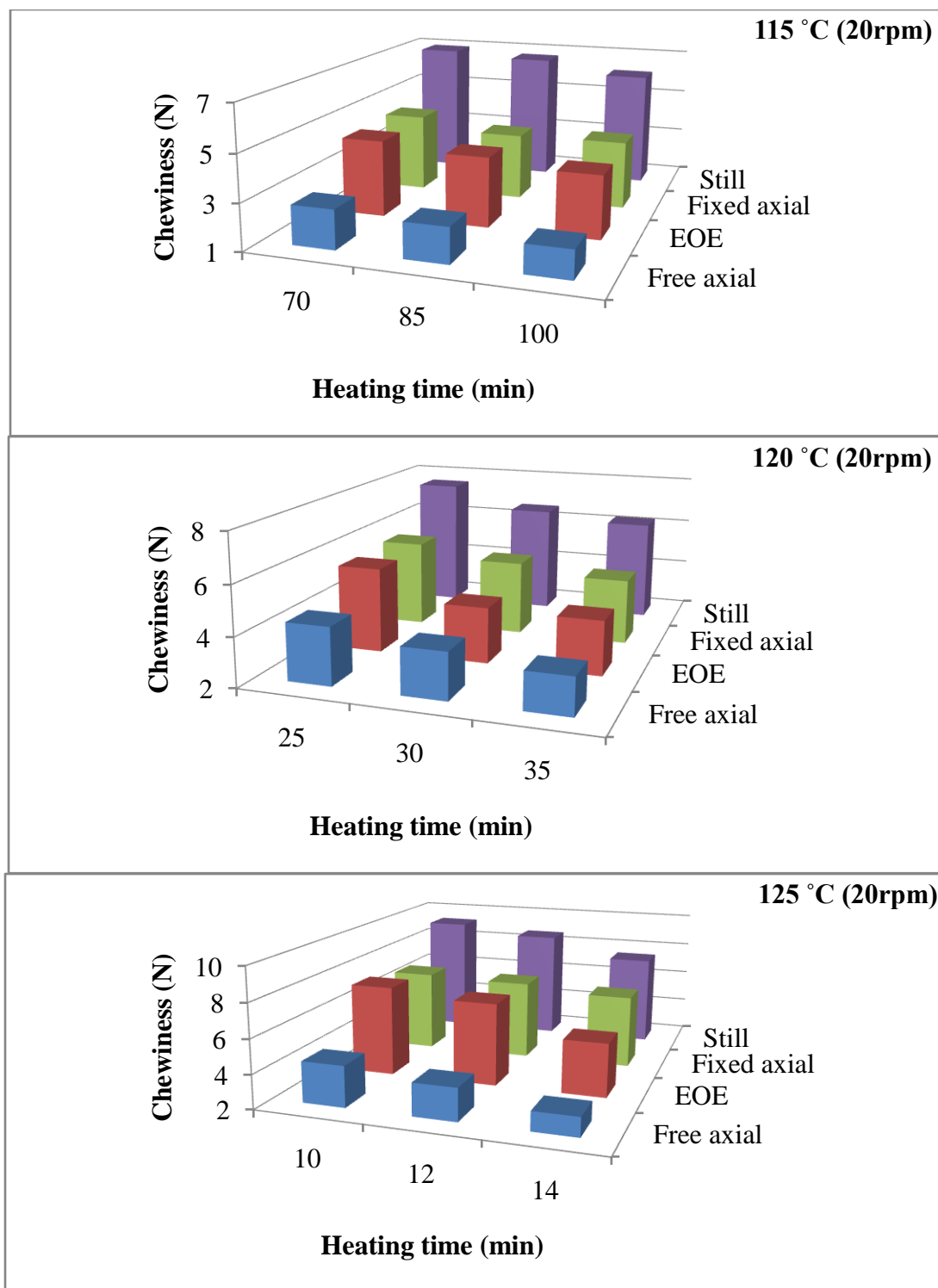
Figure 4.5 (b) Effect of processing variables on chewiness of potato cubes
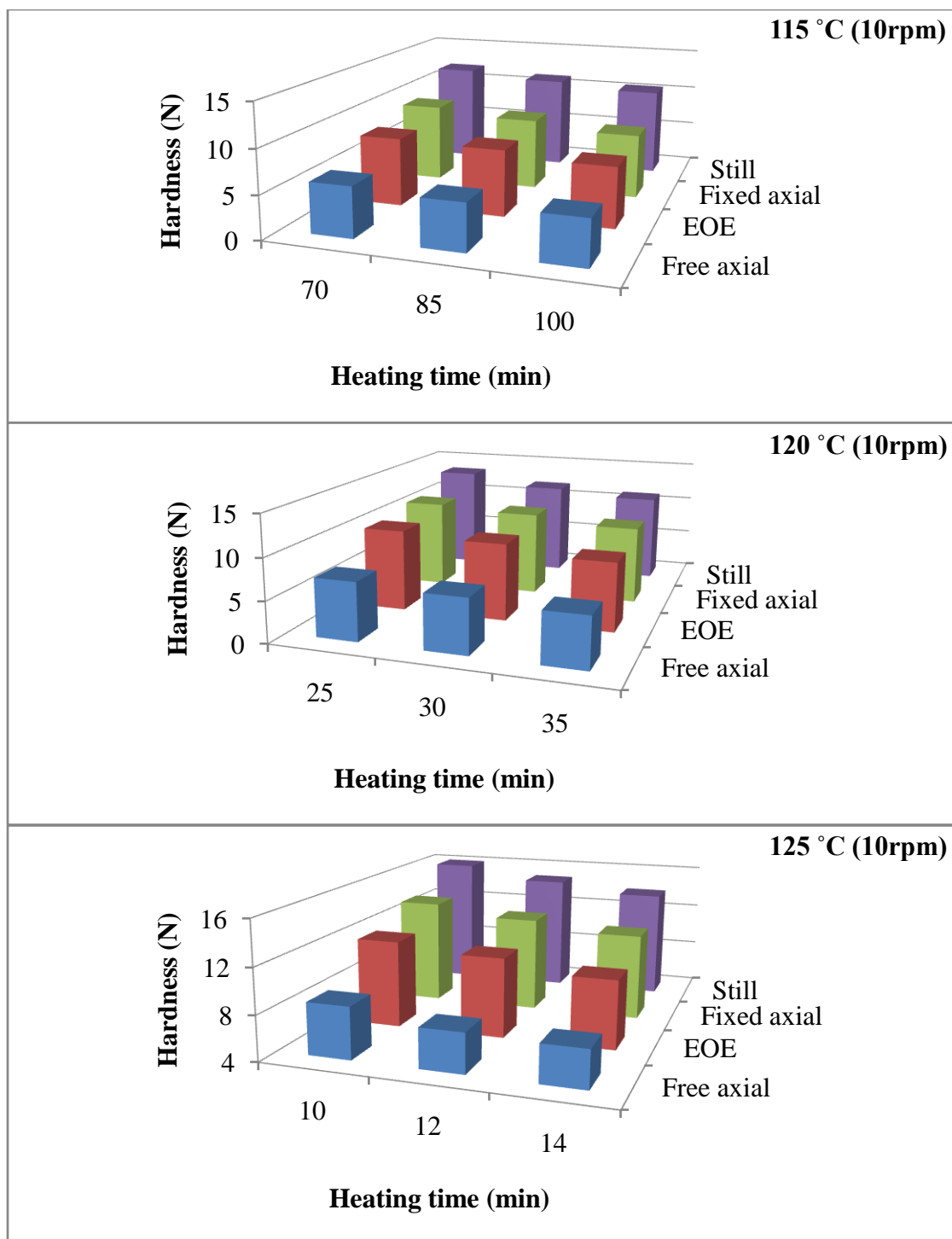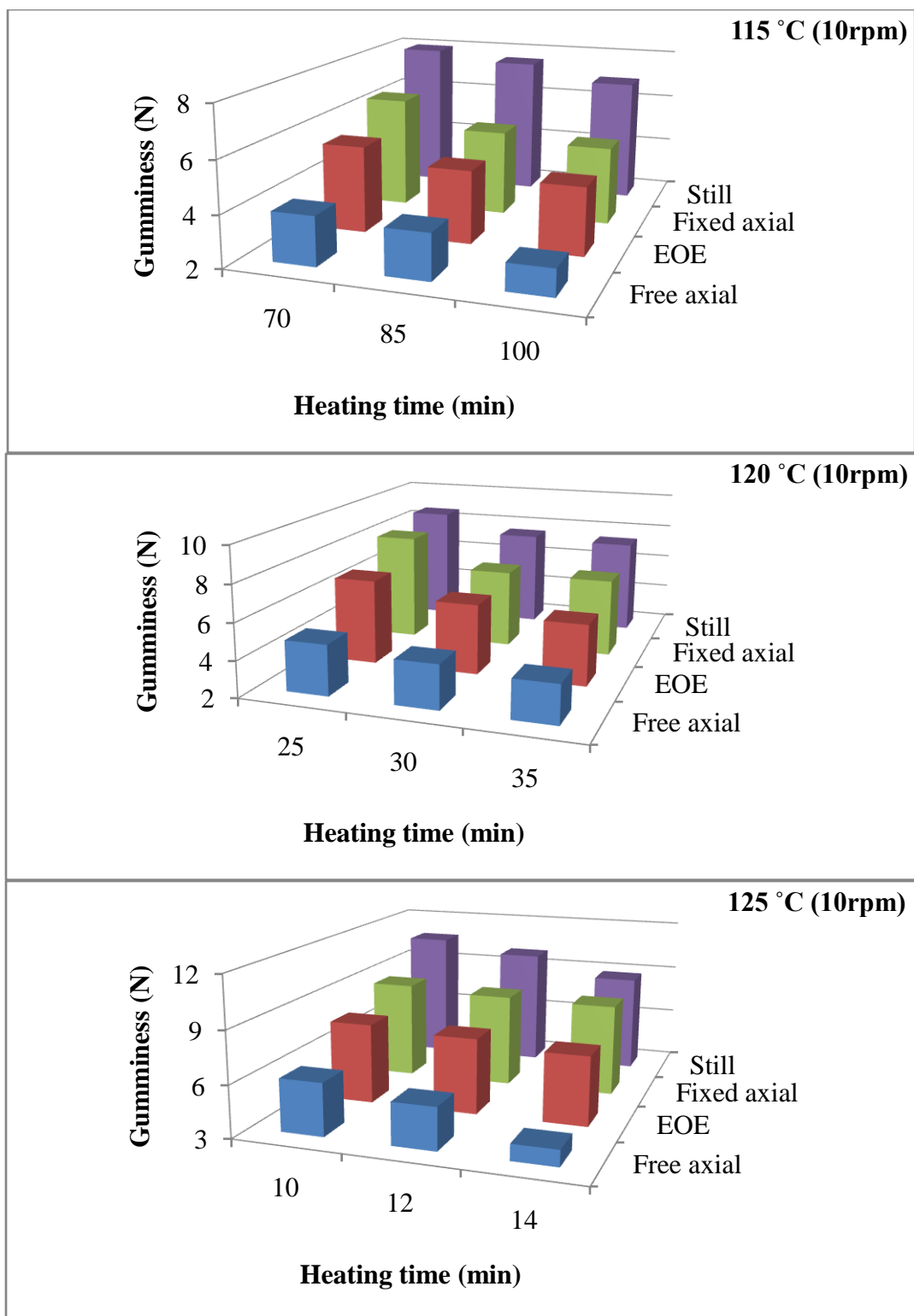
Figure 4.6 (a) Effect of processing variables on gumminess of potato cubes
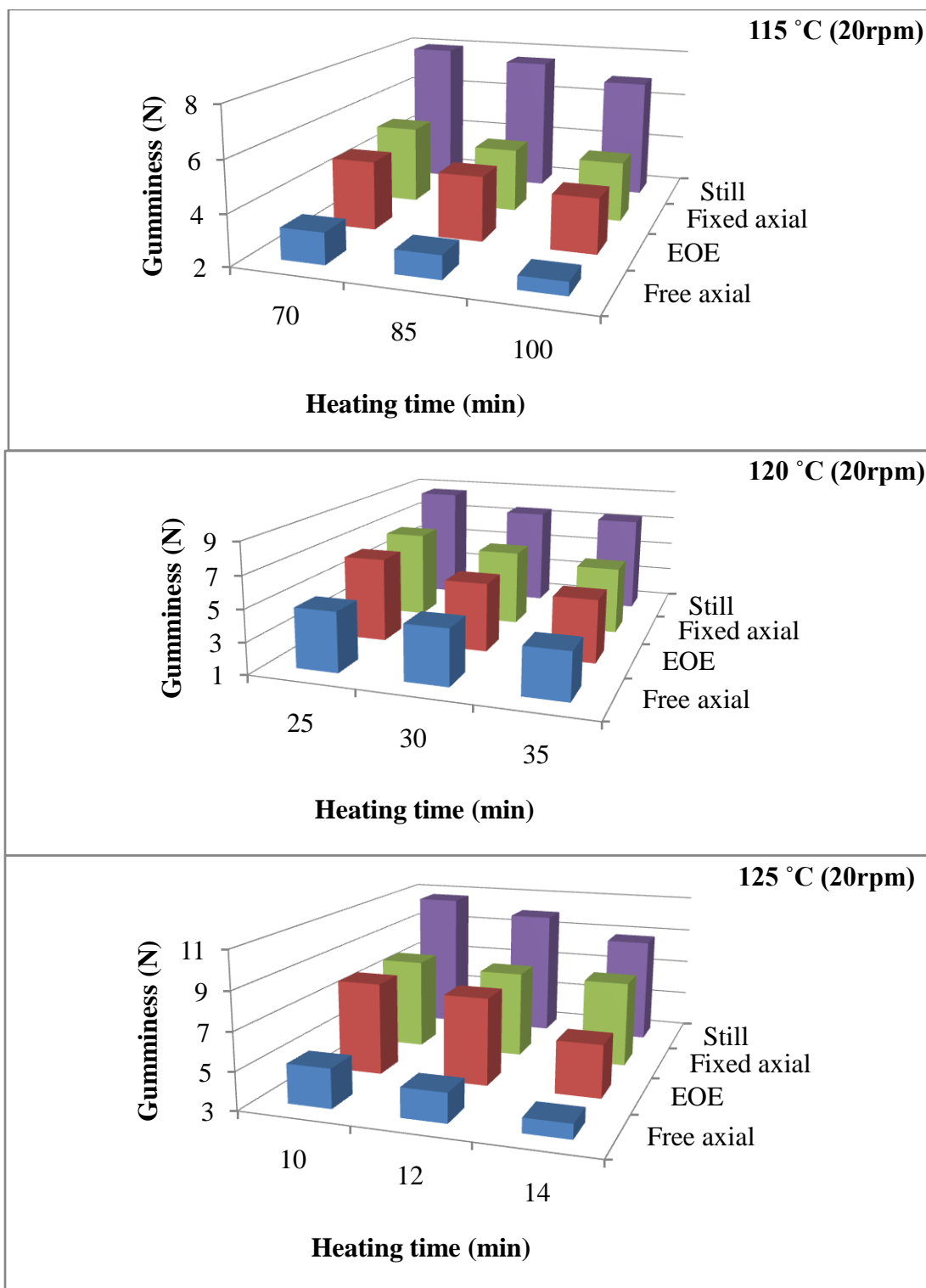
Figure 4.6 (b) Effect of processing variables on gumminess of potato cubes

4.5 Conclusions

Effects of heat treatments on color and texture indices of canned potatoes were studied and the results indicate that these quality indices are significantly influenced *(p<0.05)* by various processing variables. Under similar processing conditions lightness (L-value) and texture parameters (hardness, gumminess etc.) were found to be lowest in free axial mode followed by end-over-end, fixed axial and still mode of processing. The other color indices (b-value, ΔE) showed opposite trend; they were found to be highest in free axial mode followed by end-over-end, fixed axial and still mode of processing under similar processing conditions. The above mentioned trends that were observed in color and texture parameters are indicative of poorer quality. So, maximum quality destruction was observed in free axial mode (although degree of cooking was found to be lowest), because under similar processing conditions maximum heat transfer took place in free axial mode. Hence in order to identify optimal processing conditions to achieve maximum quality retention, further studies are required by adjusting processing times in order to impart equivalent heat treatments.

PREFACE TO CHAPTER V

In previous two chapters, the experiments were performed at conditions in which process times were kept constant during all the modes of processing. As observed, heating behavior and associated quality changes that took place in different modes were found to be significantly different. In order to identify optimum conditions of processing for maximum retention of quality parameters, it is very important to compare heating behavior and quality changes after subjecting the product to equivalent heat treatments.

Process times (to impart equivalent lethality of 10 min at particle center) were evaluated on basis of heat transfer studies performed in Chapter III. Further, heating behavior of potatoes and CMC was studied in terms of degree of cooking (C_o/F_o) achieved after processing in different modes. Furthermore, the impact of thermal processing on color (L, b, h-angle, ΔE values) and texture (hardness, chewiness, gumminess) parameters of processed potato cubes was evaluated. Optimal conditions were identified based on the heat transfer and quality related results.

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

Chapter V

OPTIMIZATION OF PROCESSING CONDITIONS FOR MAXIMUM RETENTION OF COLOR AND TEXTURAL ATTRIBUTES OF CANNED POTATOES

5.1 Abstract

The study was conducted to identify the optimal conditions for maximum quality retention in the canned potatoes. The effects of thermal treatments were evaluated in terms of lethality values achieved at the particle center and simultaneously their effects were studied on color and texture of canned potatoes under different processing conditions (retort temperature 115–125°C; rotation speed 10, 20 rpm; can headspace 10 mm; still and agitating modes). Potatoes were prepared as cubes of 1.6x1.6x1.6 cm, filled in 307x409 cans, covered with 1% aqueous solution of carboxy methyl cellulose and the processing times were selected to provide equivalent lethality of 10 min. A retrofitted, single basket rotary retort was used to perform the processing experiments. The selected color (L, b, h-angle and ΔE values), textural (hardness, chewiness and gumminess) characteristics as well as the cooking quality index, C_o/F_o were evaluated for each processing condition. The study indicated that potato particles processed in still mode had more quality deterioration as compared to end-over-end, fixed and free axial modes. Overall particles processed at higher temperature and under agitating modes demonstrated better quality retention.

5.2 Introduction

The canning technology has proven to be very effective and widespread amongst all the other processing or preservation technologies. The heat sterilization is based on providing suitable combinations of time-temperature treatments that can inactivate microorganisms, spores and enzymes (Maesmans *et al*., 1994). Although the thermal processing tackles safety issues pertaining to food, but they often result in destruction of nutrients and other likeable attributes (Priestly, 1979). The advancements in the Canning industry are focused on developing those technologies which have potential to inflict reduced damage of quality attributes by way of reducing the exposure times at optimized heating temperatures (Awuah *et al*., 2007).

Rapid and uniform heat transfer is the key for achieving optimum quality of processed products in the thermal process (Ramaswamy & Marcotte, 2006). Although, the use of thin profile pouches and aseptic processing technologies both promotes rapid heat transfer but, agitation during thermal processing is also a very effective means of providing forced convection which eventually results in rapid heating. Agitation can be achieved by rotating cans in either end-over-end and or axial modes. Clifcorn *et al*. (1950) suggested the use of end-over-end rotation in which the sealed can rotates in circular fashion in a vertical plane. Sophisticated equipments like, Continuous turbo cookers, Sterilmatic and Steritort (FMC Corp., San Jose, CA, USA) are gaining a lot of interest in Canning industry. These continuous retorts are designed with two cylindrical shells through which the cans are carried and advanced further on a revolving reel. Considering the ever increasing demand of canned foods, industries are always in search of advanced thermal processing equipments. And these continuous retorts offer several advantages

over their batch counterparts such as, high productivity, reduced consumption of heating medium (steam, water) and lower labor requirements.

Optimization of the processing conditions becomes even more important due to the fact that acceptance or rejection of most foods relies on their texture and external appearance. High temperature short time processing achieved through rotary processing provides improved heat transfer, reduced process times and hence they account for better quality. Due to the fact that, being external attributes, both color and texture contributes to esthetic quality of food and hence they have been studied extensively by many researchers (Hayakawa and Timbers, 1977; Paulus and Saguy, 1980; Rao *et al*., 1981; Abou-Fadel and Miller, 1983; Huang and Bourne, 1983; Anantheswaran and Rao, 1985; Rao and Lund, 1986; Steele, 1987; Gnanasekharan *et al*., 1992; Abbatemarco and Ramaswamy, 1994; Shin and Bhowmik, 1995; Ahmed *et al*., 2002a, b; Garrote *et al*., 2008).

The changes in the quality factors are good indicators to judge the severity of thermal treatment and the extent of damage that it causes (Shin and Bhowmik, 1995). Nourian and Ramaswamy (2003a,b) studied the effect of thermal treatments on color and texture of potatoes. Their study reported that with increasing severity of the thermal treatments the texture of potatoes become softer and the appearance become darker. Hence the objective of this study was to identify the processing conditions that can provide the potatoes that have better color and texture after being subjected to different modes of rotary processing.

5.3 Materials and methods

5.3.1 Processing conditions

The processing conditions were computed based on the data from the heat transfer studies conducted in Chapter 3. The improved general method and interpolation/extrapolation of the heating profile (from Chapter 3) was used to select the processing conditions imparting lethality values of 10 min. Total of 12 experiments were performed at three temperatures (115-120 $^{\circ}$C); rotational speeds 0, 20 rpm; in end-over-end, both axial and still modes.

5.3.2 Temperature measurements

Temperature data gathering was done during rotational processing on real time basis. Methodology for attaching thermocouples and data gathering is explained in Chapter 3.

5.3.3 Lethality and Cook value calculations

The improved general method was used to calculate the accumulated lethality value (F_o) at particle centre and at geometrical centre of can. The following numerical integration was performed to calculate lethality:

$$F_o = \int 10^{(T-121.1)/10} dt \qquad\qquad (5.1)$$

A cook value of the process C_o was computed as equivalent minutes of heating at 100 $^{\circ}$C with z value of 33 $^{\circ}$C (Eisner, 1988). Cook value was also computed by using numerical integration technique.

$$C_o = \int 10^{(T-100)/33} dt \qquad\qquad (5.2)$$

5.3.4 Quality analysis

The texture and color measurements were done according to the detailed procedures explained in Chapter 4.

5.3.5 Statistical analysis

Statistical analysis of data was performed by using IBM®SPSS® statistical package. Analysis of variance (ANOVA) was conducted and the significant differences were computed between the means with Least Square Difference (LSD) range test *(p < 0.05)*.

5.4 Results and discussions

5.4.1 Processing times

Experiments in agitating modes were performed at a single level of rotational speed (20rpm) as it was inferred from the Chapter 4 that the quality changes in particles were not much significantly different when rotational speed was changed from 10 to 20 rpm.

Processing times to deliver equivalent lethality of 10 min for each mode of processing at three temperatures (115, 120 and 125 ˚C) and at one level of rotation speed (20rpm) were deduced by extrapolation and interpolation of corresponding temperature-time profiles obtained in Chapter 3. The interpolation and extrapolation of the profile was done only at the region where temperature became constant i.e. once the particle reached the set temperature. Furthermore, improved general method was used in back propagation order to calculate process times (Table 5.1) corresponding to accumulated lethality of 10 min. As the temperature-time profiles for particles under free axial mode of processing could not be gathered due to difficulty in attaching thermocouples so, the process times estimated for end-over-end mode were employed because

the cans in end-over-end mode demonstrate the closest heating behavior to that of free axially rotating cans.

As we can see that by increasing the temperature the process times required to achieve F_o of 10min decreases significantly $(p<0.05)$. Also, the process times in rotational modes are significantly lower than the process times in still mode of processing. These reductions in process times are expected to give significant improvements in the quality parameters.

Table 5.1 Estimated process times (min) to achieve accumulated lethality of 10min

Temperature	Modes of Rotation (0, 20 rpm)			
(˚C)	Fixed Axial	EOE	Free Axial	Still
115	47	42	42	60
120	25	22	22	35
125	14	12	12	25

5.4.2 Cooking quality

Cook values are indicators used for describing extent of damage to food quality. C_o/F_o ratios are commonly used in place of cook values for comparing different processes where the delivered lethalities may vary. Degree of cooking was estimated from C_o/F_o values that were evaluated from temperature data gathered at geometrical center of can and at particle center, during processing experiments according to adjusted times (Table 5.1). Lower C_o/F_o values are expected to be associated with lower quality destruction and vice versa.

Analysis of variance results for C_o/F_o values for liquid and particle heating are presented in Tables 5.2 and 5.3 respectively. From the results obtained it can be concluded that temperature, mode and their interactive effects significantly influence the C_o/F_o values in both liquid heating and particle heating. Analysis of variance for C_o/F_o in both liquid and particle heating showed that temperature had more significant influence on C_o/F_o ratio. For liquid, in free axial mode, by increasing temperature from 115 to 125°C C_o/F_o value dropped by 70%, which was found to be highest in magnitude, than the corresponding drops in C_o/F_o values of 68%, 65% and 60% respectively in end-over-end, fixed axial and still modes of processing. For particle heating also, similar results were observed. C_o/F_o values in end-over-end mode plummeted by 68% when the retort temperature was increased from 115 to 125°C and the corresponding decrease with increase in temperature in fixed axial and still mode of processing were approximately 65% and 58% respectively. This demonstrates usefulness of high temperature short time processes. The trends for C_o/F_o values are presented graphically in Figure 5.1.

Mode of rotation was found to be the next significant factor influencing the degree of cooking. At 115°C for liquid heating, C_o/F_o values in free axial mode were approximately, 14%, 24% and 35% lower than C_o/F_o values in end-over-end, fixed axial and still modes of processing. For particle heating the C_o/F_o values in end-over-end mode were nearly, 11% and 24% lower than C_o/F_o values in fixed axial and still modes when processed at 115°C retort temperature. Clearly, these results indicate advantage of rapid heating mechanisms in terms of lowering the degree of cooking in product.

Table 5.2: Analysis of variance for C_o/F_o ratios in liquid heating

Tests of Between-Subjects Effects

Dependent Variable: C_o/F_o Liquid

Source	Type III Sum of Squares	Mean Square	F	Sig.
Temp	220.256	110.128	3.610E3	.000
Mode	31.167	10.389	340.564	.000
Temp * Mode	5.905	.984	32.261	.000

Table 5.3: Analysis of variance for C_o/F_o ratios in particle heating

Tests of Between-Subjects Effects

Dependent Variable: C_o/F_o Particle

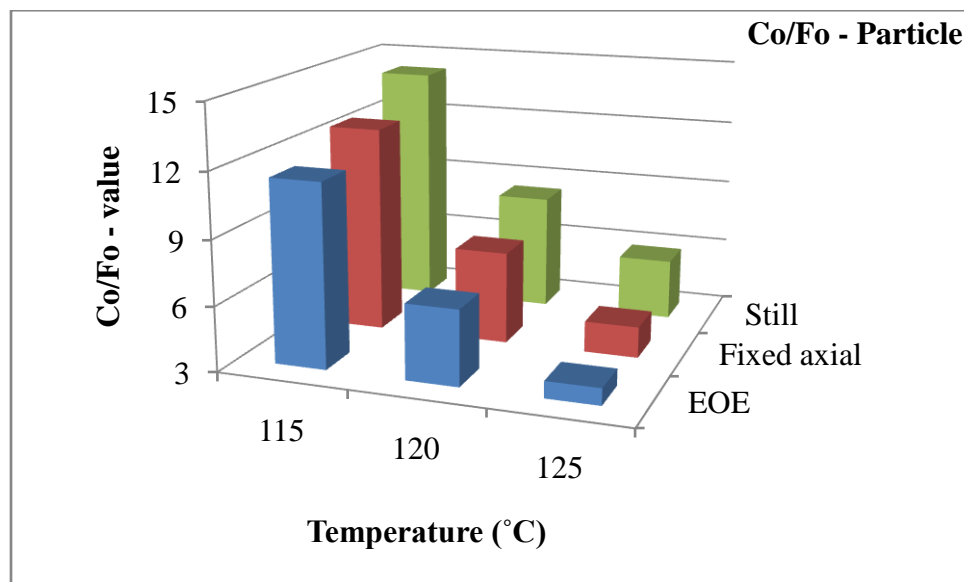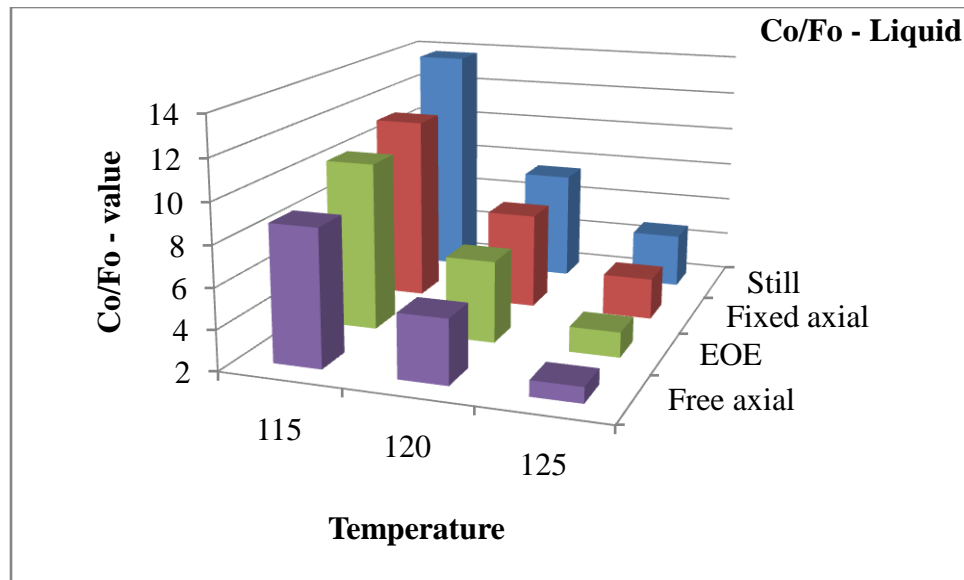| Source	Type III Sum of Squares	Mean Square	F	Sig.
Temp	203.111	101.556	4.734E3	.000
Mode	15.032	7.516	350.365	.000
Temp * Mode	.422	.105	4.918	.022

Figure 5.1: Effect of processing variables on C_o/F_o ratios for liquid and particle heating

5.4.3 Color changes

Analysis of variance (Table 5.4) for all the color parameters studied, showed that temperature and mode of processing had significant influence on these parameters *(p<0.05)*. Effect of temperature accounted for more variance than the mode of processing for all the color parameters; especially its effect was more prominent on hue angle. The interactive effects of temperature and mode were found insignificant for all the color parameters (lightness, yellowness, hue angle and total color difference).

The effects of processing variables on each color parameter are presented in the form of bar graphs (Figures 5.2 and 5.3). Lightness (L-value) of potato cubes was found to be lower at 115˚C as compared to the L-values of potato cubes at 120 and 125˚C, indicating darker and lesser attractive products at 115˚C. The original sample had mean L-value of approximately 64 which was reduced by 9%, 8% and 6% respectively after processing at 115, 120 and 125˚C respectively.

Different time temperature combinations were employed to achieve targeted lethality in different modes of processing. Due to difficulty in temperature data gathering in free axial mode, the processing times employed for end-over-end mode were used for free axial mode as well. From Figure 5.2 it can be observed that lightness values were lowest in still mode of rotation followed by fixed axial, free axial and end-over-end mode of processing. This indicates that more quality destruction takes place in still mode than all other agitating modes of processing (indicated by darker products). In end-over-end mode, heat transfer is rapid than the fixed axial mode, hence longer processing time was required to achieve target lethality in fixed axial mode of processing. This longer processing resulted in more damage of color quality of potatoes in fixed axial than that of end-over-processing. In free axial mode, the potato particles showed more quality

destruction than end-over-end mode; but both L and h-angle values were significantly $(p<0.05)$ higher in free axial mode than fixed axial and still mode of processing, hence demonstrating better retention of quality parameters than these modes. It was found that, after processing in free axial mode the potato cubes had lightness values approximately 3-6% lower than the potato cubes processed in end-over-end mode.

Higher quality loss was characterized by higher dropping of L-values (i.e. lower L-value) which resulted in darker and visually less appealing potato cubes. Overall, the lightness values were better retained at 125˚C and in rotational modes of processing especially in end-over-end and free axial modes.

Trends similar to those for L-values were observed in hue angle ($\tan^{-1}$ b/a) values for potato cubes as well (Figure 5.2). When the hue angle decreases it signifies the product is becoming more yellowish and less bright. Hence, with increasing quality damage the hue angle was found to be decreasing therefore, at lower temperatures and in still mode of processing the h-angle was lowest whereas, the highest h-angles were observed in end-over-end and free axial modes of processing. For example, reduction in mean h-angle values in all modes was approximately by 9-16% when the temperature was raised from 115˚C to 125˚C, thereby demonstrating lesser quality deterioration at higher temperatures

The yellowness (b-value) and total color difference values as influenced by processing variables are shown in Figure 5.3. The behavior depicted by these two color parameters is opposite to that of texture parameters, L and h-angle values. With increasing quality deterioration they were found to increase. Under constant processing conditions the potato cubes processed in still mode were found to be (15 - 85) % more yellowish than the potato cubes processed in agitating modes

at all three retort temperatures. The potato cubes processed in end-over-end and free axial mode demonstrated lower cooking effect as they were characterized by comparatively lower b-values.

Table 5.4: Analysis of variance for lightness, yellowness, hue angle and total color difference

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	Mean Square	F	Sig.
Lightness				
Temp	136.880	68.440	13.430	.000
Mode	71.037	23.679	4.647	.006
Temp * Mode	19.169	3.195	.627	.708
Hue angle				
Temp	3473.278	1736.639	66.718	.000
Mode	2400.845	800.282	30.745	.000
Temp * Mode	207.279	34.547	1.327	.264
Yellowness				
Temp	66.529	33.265	96.556	.000
Mode	61.781	20.594	59.776	.000
Temp * Mode	3.044	.507	1.473	.208
Delta E				
Temp	157.310	78.655	29.173	.000
Mode	93.961	31.320	11.617	.000
Temp * Mode	12.622	2.104	.780	.590

The total color difference under constant processing conditions was found to depict similar behavior to that of b-value (Figure 5.3). ΔE was calculated by using Equation 4.1 and the mean values of hunter color parameters used for raw potato samples were L_o: 63.82, a_o: -1.98, b_o: 1.74; L, a and b were the mean values of potatoes processed at different conditions. At 115˚C the ΔE values were significantly higher than those at 125˚C. This indicates more quality damage by means of higher cooking effects incurred due to prolonged heating at lower temperatures, which eventually leads to surface overcooking. Total color change was found to be lowest in end-over-end and free axial modes thereby depicting usefulness of rapid heating mechanisms in preserving quality parameters.

All of the results obtained from color analysis indicate that as the temperature was lowered the samples became darker (lower L-values), more yellowish (higher b-values) and furthermore these resulted in lower h-angle values and higher ΔE values. Also, the rapid heating mechanisms promoted better quality retention and therefore they were characterized by higher L-values, less yellowish and higher h-angle and ΔE values.
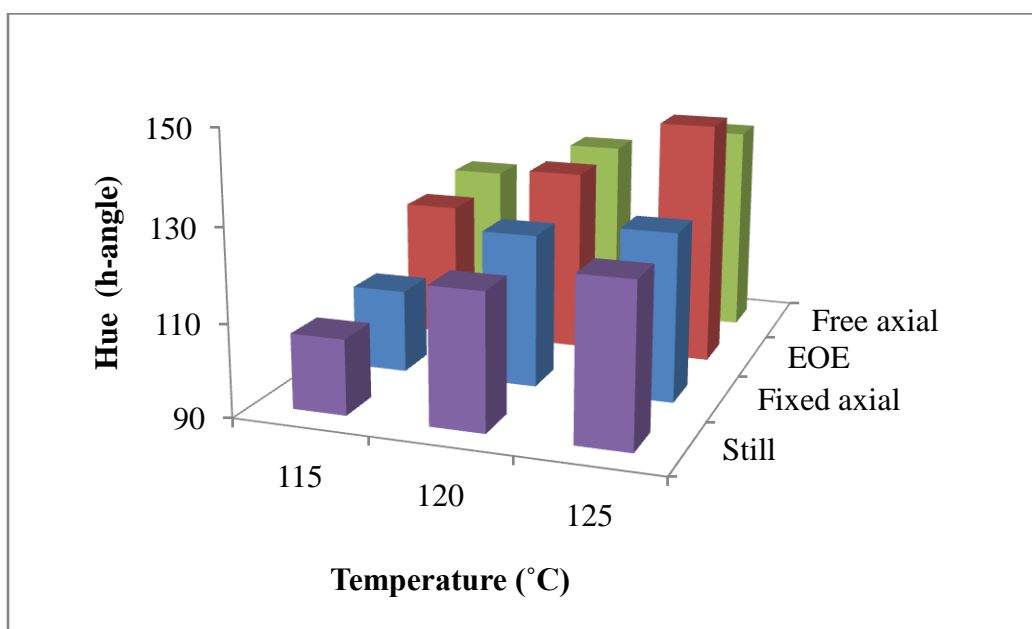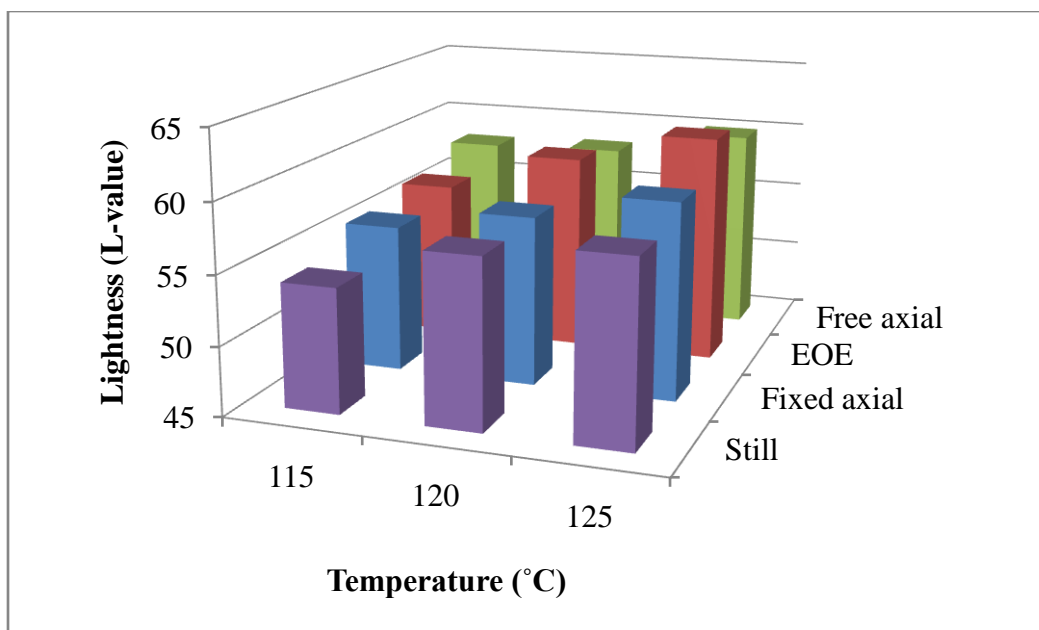
Figure 5.2 Effect of processing variables on lightness (L-value) and hue angle (h-angle) of
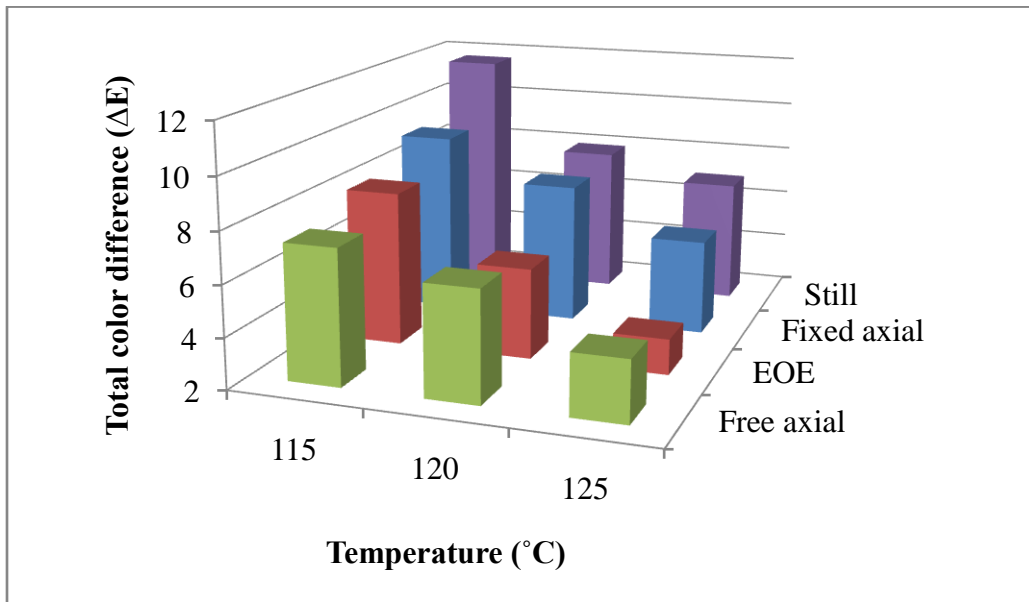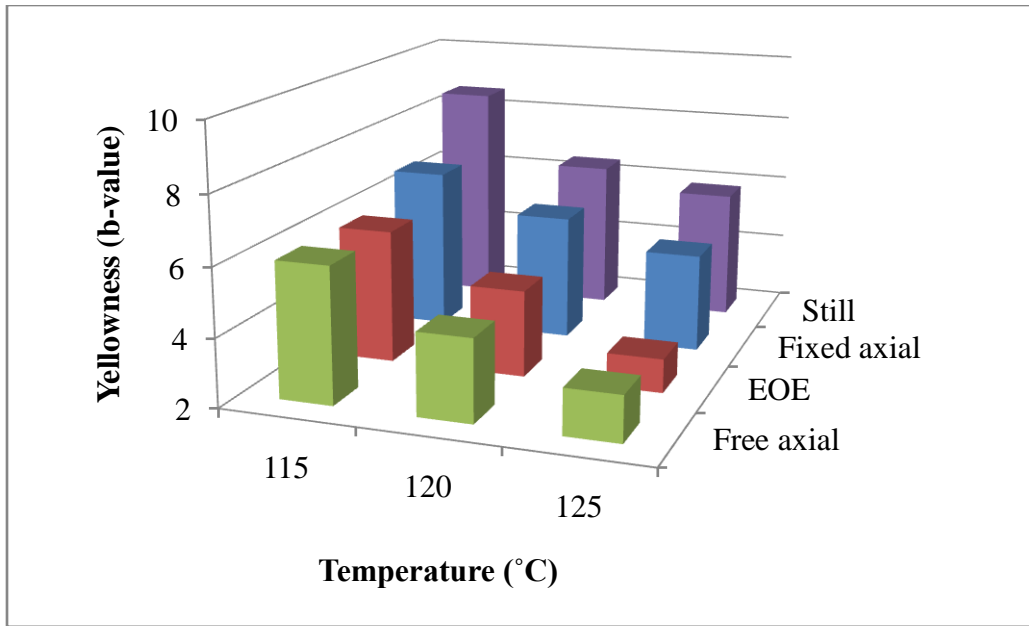
potato cubes

Figure 5.3Effect of processing variables yellowness (b-value) and total color difference (ΔE) of potato cubes

5.4.3 Texture analysis

Analysis of variance results of various texture parameters that were obtained by performing texture profile analysis are presented in Table 5.5. Results for hardness, chewiness and gumminess indicates that temperature and mode of processing significantly influence these texture parameters $(p<0.05)$. Processing temperature showed higher significance than mode of rotation for all the three parameters studied. The interactive effects of temperature and mode were found to be significantly influencing only the hardness values of the potato particles.

Table 5.5: Analysis of variance for hardness, chewiness and gumminess of potato cubes

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	Mean Square	F	Sig.
Hardness				
Temp	33.407	16.703	124.082	.000
Mode	43.511	14.504	107.742	.000
Temp * Mode	2.485	.414	3.077	.012
Chewiness				
Temp	11.760	5.880	18.189	.000
Mode	11.786	3.929	12.153	.000
Temp * Mode	1.567	.261	.808	.569
Gumminess				
Temp	17.563	8.781	26.686	.000
Mode	17.184	5.728	17.407	.000
Temp * Mode	2.977	.496	1.508	.196

The trends observed in textural parameters were similar to those observed for L-value and h-angle values. The effects of different processing variables on texture parameters are presented graphically in Figure 5.4. The hardness values were found to be lower when processing at lower temperature under all the modes of processing (quality overdone while achieving the target degree of lethality). In free axial mode, at 115˚C the hardness values of potato cubes were approximately 11% and18% lower than the hardness values of potatoes at 120˚C and 125˚C respectively. Similarly, for end-over-end, fixed axial and still modes of processing the hardness of potato cubes was found to be lower at 115˚C than at 120 and 125˚C. These results clearly demonstrate the usefulness of high temperature short time processing in preserving the product's textural quality. Prolonged heating at lower temperature results in complex chemical changes in cell polysaccharides, which results in more damage to cell matrix and thereby resulting in softer product. The behavior of gumminess and chewiness were found similar to that of hardness and the behavior is justified because gumminess and chewiness are the parameters that are directly related to hardness.
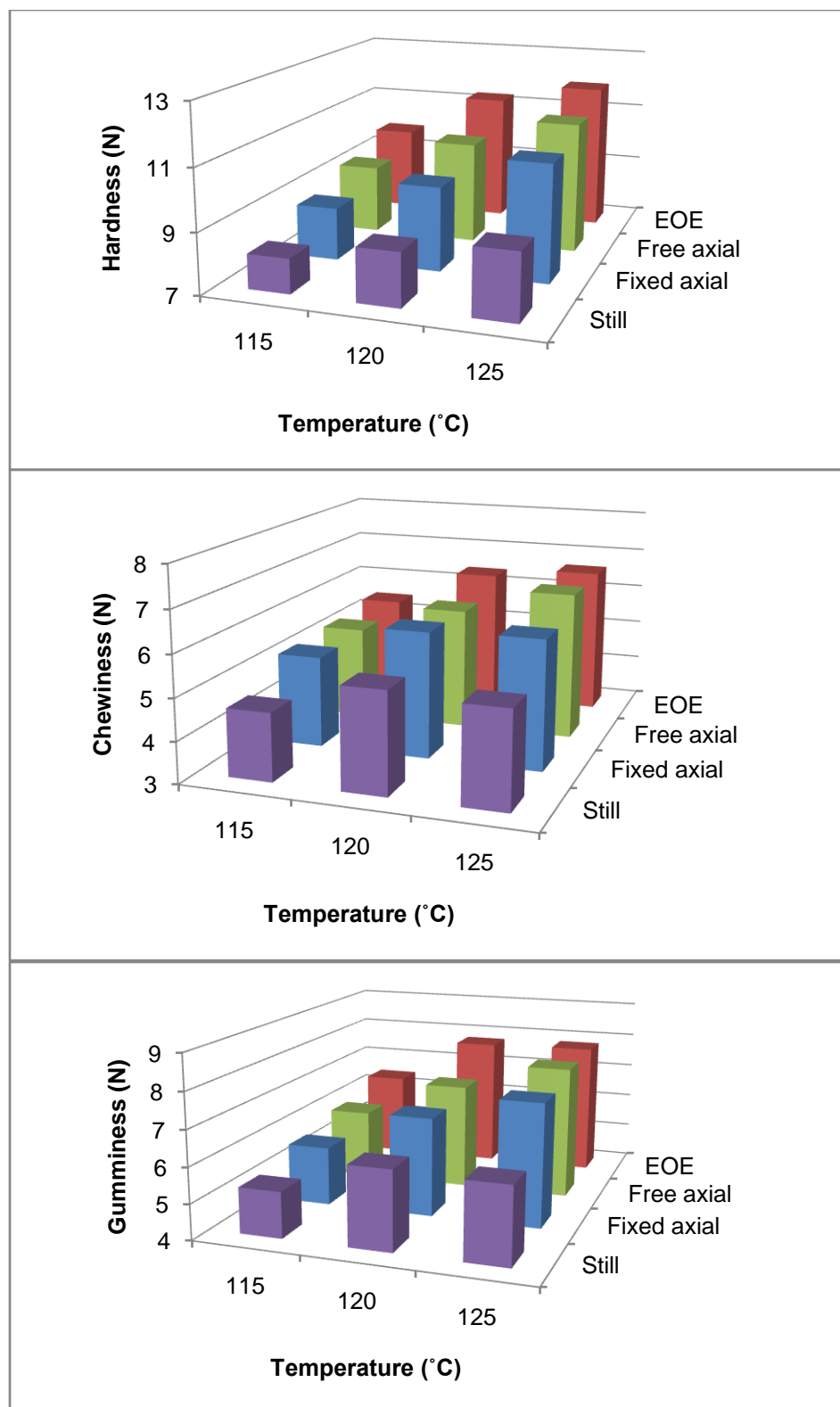
Figure 5.4: Effect of processing variables on hardness, chewiness and gumminess of potato cubes

5.5 Conclusions

The study suggests that cooking quality, texture and color indices are significantly changed *(p<0.05)* during the processing in all the modes. Rapid heating is characterized by lower C_o/F_o values hence, the lowest values were observed in free axial mode and the highest C_o/F_o values were observed in still mode of processing

Lightness and hue angle as well as the texture parameters were found to be lower at lower temperatures indicating more quality damage by low temperature long time processing. Likewise their values were found to be significantly lower in still mode of processing as compared to agitating modes. Other two parameters, b-value and total color difference showed opposite trends to that of texture and the other two color indices, but they too were found to be indicative of more quality damage.

As there is a very narrow difference in both quality parameters (color and texture) of potatoes processed in free axial and end-over-end mode of processing, it can be safely concluded that if the processing times are shortened for free axial mode then it can definitely provide edge in quality retention over all other modes of processing.

Chapter VI

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Thermal processing is an important preservation method that has been used for many years to produce shelf stable and safe foods. The technique has continually been passing through improvement phases from the time since it came into inception. Firstly the focus was just to obtain shelf stable product, which then shifted towards obtaining shelf stable and better quality products. Thermal processing is associated with considerable degradation of color, texture, taste and other organoleptic attributes of food. Hence thermal process is always optimized in order to minimize damages to these quality attributes. The main objective of this research was to study the optimization of quality retention in potatoes by subjecting it to varying modes of canning operations. With the advent of continuous retorts, axial type of agitation is gaining a lot importance because of its associated advantages but still, industries are using end-over-end type of agitation processing as well. So specifically the aim of this study was to understand comparatively, the heating behavior of the canned potatoes and associated quality changes in both axial modes and end-over-end mode of processing and furthermore to identify the conditions resulting in lower quality losses.

Standard type 307x409 size can was used and the potato cubes were suspended in carboxy methyl cellulose (1%) which simulates viscosity conditions of vegetable soups and other type of products such as meat particles in gravy. Three different temperatures were employed (115-125˚C) and the canned potatoes were processed in different modes of processing: still and agitating (10, 20rpm)

Results of the heat transfer study suggested that better heat transfer takes place in free axially rotating cans. Under similar processing conditions, free axially rotating cans gave much higher lethality and cook values and they were characterized by lower heating rate index values as well. End-over-end mode of processing was also found to show good heat transfer results than fixed axial and still mode of processing. Simultaneously, texture and color changes were also studied qualitatively and quantitatively. As under similar conditions of processing, free axial mode of rotation gave highest lethality values so the quality loss in free axial mode were found to be highest as well. A parameter for estimating degree of cooking (C_o/F_o) was found to be lowest for products undergoing free axial rotation which indicate prevalence of rapid heat transfer mechanisms in free axial.

The processing times were adjusted to impart equivalent amount of heat treatments to the canned potatoes. Increasing the retort temperature and when processing in agitating modes, considerable reduction in process times were seen. This reduction in process times resulted in better quality retention in texture and color indices of canned potatoes. Overall high temperature short time and rapidly heating mechanisms demonstrated lesser damage to the quality of canned potatoes.

Due to practical implications, in the current study thermocouples could not be attached to the particles rotating in free axial mode of agitation. So, further studies are suggested in which the temperature data at the center of particles rotating in free axial mode could be gathered. By gathering the temperature profile, accurate processing times can be calculated; which further can be employed to achieve quality advantage and furthermore it will also result in lower energy consumptions in free axial mode of rotation. Two approaches can be followed in order to obtain temperature profiles of particle centers rotating in free axial mode. Firstly, specialized slip ring assembly that can fit individually on a can, could be used. This will prevent breaking of

thermocouple wires during the dual mode of rotation during free axial rotation of cans. Other technique could be based on mathematical modeling in which the heat transfer coefficients (U and h_{fp}) are calculated and then by following empirical methodology developed by Dwivedi and Ramaswamy (2010) time-temperature profile of particle center in free axially rotating cans can be obtained.

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