HEATING BEHAVIOR AND QUALITY FACTOR RETENTION IN CANNED POTATOES AS INFLUENCED BY PROCESS VARIABLES DURING END-OVER-END ROTATIONAL PROCESSING

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A Thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Masters of Science

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SHORT TITLE

Heating Behavior and Quality Retention During Agitation Processing

DEDICATION

This thesis is dedicated to my wife Awa Jobe, and my children Sheikh Jobe, Amie Jobe and Muhammed Jobe for their patience and understanding during my stay in Canada.

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ABSTRACT

Thermal processing involves application of heat to destroy pathogenic microorganisms of public heath concern and to reduce the activity of microorganisms and enzymes that spoil the food. However, the technique is associated with considerable degradation of taste, color, texture, flavor and nutritional quality of processed foods. Data on kinetics of changes in quality factors and their temperature dependence, as well as the heat penetration behavior of the food during processing are necessary to predict and optimize the extent of quality retention. The objectives of this study were: a) to evaluate the kinetics of thermal softening, color degradation and loss of ascorbic acid in potato (*Solanum tuberosum*) at selected temperatures (70-100°C) and to evaluate their temperature dependence; b) to evaluate the effect of process variables (temperature, rotational speed, can size and nature of the covering fluid) on heating behavior of canned potatoes and c) to determine the influence of the above process variables on process time and product quality.

Prepared potato cubes (1.5 cm) were heated in a constant temperature water bath at various temperatures to study the kinetics of quality degradation. Texture, color and ascorbic acid content of treated samples were evaluated. Results indicated that softening of potatoes followed pseudo-first order reaction kinetics, while the color change and ascorbic acid loss obeyed a simple first order. The temperature dependence of rate constants obeyed the Arrhenius relationship.

Heat penetration tests were carried out during continuous end-over-end agitation processing in a pilot-scale rotary, single cage full water immersion retort, with three can sizes (211x400, 307x409 and 401x411), 3 temperatures (110, 120 and130C) and three rotation speeds (0, 10 and 20 rpm). Cans were filled with potato cubes (68.5%) and covering medium (water or 1%CMC), and both liquid and particle temperatures were measured. Heat penetration parameters (heating and cooling rate indices (f_h & f_c) and lag factors (j_{ch} & j_{ch}), process lethality (F_o) and cook values (C_o) were evaluated from the time-temperature data. Higher rotational speed, smaller can size and higher temperature

significantly ($p<0.05$) improved the thermal process parameters. In general, all factors that enhance heat transfer were found to have increasing effect on the process lethality (F_o) and cook values (C_o) accompanied by a decrease in process time and Co/Fo ratio an indicator of conditions promoting better quality.

Similarly, increasing the rotational speed from 0 to 20 rpm resulted in 7, 18 and 35% reduction in process time, at (110, 120 and 130°C), respectively. The achieved reduction resulted better quality retention in texture and color indicator (L, a and b values). The oscillatory mode was found to be slightly better than continuous form in CMC, but no significant ($p<0.05$) difference was observed in case of water cans. It can be concluded that processing at higher temperature, higher rotational speed, and smaller can size promote better quality in both liquids.

RÉSUMÉ

Le processus thermique comprend l'application de la chaleur pour detruire les micro-organismes pathogeniques qui inquiètent la population en matière de santé afin de reduire l'activité des micro-organismes et enzymes qui gatent la nourriture. Cependant, cette technique est associée à une dégradation considérable du gout, de la couleur, de la texture et des qualities nutritives des denrées procédées ainsi. L'information sur les changements cinetiques des facteurs de qualité et leur dépendance sur la temperature, ainsi que l'activité en cours lors de l'application du procédé sont necessaries pour prédire et optimiser la conservation de la qualité. Les objectifs de cette etude furent: a) evaluer la cinétique de l'amolissement thermique, la dégradation de la couleur, et la perte de l''acide "asorbic" dans les pommes de terre (Solanum tuberosum) à des température sélectionnées (70-100°C) et d'évaluer le dépendence sur la température, b) évaluer l'effet des variantes du processus (température, vitesse de rotation, grosseur des contenants et la nature des liquides recouvrant le produit) ainsi que de comprendre le phénomènes caloriques sur les pommes de terre en canne, c) déterminer l'inluence des variantes précitées sur les temps de processus et la qualité du produit.

Des pommes de terre préparées en cubes (1.5 cm) dans un bain d'eau à température constante furent cuites à différentes températures afin d'étudier la cinétique de la dégradation de la qualité. La texture, la couleur et le contenu acide des échantillons ansi traités furent evalué. Les résultats indiquent l''amolissement des pommes de terre suivirent une réaction cinétique de pseudo-premier ordre, tandis que le changement de la couleur et la perte ascorbique obéissent un simple premier ordre. La dépendence sur la température des constantes du ration obéirent à la relation Arrhenius.

On procéda à des tests de pénétration thermique lors du processus d'agitation "end-over-end" dans un "pilot-scale rotary, cage unique d''immersion complète retort, avec trois format de contenant (211x400, 307x409 and 401x411), 3 températures (110, 120 and130C) et trois vitesses de rotation (0, 10 and 20 rpm). Les contenants furent remplis de cubes de pommes de terre (68.5%) et un medium de recouvrement (eau ou

1%CMC), et les deux liquides et les particule de temperature furent mesurés. Les paramètres de pénétration thermique (l'indice du rapport application de la chaleur et refroidissement (f_h & f_c) et le facteur de delai (j_{ch} & j_{ch}), le processus "lethatlity" (Fo) et les valeurs de cuisson (Co) furent évaluer à partir de l'information temps-température. Des vitesses de rotation plus élevées, format des contenants plus petit, et plus haute température amilorèrent de façon significative ($p<0.05$) les paramètres du procédé thermique. En général, tous les facteurs qui améliorent le transfer thermique ont un effet accru sur le processus lethality (Fo) and sur les valeurs de cuisson (Co) accompanié d'une diminution de temps de procédé et du rapport Co/Fo comme indicateur d'amélioration d'une meilleure qualité.

De façon similaire, l'augmentation de la vitesse de rotation entre 0 et 20 rpm résultèrent en une réduction de 7, 18 et 35% du temps de procédé, à (110, 120 et 130°C), respectivement. La réduction résulte en une meilleure retenu de la qualité en texture et indication de la couleur (valeurs L, a et b). La méthode d'oscillation est quelque peu meilleure que la méthode de forme continue dans CMC, mais aucune différence signifative ($p<0.05$) fut observée dans le cas des cannes d'eau. On peut conclure que procéder à de plus haute température, plus haute vitesse rotationelle, et de plus petits formats de contenants améliorent la qualité dans les deux liquides.

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CHAPTER 1

INTRODUCTION

Owing to their convenience, long shelf life and economy, canned foods are likely to stay for sometime. Thermal sterilization of canned foods is about 2-century-old technology and as such it appears in the first instant that there is a little room for further development. In reality, the situation is different. Over the years, the technology continues to grow and evolve. Since Nicholas Appert, in 1809, invented the art of thermal processing the canning industry has witnessed tremendous improvements. Several scientists have contributed to the status-quo of the technology. In 1920, Bigelow and Ball presented the first scientifically based graphical method for calculating minimum process conditions for safe sterilization. In 1923, Ball developed a mathematical model for determination of sterilization process. This was followed by a nomographic method for process determination by Olson in 1939. In 1957, Ball and Olson compiled the research findings of others including their own and published a book on heat sterilization. Since then the technology continued to evolve and grow. To date focus of the current developments have been geared towards increased efficiency in energy utilization and production, easy handling, more attractive packaging and better sensory quality (Durance, 1997). Driven by consumer's food choice based on the issues of safety, taste and convenience, there has been a growing interest in the area of non-thermal processing of foods. Innovations in the area of pulsed electric fields and high pressure have raised the interest of many researchers to seek new materials for equipment, determine process conditions for high-quality foods while ensuring the safety and reliability of the process. At present, successful thermal sterilization process necessitates balancing the beneficial and destructive influence of heat on the desirable characteristics of foods. Several changes occur in food during thermal processing. Some of them are desirable and some are not. On the good side, microbial pathogens and spoilage enzymes that would render the food unfit for consumption are inactivated. On the other hand, the concentration of heat sensitive nutrients such as ascorbic acid and thiamine are greatly reduced and texture of thermally processed vegetables is excessively softened in many occasions. For example, canned vegetables may be too soft due to the disintegration of cell wall materials. The surface of canned meats and other solid-packed products may be darkened by contact with the inner surface of the hot can (Durance, 1997).

Fortunately, microbial destruction kinetics and quality losses usually do not proceed at the same rate. Studies have shown that thermal death rates of bacteria generally proceed much faster with increased temperature than simultaneous reactions that would lead to quality diminishing. For this reason, it is possible to apply the principle of high-temperature short-time (HTST) and ultrahigh-temperature process for better quality retention. However, conduction-heating foods usually do not benefit from this principle because of their slow heating rates. Three approaches have been developed and tested in order to increase the rate of heat transfer into the food primarily to reduce process time and maximize the retention of quality factors. These are (1) thin profile processing (2) aseptic processing and (3) agitation processing. Thin profile concept utilizes, the larger surface area for rapid heating and cooling of foods packed in retort pouches or thin profile containers. In aseptic processing sterile food through different stages of heat exchangers is filled and sealed aseptically into sterile containers. Again high viscous foods and foods containing large particles such as thick soups and meat chunks faces some problems. Agitation processing at high temperature and short time has been recognized to be an effective way of attaining safe and high quality food. It has been established that heat penetration to the critical point of foods packed in containers with viscous or semi-solid foods could be achieved much faster with agitation processing (Clifcorn et al., 1950). The associated improved heat transfer and reduced process time both promote better quality. In addition to reliable kinetic data required for predicting the behavior of quality parameters under a variety of processing conditions, thermal process parameters such as heating rate index (f_h), heating lag factor (j_{ch}) and cooling lag factor (j_{cc}) for particles are also indispensable in determining the process time and optimal conditions for heat sterilization. However, these parameters are influenced by many factors. Prominent among them are mode of agitation, type of heating medium, temperature, rotational speed, headspace, can size and shape, product shape and size and carrier fluid viscosity (Sablani, 1996; Sablani and Ramaswamy, 1995; Ramawamy and Sablani, 1997a). While some of these factors have been evaluated in detail, others need further investigation.

Potato is a historic crop of economic importance to many people. Perhaps it is the fourth most important crop in the world, next to wheat, maize and rice in global tonnage. The main processing methods of potatoes include boiling, cooking in oil, frying and baking. Dehydration and canning are also important methods of processing potato. Potatoes in different forms, including whole, diced, sliced and strips are process. However whole potatoes, usually smaller than 1.5" in diameter constitute the bulk of potatoes that are canned.

Therefore the objectives of this study were:

1. To investigate the effect of cooking temperature on kinetics of selected quality attributes (texture, color and ascorbic acid) of potatoes, and to establish the kinetic parameters
2. To investigate the effects of processing temperature, rotational speed and can size on the thermal process parameters and to relate these to an equivalent process time, which has bearing on quality attributes such as texture and color.
3. To investigate the effects of processing temperature, rotational speed and can size on the quality attributes of canned potatoes.

CHAPTER 2

LITERATURE REVIEW

2.1. Principles of thermal processing

Since the art of thermal processing was invented in 1809, it continued to be the most common sterilization method for microbial destruction in food preservation. Stabilization of food by heat has been in use for decades without proper understanding of the mechanism. The effect of heat on microorganisms and enzymes was investigated and explained by Louis Pasteur in1880. He found that both microorganisms and enzymes could be inactivated by heat in order to prolong the shelf life of food. His discoveries form the basis of pasteurization, which is still applicable in many areas such as the dairy and citrus industry (Willenborg, 1981).

Depending on the severity of the heat treatment and the purpose of the process, different thermal process regimes such as pasteurization and sterilization can be described (Lund, 1975). Pasteurization involves application of mild heat treatment with the purpose of inactivating enzymes and destroying spoilage vegetative microorganisms (bacteria, yeast, and molds) present in low-acid foods ($pH<4.6$). Alternatively, if the pH of the foods were high ($pH>4.6$) the main concern would be the destruction of pathogenic microorganisms of public health risk. Such process is referred to as commercial sterilization. It is carried out in combination with other external factors such as controlling the storage temperature and packaging environment for ensuring long-term safety. The basic consideration for thermal process design is depicted in (Figure 2.1) below:

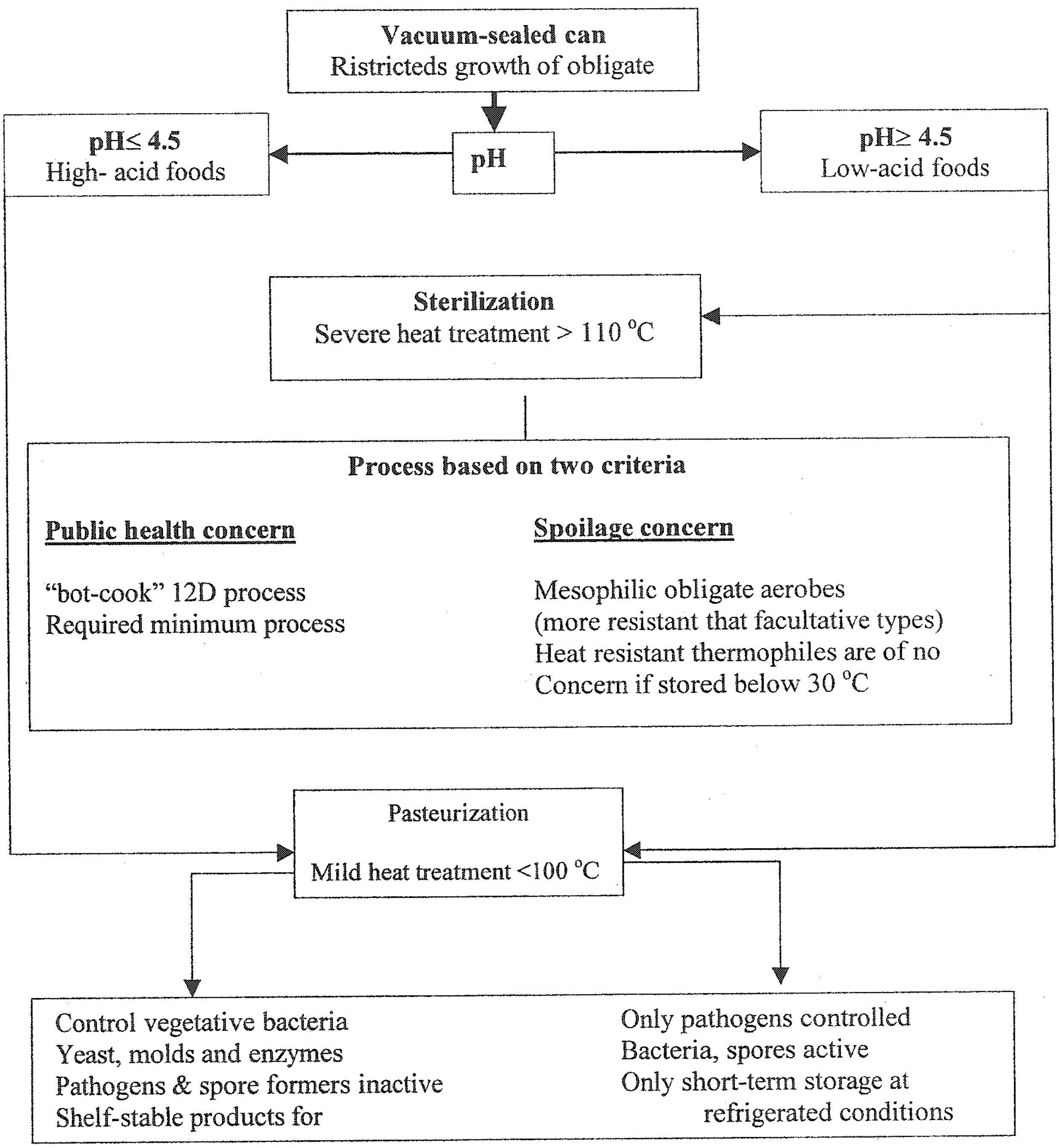


Figure 2.1 A schematic illustrating the principles involved in thermal process applications (Source: Ramaswamy and Abbatemarco, 1996)

2.2. Heat transfer consideration

The common modes of heat transfers in thermal processing are conduction, convection and radiation. Conduction is the transfer of heat by molecular motion in solid bodies, the food does not move and there is no mixing of hot food with cold food. On the other hand, convection is the transfer of heat by fluid flow, as a result of difference in densities and buoyancy effects in fluid products. It involves movement of the heating foods that will result in faster temperature rise of the entire content of the can. Radiation is the transfer of electromagnetic energy between tow bodies at different temperatures.

2.2.1. Factors that affect heat transfer

Penetration of heat into the cold spot of food is confronted by, convective resistance, from heating medium to outer surface of the container and from inner surface to product, as well as the resistance of the packaging material (Figure 2.2). The internal resistance depends on the thermo physical properties, geometry and dimensions of the product (Silva et al., 1992). The mechanism of heat transfer through the container wall is by conduction. For metallic containers of normal thickness and thermal conductivity, there is no appreciable resistance to heat transfer. With regard to the heat transfer from the container wall into the product the mechanism largely depends on the consistency of the food. Foods behave differently during processing. Liquid and semi-liquid foods are mainly heated by convection while solid foods are heated by conduction. However, increase in viscosity and presence of solid particles in semi liquids retard the rate of heating and make the process more complex.

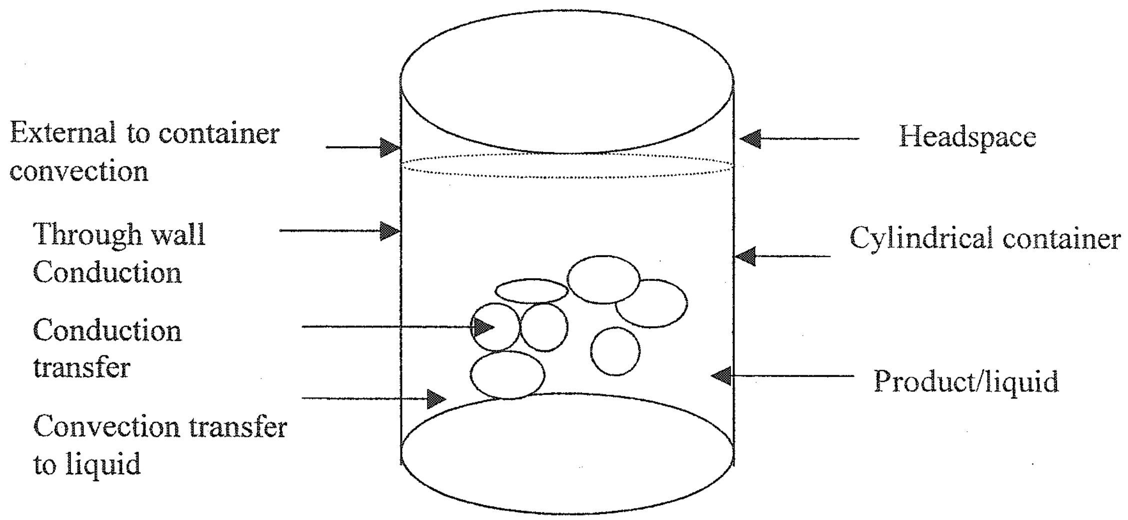


Figure 2.2 : Heat transfer to food product in a cylindrical container (Adopted from Holdwsworth, 1997)

Consequently, semi-liquid products are heated by both convection and conduction implying a longer process time due to the slow rate of heat transfer. In such instances, movement of contents along the can wall is usually slow resulting in over cooking and scorching of the product (Clifcorn et al., 1950). In general the foods nearest to the can surface will sterilize before the food at slowest heating point. In canned solid foods heated by conduction, the slowest heating point is at the geometrical center of the can while in convection heating foods; the cold point is below the center of the can. To ensure that adequate sterilization is achieved, sufficient time must be allowed for the cold point to reach the desired temperature and lethality.

2.2.2. Conduction heat transfer

Conduction heat transfer occurs when different parts of a solid body experiences differences in temperature. As a result, the energy flows from hotter regions to the colder ones. The governing equation under steady-state condition is given by:

$$Q = \frac{k(T_1 - T_2)}{x} At \qquad (2.1)$$

Q = quantity of heat (J or Nm)

T_1 = temperature in (K or °C), subscripts 1,2 refers to the tow sides of the body

t = time (s)

x = distance (m)

A = cross sectional area (m^2) for heat flow

K = thermal conductivity (W m^{-1} K^{-1})

To make it simpler, the above equation can be expressed in differential form, which relates rate of heat flow (dQ/dt) to the temperature gradient (dT/dx). (Holdsworth, 1997)

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \qquad (2.2)$$

Under unsteady-state condition the basis of heat transfer is the famous Fourier's equation expressed in the form of

$$\rho c\ \delta T/\delta t = \nabla k \nabla T, \qquad (2.3)$$

where ρ is the density (kgm^{-3}), c the specific heat ($Jkg^{-1}K^{-1}$) and ∇ the differential operator which equals to $\nabla = \delta/\delta x + \delta/\delta y + \delta/\delta z$ (Holdsworth, 1997).

2.2.3. Convection heat transfer

In the case of convective heat transfer inside containers, the mathematical models required for the prediction of temperatures in order to determine the process requirements are more complicated. Three approaches are used in convective heat transfer. They are (1) film theory, (2) use of dimensionless numbers and (3) use of mathematical treatment of the basic fluid dynamic and heat transfer models. Of the three approaches film theory happens to be less complicated and therefore widely applied. The approach employs the basic heat transfer for convection expressed as

$$Q = h_s A(T_b - T_s), \tag{2.4}$$

where Q is the quantity of the heat flowing (Js^{-1}), h_s the surface heat transfer coefficient ($Wm^{-2}K^{-1}$), A the surface area (m^2), T_b the bulk fluid temperature (K) and T_s the surface temperature. In order to consider the overall heat transfer coefficient equation (2.4) can be expressed as

$$Q = UA(T_1 - T_2), \tag{2.5}$$

Where

$$1/U = 1/h_s + x_w/k_w + 1/h_b$$

h_s and h_b are the heat transfer coefficients for the surface being heated and bulk of the fluid, x_w is the thickness of the wall (m). U is the overall heat transfer coefficient. (Holdsworth, 1997)

2.3. Safety and quality concerns

For technical reasons, quantitative evaluation of the impact of a thermal process in terms of safety and quality is a prerequisite in process design, optimization and monitoring. The effect of thermal treatment on product safety and quality factor depends on the time of exposure and the rate of the heat-induced changes that affect the attribute of interest. The final quality of a food product is determined by the integrated impact of all reactions occurring in the entire food chain. A number of food and process specific factors that influence status of a food are illustrated in the concept of 'preservation reactor' developed by Van Loey et al. 1996 and presented in Figure 2.3.

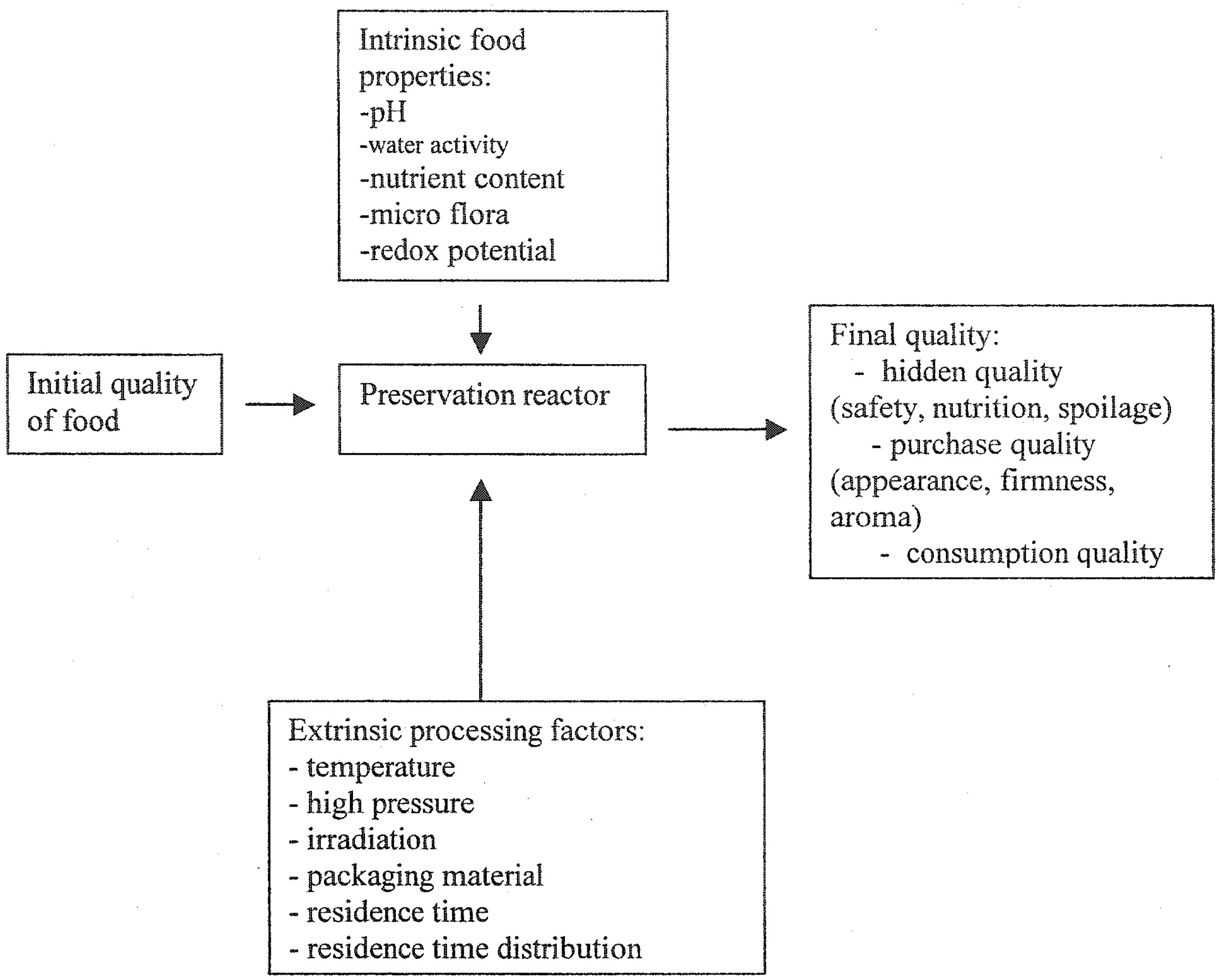


Figure 2.3: Preservation reactor: Factors influencing quality of food (From Van Loey et al; 1996)

Temperature is a primary extrinsic factor for achieving microbial stability during production and long-term storage of food in ambient condition. In spite of the recognition of thermal processing for assuring food safety, the technique is associated with inherent losses in nutritional and sensorial qualities of food. In recent years, considerable changes in habits and trends related to food consumption have been observed. As a result, thermal processing operations and the equipment used in the process have undergone major improvements in the efforts to satisfy consumers and to be compliant with the safety regulations (Martinez et al., 1999). To date, new heating techniques, such as continuous processing in rotary retorts and aseptic units, ohmic and microwave heating of foods comprising liquids and solid including combination of heat with high hydrostatic pressure are increasingly getting popular. In any thermal process application, there are microorganisms and quality related factors that need consideration. These include accuracy in the calculation of kinetic parameters and the deviations that may occur when values taken from literature, obtained from reference media or over a range of conventional temperature, are extrapolated to higher temperatures such as HTST conditions (Martinez et al., 1999).

In order to achieve an optimum commercial sterilization it is essential to have correct kinetic data for microorganisms and quality factors as well as destructive prediction models that facilitate use of time-temperature combination to evaluate the impact of heat on these factors in a variety of processing situations. It is only after having assured the safety of the food that the processor can think of choosing appropriate temperature-time combinations that would optimize nutrient and organoleptic quality retention. Fortunately, microorganisms and quality attributes have different temperature dependence of thermal degradation kinetics. This variation which forms the basis of high temperature short time principle has made it possible to find different time-temperature combinations that will give the same process lethality but leading to different quality losses. At high temperatures, the quality factors are relatively more thermal resistant. Consequently, a HTST process when applicable, results in products with superior quality.

Kinetic studies of microbial or enzyme inactivation involves selection of an appropriate kinetic inactivation model (e.g. zero order, first order), selection of a suitable temperature dependence model (e.g., thermal death time model –TDT, Arrhenius model) and the choice of a regression model that gives high probability of correct estimation of the kinetic values (Martinez et al.,1999).

2.3.1. Target microorganisms

The common microorganisms present in food are classified into three categories namely moulds, yeasts and bacteria. Full-grown molds cannot withstand heat treatment and as such do not constitute a serious public health risk. Similarly, yeasts are also considered to have low tolerance of heat and to a large extent are regarded as harmless even when ingested in high amounts through fermented foods. Therefore, in canned foods the primary concern is with bacteria. These are unicellular organisms less than 3μm in size. They are divided into families and genera. Two of the more important genera are *Bacillus and Clostridium*, whose species are capable of forming spores. These spores can withstand hash condition with little or no metabolic feed. They are extremely resistant to chemical and physical treatments and can resume active life through activation or germination, under anaerobic condition. In containers that are hermetically sealed under vacuum, oxygen supply will be low and the growth of microorganisms that require oxygen (obligate aerobes) to cause spoilage or health hazard will be suppressed. Fortunately, their spores are less heat resistant than the microbial spores of the anaerobic type, which are usually the target in thermal process operations. With reference to *Clostridium botulinum*, prevalence of anaerobic condition can lead to the production of a deadly toxin and cause the disease known as botulism, which can be fatal.

On the basis of survival temperature, bacteria can be classified as psychrophiles, with optimum growth between 14°C and 20°C, mesophiles, with optimum growth between 35°C and 46°C, facultative thermophiles with optimum growth between 30°C and 36°C and thermophiles with optimum growth between 46°C and 50°C (Willenborg, 1981). In many cases bacterial endospores are known to have high heat resistance, those of *Clostridium botulinum* being among the most resistant pathogenic microorganisms. Therefore, normally used as the target for thermal process design.

2.3.2. Factors affecting microbial heat resistance

There are many factors that affect microbial heat resistance. The most common is the acidity of the medium in which microorganisms are present. In general, bacterial growth ceases at pH below 4.6. However, in food with pH higher than 4.6 many pathogenic microorganisms can comfortably grow and produce toxin. With regard to anaerobic microorganisms, their growth and activity is largely pH dependant and it has been generally recognized that *Clostridium botilinum* does not grow and produce toxin below pH of 4.6. Taherian (1995) reported that not only are the food poisoning bacteria incapable of reproducing in acid foods but that large numbers deliberately added to such acid foods actually perish in relatively short period of time. Consequently, the borderline between medium and low acid foods is set at pH of 4.5. Other factors that influence heat resistance of the microorganism or enzyme include heat transfer characteristics of the food, the processing system, storage condition, the initial load of microorganism and the concentration of the heat resistant enzymes (Teheran, 1995). Therefore, successful application of thermal sterilization requires a good understanding of microbial and enzyme activity in canned foods.

2.3.3. Microbial activity in food

When a microorganism lands on food, it may die if the conditions are not favorable for growth. The other possibility is that it can grow and cause spoilage or produce toxic materials that are harmful to health of those who consume the food. Because of this problem it is a requirement for any thermal process intended for long term safety that all microorganisms that constitute public heath risk be destroyed. From a practical viewpoint, microbiologists define the death of bacteria as in ability to produce (Stumbo, 1973). Hence studies on death of bacteria are based on the criterion of failure to reproduce. Several studies have illustrated that when bacteria are subjected to moist heat death occurs in an orderly manner. Generally, the number of viable cells reduces exponentially with the exposure time to lethal temperature. As a result, plot of logarithm of numbers of survivors against the time of exposure gives a straight line. This orderly pattern of death is commonly referred as logarithmic death. There are number of exceptions when the death of bacteria due to heat treatment deviates from the logarithmic form, however, and from thermal process evaluation viewpoint it is conventionally accepted that the death is essentially logarithmic.

Several explanations have been given regarding the logarithmic death of bacteria. One of the soundest explanations was that given by Raln (1929;1945), which associate loss of reproductive power of a bacteria cell when subjected to moist heat to the denaturation of one gene essential to reproduction (Stumbo, 1973). Acceptance of death of bacteria to be logarithmic in nature will allow bacteriologists to describe it mathematically in the same way as a unimoleuclar or first order bimolecular chemical reaction. Unimolecular reaction involves only one substance, and its rate of decomposition is directly proportional to its concentration and decomposition of phosphorus pentoxide is given as an example. Similarly, in a first order bimolecular reaction one reactant is in so many surpluses that variation in its concentration is negligible and as such the rate of decomposition of the second is directly proportional to its concentration. This type of reaction has been exemplified as sucrose in large amount of water. Traditionally, heat inactivation curves of both enzymes and microorganisms are found to follow first order decay kinetics. The common basic equation for studying reaction kinetic for inactivation or degradation of biological materials is generally given as:

$$-dC/dt = k_n c^n \tag{2.6}$$

where C is the concentration of a reacting species at any time t, k_n, is the specific reaction rate, with units $[concentration]^{1-n}$ $[time]^{-1}$, and n is the order of the reaction. Many authors reported that heat inactivation of microorganisms, enzymes or quality factors can be satisfactorily described by the zero order (equation 2.7), first order (equation 2.8) or second order reaction models (equation 2.9):

$$C = C_o - kt \tag{2.7}$$

$$C = C_o\exp(-kt) \tag{2.8}$$

$$1/C = 1/C_o + kt \tag{2.9}$$

where C is the measured concentration of microorganisms, enzymes, or quality attributes, C_o the initial concentration, t the heating time and k the reaction rate constant (min^{-1}). From the survivor curve (Figure 2.4a) let us assume that N_o stands for the initial number of cells like C_o and N represents number of surviving cells after treatment time t, then:

$$t = \frac{2.303}{k} \log \frac{N_o}{N} \tag{2.10}$$

From the figure it can be noted that the time required to kill 90% of the initial cell population is the time required for the curve to pass one log cycle. Therefore if this time is taken as D, then the slope of the survivor curve can be represented as:

$$\frac{\log N_o - \log N}{D} = \frac{1}{D} \tag{2.11}$$

Substituting in the general equation of a straight line gives,

$$\log N_o - \log N = \frac{1}{D}t \quad \text{or} \quad D = -\frac{t}{\log N / No} \tag{2.12}$$

where N is enzyme/microbial concentration at time t; N_o is initial concentration, "t" is the pasteurization/sterilization time and D is the decimal reduction time (the time to reduce 90% of enzyme or microbial concentration at a specific temperature).

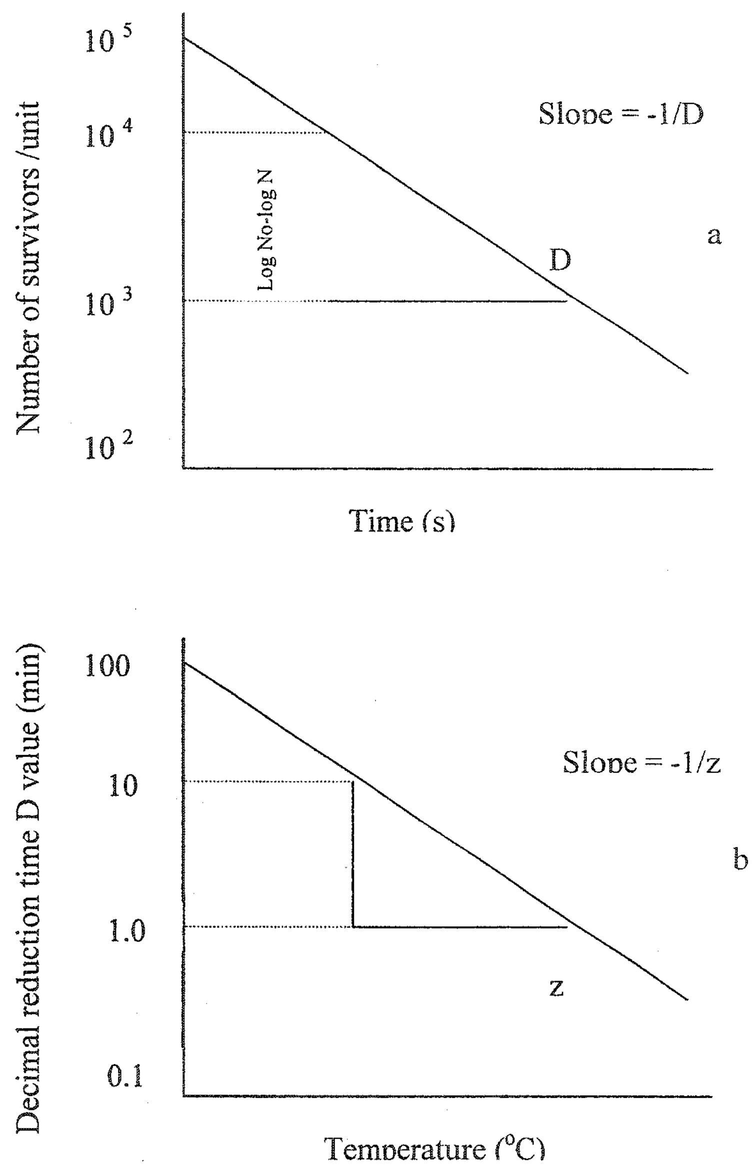


Figure 2.4: Typical D and z value curves

In many cases, the Bigelow (TDT) model (Ball and Olson, 1957) is frequently employed especially in the microbiology studies.

$$D = \ln(10)/k \quad (2.13)$$

$$D = D_{Tref} * 10^{(Tref - T)/z} \quad (2.14)$$

where D is the decimal reduction time (time required for the concentration of microbial spores to be reduced by a factor of 10 at a given temperature, min), D_{Tref} the decimal reduction time at reference temperature (min), T_{ref} the reference temperature (°C), and z the z-value (number of degrees Celsius required to reduce the D value by a factor of 10). The z-value of a given constituent is obtained by plotting D values on a logarithmic scale against temperature on a linear scale as shown in (Figure 2.4b). It represents the negative reciprocal slope of the curve.

In industry, D_o and z are used to denote the thermal resistance of many food components such as vitamins, color, texture, flavor, enzymes, vegetative cell and spores. D_o is defined as the time at the reference temperature of 121.1°C required to decrease the constituents by 90% (Lund, 1975). In thermal death studies on spore suspension, the logarithmic survival curve is used to calculate this decimal reduction value. In reality, the criterion of process adequacy is based on the reduction of the bacterial population to a tolerable level. In low acid canned foods pH <4.5 the organism of primary concern is Clostridium botulinum. It has been established that the minimum safe heat process given to low-acid food should decrease the population by 12 logarithmic cycles the basis of the 12D concept or "bot cook". The D_o value for *C. botulinum* is estimated as 0.21 min (1D at 121.1°C) with a z of 10 °C. With respect to quality factors, D_o values for vitamins; color and texture are generally 100-1000 times bigger than those of microorganism, enzymes, vegetative cells and spores (Lund, 1988). The difference in D values will make it possible to maximize quality factors while ensuring adequate safety by using High Temperature Short Time principle (HTST).

2.4. Thermal processing and destruction kinetics

To achieve the primary goal of thermal processing, sufficient amount of heat must be applied for a predetermined time in order to inactivate microorganisms that can spoil food or act as potential risk to human health. For this reason, it is essential to know how heat-resistant microorganisms are, in order to design a suitable time-temperature combination for their inactivation. Two common methods are used to measure thermal resistance of bacteria. The first is thermal death time method. In this method inoculated product in sealed tubes are subjected to heat for a specific time followed by cooling. The content is then cultured and the number of survivors determined. Alternatively, inoculated product in cans can be used. In this case, cans are heated in small controlled steam retorts. The cans then are cooled by water in the retort after which they are sub cultured or incubated to determine the number of survivors (Stumbo, 1973)

The theory of thermal process on the basis of microbial killing was developed by Bigelow (1921) and Ball (1923). It emanated from the concept that microbial spores perish at all temperatures; however, the higher the temperature the more likely it is that death will occur (Holdsworth, 1997). The statistical implication of the theory is that every spore also has the chance of escaping death, which does not change with time. If "P" represents the probability of escaping death for unit time, then the chance of surviving for *t* units of time will be P^t. This suggest that if number of spores (N) of equal resistance are taken into consideration, the number of survivors S expected after time t will be

$$S = NP^t \tag{2.16}$$

By taking log on both sides

$$\text{Log}(S) = \log(N) + t*\log P. \tag{2.17}$$

This means that bacterial death is of a logarithmic order, and a plot of log S versus time will yield a straight-line. With slope d(log(S))/ dt = log(P) (a constant). Since the probability of escaping death range from 0 to 1, then log P is negative. Therefore, if log P = -1/D (slope of Figure 2.5) then,

$$S = N \times 10^{-t/D} \tag{2.18}$$

where D is the decimal reduction time measured in minutes.

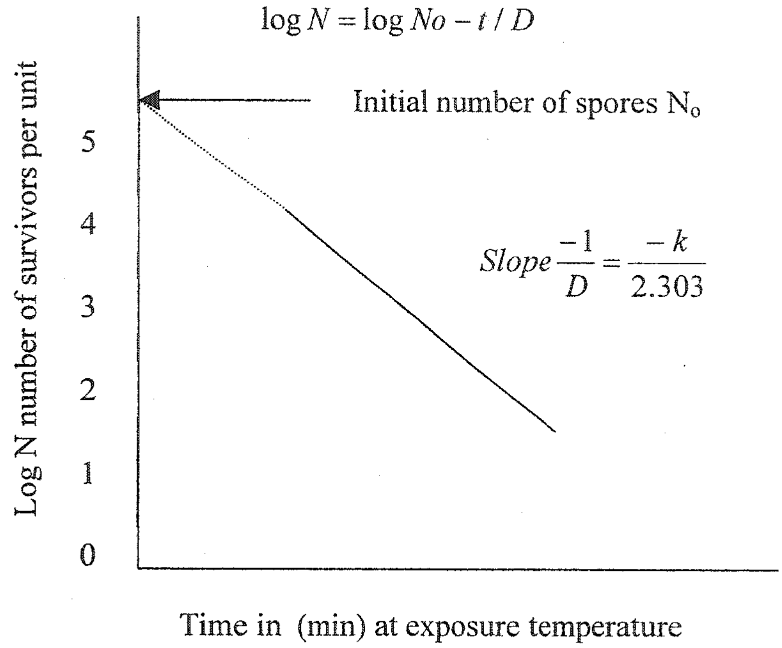


Figure 2.5: Semi-logarithmic survivor curve

In practical terms the logarithmic order of death implies that it is not possible to give a time and temperature combination that will kill all the spores that may be present in canned foods but by increasing the process, the degree of sterilization also increases. Therefore, in order to produce safe low-acid foods the aim should be to achieve probability of spore survival of one in 10^{12} units or less, corresponding to a 12D process mentioned earlier on.

2.4.1. Temperature dependence of death rate

The effect of temperature on growth and inactivation rates of microorganisms and other quality attributes has been widely studied. The dependency nature of death rate to temperature is of great significance in all aspects of thermal processing. The importance will be more appreciated when one faces the challenge of establishing adequate process for foods. Two approaches are used to explain the nature of this dependence. The first one is Thermal Death Time approach (TDT) and the second is Arrhenius kinetic approach.

The (TDT) concept was first introduced by Bigelow and Esty (1920) based on empirical model to the temperature dependence of the first order destruction of microorganisms and was first applied by Bigelow in 1921 in connection with the minimum time required for the total destruction of a microbial population. He discovered that a plot of temperature versus log time would result in a straight-line relationship. The slope of the curve represents negative reciprocal of the z value defined as " number of degrees required for a specific thermal death time curve to pass through one log cycle (change by a factor of 10)".

$$D = D_r 10^{-(T-T_r)/z} \tag{2.19}$$

T is the processing temperature, T_r the reference temperature, z is the degree temperature required to obtain 10- fold change in inactivation time. It is worth to note that different organisms in a given food will have different z values and a given organism will have different z values in different foods.

Arrhenius approach is based on thermodynamic concept of chemical reaction rate constant, which relate the reaction rate constant, activation energy and absolute temperature in the following equation:

$$k_T = k_{ref}[(E_a / R_g)(1/T_{ref} - 1/T)] \tag{2.20}$$

where R_g is the universal gas constant. The z-value and E_a concepts rely on different mathematical models. A log-linear model is suggested in the TDT concept (Figure 2.6), whereas the Arrhenius equation proposes a log-linear relationship between rate constant and the inverse absolute temperature with activation energy (E_a) representing the slope index of the semi-logarithmic curve. Both concepts are valid within a finite temperature range (Hendrickx et al., 1995). In the sterilization temperature range of 135 to150 °C, kinetic data for proper process design are not readily available and quite often based on extrapolation of kinetic information gathered at lower temperatures. Ramaswamy et al. (1989) have noted differences in decimal reduction time extrapolated from the TDT and the Arrhenius models and therefore reported possible discrepancy in the conversion of factors from one system to the other outside the temperature limits over which original data were obtained:

$$z = \frac{(T2 - T1)}{(\log D1 - \log D2} \quad (2.21)$$

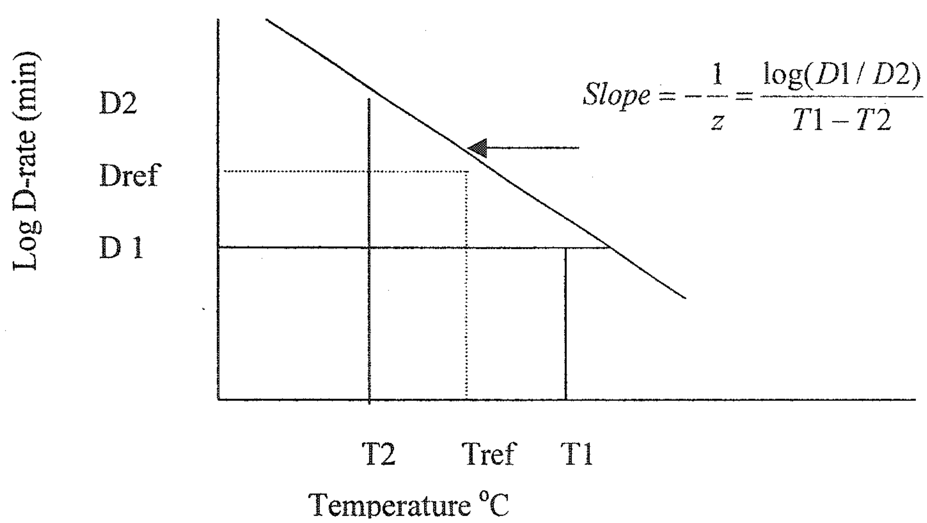


Figure 2.6: Thermal death time curve to obtain z value

2.5. Quality factor destruction kinetics

When heat is applied to inactivate enzymes and destroy microorganisms, several types of chemical and physico-chemical reactions also take place. Some are desirable but often exceed the limits (e.g. cooking) others are less desirable but unavoidable (nutrients and other quality factor loss). Many researchers have extensively studied the degradation kinetics of quality factors (Lund,1975; Holdswort,1985; Abbatemarco and Ramaswamy, 1994 and Isabel and Silva, 1999) described nutrient content and sensory properties as very important factors in consumer acceptability of certain food products. Lund (1982) viewed sensorial quality as more important characteristics of food since it concerns attributes that are visible to the consumer. For these reasons, it is essential to make a balance between microbial destruction and quality retention to satisfy consumers.

Irrespective of the fact that both follow the first order kinetic theory, sensitivity of vegetative cells, microbial spores and quality attributes to heat are not the same. Clifcorn et al. (1950) reported that the destruction of bacteria increases tenfold for each 18°F (10°C) rise in temperature while the reaction rate responsible for quality deterioration is only doubled. This fact could enable food processors to optimize quality characteristics and produce foods of high quality, which are microbialy, stable. However, this situation may pose a problem since enzymes are also inactivated more slowly than microorganisms. Consequently, there is a possibility of having residual enzymatic activity, which by itself, or by regeneration of the enzyme negatively influence the quality during storage (Martinez et al., 1999). This problem can be solved by optimized sterilization and ensuring precise kinetic parameters for inactivation and regeneration of control enzymes and peroxidase has conventionally been used for this purpose. It is one of the most heat resistant found enzymes in numerous vegetables. One of the major problems of peroxidase is the ability of the enzyme to regenerate after a sterilization process. A characteristic that seems to depend on the type of vegetable, the isoenzyme and the heating time at specific temperature (Adams, 1978).

2.6. Effects of thermal processing on quality attributes of food

Numerous studies have shown that nutrients and other quality attributes are negatively affected during thermal processing. The changes that occur during processing include protein denaturation, aggregation and degradation, fat liquidation and subsequent breakdown reactions. Enzymes and microbial destruction, loss of some trace nutrients (soluble proteins, minerals and vitamins), reaction between sugars and amines and interactions between flavor precursors are common (Meyer, 1978; Lawrie, 1985). These changes are undesirable but sometimes they impart the desirable cooking and flavor characteristics to the food. Cooking therefore plays a significant role in developing desirable quality and palatability traits such as flavor, juiciness, tenderness, color and overall acceptability. For example, in meat processing, the thermally induced protein-protein association results into inter-linked gel matrix which contribute considerably to the binding and fat immobilization in processed meat and poultry products (Ziegler and Acton,1984).

2.6.1. Thermal processing and nutrient retention:

The increase in the nutritional awareness of consumers in last decades manifested in a higher demand of products with high sensory and nutritional quality constituted a growing challenge to food processors. This has resulted in stronger desire to optimize the processing conditions in order to produce foods of high quality. Consequently, thermal process has to be designed in such a way that it delivers the desired lethality without necessarily reducing other food qualities to nil. The processing temperature should result in minimum surface cook-value after achieving the desired degree of sterility (optimal temperature).

2.7. Thermal process evaluation

The two well-established techniques for evaluating thermal processes are the in situ approach and the physical-mathematical method. In the in situ method, changes in the actual quality or safety attribute are determined before and after processing to have a reliable estimate on the status of the attribute of interest. In practice, measurement of microbial counts, texture, and vitamin content and organoleptic quality by in situ method is usually slow, costly and sometimes infeasible due to detection limit or sampling difficulties.

2.7.1. F_0 value

In the physical-mathematical method, the time-temperature profile imposed on the food is integrated to evaluate the impact of a thermal treatment on the parameter of interest. The exercise is carried out either to determine the F-value for a given process time or to calculate the process time for a given F-value. F-value is defined as the number of minutes at a specific temperature required to destroy a specific number of organisms having a specific z value (Potter and Hotchkiss,1995). The required information is the time-temperature history of the product at the slowest heating point and the f_h-and j values. The calculation requires solution of the basic integral equation of F_o or its Arrhenius counterpart.

$$F_o = \int_0^t 10^{(T - Tref)/z} dt \tag{2.21}$$

$$F_o = \int_0^t e^{2.303(T - Tref)/z} dt \tag{2.22}$$

Numerous physical-mathematical methods are employed for thermal process calculation. The universally agreed ones are (1) the general method which include graphical and numerical methods (2) analytical methods and (3) formula methods. The general method was developed by Bigelow et al. (1920). Its original form consists of converting the time-temperature history graph into a lethal rate graph and the area under curve is determined by using a planimeter. The numerical methods normally use the trapezoidal rule or Simpson's rule to calculate the area of irregular geometric figures (Holdsworth, 1997). In general, methods for determination of thermal process have undergone considerable development through decades. To date several formulas are presented for characterizing temperature response of foods to be sterilized. Depending on the approach to the solution of the problem they can be classified into theoretical and empirical formulas. The first makes use of analytical or numerical solutions of theoretical heat equations while the latter is based on heat penetration data. However, Pham (1987) pointed out that the formula methods are somewhat misnomer since they are invariably presented as tables rather than equations. Hayakawa (1978) further divided formula methods into two groups. First group comprised of methods that calculate the lethality at the cold spot for example such as that of Ball (1923), Jakobsen (1954) and Ball and Olson (1957). Second group consists of methods that calculate mass average lethality for whole containers. Such methods have been developed by Gillespy (1951), Ball and Olson (1957), Stumbo (1965, 1973), Hayakawa (1969) and Jen et al. (1971). This grouping is similar to what is in some places referred as biological method (Biological Indicator units) or thermocouple method commonly used to estimate process lethality. In each case a whole is to be punched and thermocouple or BIU be installed to the slowest heating rate spot. From the time-temperature profile of the cold spot of the container, the heating index $f_{h,}$ the lag factor j_h and lethality of the process (F_o), can be calculated.

2.7.2. Cook value

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

$$C = \int_0^t 10^{(T - Tref)/z_c} dt \qquad (2.23)$$

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

2.7.3. Heating and cooling rate indices (f_h, f_c, j_{ch}, and j_{cc})

These indices are considered as prerequisite tools for proper calculation of process time. They can be evaluated from the temperature-time profile. It has been shown that when the logarithm of the temperature difference between the retort and the product center known as temperature deficit (T_r –T) during heating is plotted against time on a linear scale, a straight line is obtain after the initial lag. The intercept is obtained by extending the straight line portion of the curve to the y axis representing T_{pih} such that

$$T_r - T_{pih} = j_{ch}(T_r - T_o) \text{ . or}$$

$$j_{ch} = \frac{T_r - T_{pih}}{T_r - T_o} \tag{2.24}$$

where j_{ch} is the heating lag factor, which is a measure of the thermal lag (or delay) of the beginning of uniform heating in the product. It is corresponding value during the cooling period is j_{cc} and is calculated as

$$j_{cc} = \frac{T_{pic} - T_w}{T_{ic} - T_w} \tag{2.25}$$

Part of the lag is due to the slow come-up time of the retort and this is accounted for by determining the new zero time for the process. Ball and Olson (1957) used 58% of the come-up time as useful contribution to the process and this is widely accepted (Holdsworth, 1997). This implies that 42% of the come-up time should be added to the process time at retort temperature.

The slope of the line (Figure 2.7) is given by the tangent of the angle between the line and the t-axis, which represents time for the curve to traverse one log cycle. The negative reciprocal of this slope for the heating part is referred to heating rate index (f_h) and the corresponding value for the cooling period is the cooling rate index (f_c). f_h is an indicator to the heating rate. The higher the value the longer it takes for the log to traverse one cycle indicating slow rate of heat penetration.

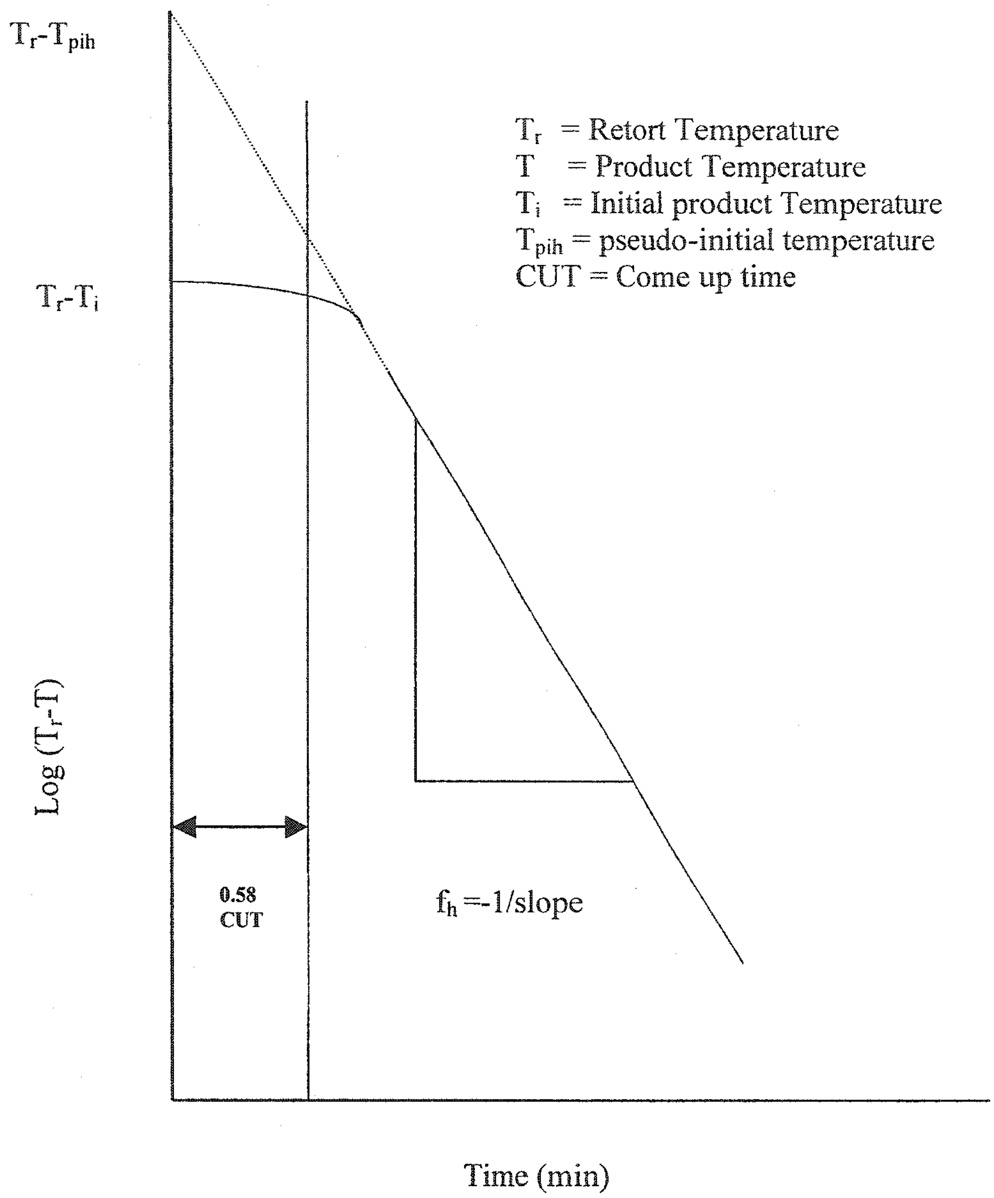


Figure 2.7: Typical semi-log plot of the heating curve

2.7.4. Temperature conversion

One of the major contributions of Schultz and Olson outlined in Stumbo (1973) was the formulation of mathematical equation that allows conversion of can temperature when the retort temperature is changed and the initial temperature remained the same or vice-versa. The conversion for the first instance is given in equation (2.26) while the latter in equation (2.27)

$$T'_c = T'_r - \frac{T'_r - T_i}{T_r - T_i}(T_r - T_c) \qquad (2.26)$$

$$T'_c = T_r - \frac{T_r - T'_i}{T_r - T_i}(T_r - T_c) \qquad (2.27)$$

T_r = original retort temperature

T'_r= new retort temperature

T_i= initial temperature

T_c= a can temperature of the original set

T'_c = a new can temperature corresponding to T'_r

2.8. Techniques in thermal processing

Foods are heterogeneous in nature. They are in the form of, fluid or solid state. This heterogeneity has considerable implications in the characteristics and behavioral properties of thermally processed foods. As such when semi-liquid and solid foods are processed in still retorts many problems are encountered. In general, still retorting is associated with slow rate of heat transfer and heavy loss in quality attributes. In order to alleviate this problem numerous thermal processing techniques have been developed. The improved methods involve carefully engineered processes such as application of high temperature short time principle in aseptic and agitating processing.

2.8.1. Aseptic processing

It involves putting commercially sterilized food into a presterilized container, which is hermetically sealed under sterile environment. The advantages include less damage to the food, shorter processing time and better quality end product. Besides that, it reduces energy consumption, suitable for new packaging, designing and readily adaptable to automatic control (Singh and Nelson, 1992). As a processing technique it evolved through various stages in the food industry. The development of new container materials such as polymer plastics and polymer-coated paper containers have remarkable influence on the increased interest and attention devoted to aseptic processing and packaging of low acid foods and even low-acid products containing particulate. The technique is based on the principle of HTST process, which is claimed to have several advantages over conventional processing. It utilizes the previous existing technology systems such as continuous processing in heat exchangers. Scraped-surface heat exchangers were given special attention, because of high viscosity of carrier fluids used and the need to agitate the liquid/particle mixture during heating and cooling (Heldman, 1989). Besides of the several benefits, (HTST) is not without shortcomings. In solid and viscous foods, the presence of thermal gradients and slow heat transfer rate to the critical point negates the advantages of the HTST principle (Lund, 1982). In addition to this the ability of HTST process to completely inactivate some of the heat resistant enzymes (e.g. peroxidase) is questionable. The efficacy of aseptic processing is influenced by many factors. The most important ones include residence time and heat transfer coefficient of the particle.

2.8.2. Thin profile processing

With the advent of thermostable microwave plastics, foods processed in thin-profile packages, such as retort pouches and semi-rigid plastic containers were popular in 1970s owing to their superiority over the conventional packaging in several aspects. Pouches provide better quality product due to rapid heat penetration, shelf stability without refrigeration, convenient end use preparation, and compact storage characteristics before and after packaging, easier opening and disposal (Ramaswamy,1988). Pouches are laminated structures that are thermally processed like a can. The operational requirements include, provision of superior barrier property for a long shelf life, seal integrity, toughness and puncture resistance with the ability to tolerate the rigor of thermal processing. The concept of retort pouch development was introduced in the United State in early 1950's. The bulk of the work was carried out by the U.S Army Natick Development Center in order to replace can component in military combat ration. Approval of the U.S Department of Agriculture was granted in 1974, but The U.S Food and Drug Administration raised certain concerns regarding the polyester and epoxy components of the laminating adhesive to migrate into the food. As a result, the approval was withdrawn in 1975 and in 1977 regulation for high temperature, which specified the materials that are permissible for making pouches, and set the extraction limits for them. However, while U.S was exploring the applicability of pouches, several low-acid foods thermally sterilized in pouches were already in market.

2.8.3. Rotational Processing

While canned food can be sterilized at relatively low temperature, the process will require considerable amount of time, which will result in product of inferior quality. Container agitation in rotary retorts during processing provides several advantages over still-retort processing. Chief among them are improved quality and reduced process time as a result of increased rate of heat penetration (Ramaswamy et al., 1993). The technique has been commercially employed in the processing of high quality peas, corn, asparagus, mushroom and a variety of semi-solid or viscous food such as sauces and soups containing meat chunks or vegetables (Eisner, 1988). Early studies have indicated that rotational thermal processing has the potential of improving the quality of canned products. Research has shown that quality factors of canned food such as color, flavor, texture and vitamin content are better preserved by the high temperature – shorter time process.

Rotational processing can be carried out in either axial or end-over-end mode. The principle of end-over-end (EOE) induced convection heating was first introduced by Clifcorn et at. (1950). It results in higher heat transfer to the product, which generally corresponds to shorter process time and improved product quality. The choice of method and rotational speed depends upon the nature of the product. The benefits include facilitation of heat penetration, prevention of caramelization that can occur at the liquid interface and circumventing the problem of crusting of the product along the container walls when elevated sterilization temperatures are used (Larouse and Brown 1997). Naveh and Kopleman (1980) reported that for viscous liquid used over a wide range of rotation speed, end-over-end was found to be more effective than axial rotation. It offers faster heating rate mainly due to the headspace bubble flow pattern, which tends to improve mixing and turbulence during processing.

Several physical parameters are reported to have influence on the bubble motion. These include rotational speed, system geometry, headspace volume, product viscosity, off-center axis of rotation, particle density and presence of particulates (Knap and Durance, 1999). It has been reported that moving the rotating can from the central to the off-center axis of rotation increases the centripetal acceleration encountered by the liquid and the greater is the bubble velocity relative to the liquid, which enhances the heat transfer coefficient (Naveh and Kopleman, 1980). With regard to the rotational speed, increasing the rotational speed to a certain limit tends to increase the heat penetration rate.

2.9. Food quality

Quality is a concept. It is not a physical entity or instance that has a fixed position in time and space (Bremner, 2000). Quiet often, authors of papers do not distinguish between the variables investigated and the concept of quality. There are many definition of quality as applied to food. Botta's definition (1995) mentioned in Bremner 2000 stated, " quality is the extent to which a product fulfils consumer needs and wants". In reality it is the degree to which the user's expectations for wholesomeness, integrity and freshness of food has been met. Kramer and Twigg (1970) described 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". These include color, texture, flavor, nutritional values and microbiological qualities.

2.9.1. Texture

Irrespective of the fact that texture is a valuable attribute that greatly influences the consumer's acceptance and preference for food, it commanded little attention from the researchers for decades. There could be several reasons for that. Firstly, consumers usually do not talk about texture unless there is a defect. Secondly it appears that they lacked the proper vocabulary to describe texture. For many years taste has been used to describe the spectrum of mouth perceptions including flavor and texture. The inability to perceive texture by physiological receptors as in the case of taste and smell makes it more complicated. Satisfactory perception of textural properties requires an active manipulation of deformation of food and is an integration of sensations arising from tactile and kinesthetic receptors in dermal, muscles and connective tissues (Christensen, 1984). To date texture is defined as sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces. The specific senses involved being vision, kinesthetic and hearing (Szczesniak, 1991). The definition recognizes texture as sensory property of multi-parameter attributes and structure and that beside the sense of feel some aspects of its parts can be detected by the sense of vision and hearing.

Further development in research resulted in the characterization of texture into mechanical, geometrical and those related to moisture and fat content. The mechanical characteristics consist of primary parameters such as hardness; cohesiveness, springiness, adhesiveness and viscosity while the secondary parameters involve fracturability, chewiness and gumminess. There is substantial level of overlapping in this characterization. Szczesniak (1963) concluded that fracturability is a product of fair level of hardness and low level of cohesiveness and that chewiness is the product of high cohesiveness, substantial springiness and mid-range hardness.

Canned vegetables of low acidic nature are usually processed at high temperature to ensure the safety of consumers. This kind of severe heat treatment has negative effect on the nutrient and other quality attributes as well. The effect of temperature on textural properties of food some time acts as a limitation to the possibility of canning and increased utilization of crop produce.

It has been observed that canned potatoes are excessively softened during thermal processing. Since firmness exerts a significant influence on acceptability of canned potatoes, there was a continued interest in increasing firmness retention during processing. It has been reported that firmness of canned potato can be increased by soaking or incorporation of $CaCl_2$ into the syrup (Scott and Twigg, 1969; Woodroof et al., 1955). It is presumed that Calcium chloride interacts with pectic substances in a divalent cation cross-linking and thus forms intercellular polyelectrolytes, which significantly contribute to the texture quality (Jen, 1989).

2.9.2. Color

Color is a valuable quality attribute that influences the acceptability and consumer appeal of food. However, many foods especially green fruits and vegetable suffer from color degradation during thermal processing due to the conversion of chlorophyll to chlorophyllide or pheophytin. The former retains the magnesium atom in the tetrapyrol nucleus and are green in color while the latter are magnesium free derivatives, which include olive-brown, hydrogen containing compounds and the metalo-complexes. Chlorophyll exist in a and b forms. The two structures differ only in the presence of methyl or formyl group at the C-3 carbon atom. Chlorophyllide are formed as a result of hydrolysis of the C-7 propionic acid phytol ester bond catalyzed by the heat activated chlorophyllase enzymes believed to be present in all plants in varying amounts. Gupte et al. (1964) reported that chlorophyll b is more heat stable than chlorophyll a. Sweeney and Martin (1961) observed that chlorophyll retention in cooked vegetable is highly influenced by the pH medium. Haisman and Clark (1975) found that formation of combined pheophytin a and b tends to be greater in plant tissues with low pH values when immersed in water at 60°C. Serious efforts have been made to improve the quality of thermally processed green vegetables but with limited success. pH control of process solutions, high temperature short time processing and enzymatic alteration of chlorophyll within plant tissues to increase its stability were tested by many researchers, however, none of these methods have been entirely successful (Joachim et al., 1989).

Tristmulus colorimeters are generally employed to objectively describe color as a combination of the three primary color intensities (red, green and blue) as specific point in three-dimensional space. Hunter L*,a*, b* notations are commonly used to describe instrumental sensitivity to color. For example, L is a measure of lightness/brightness indicator (a higher L value indicates a lighter/brighter sample), a* indicates degree of greenness (if negative) or redness (if positive) and b* indicates blueness (if negative) and yellowness (if positive). In order to make it much simpler, some researchers have combined the individual differences in L*, a* and b* values to obtain a total color difference (ΔE) in foods using the following equation (Francis and Clydesdale, 1975):

$$\Delta E^2 = (\Delta L^2 + \Delta a^2 + \Delta b^2) \qquad (2.28)$$

However, Setser (1984) reported that the above equation indeed provides very limited information regarding the nature of color difference between tow samples.

2.9.3. Vitamins

Vitamins are important quality factors of food. Unfortunately, some of them are very sensitive to heat and therefore suffer considerable loss during thermal processing. Ascorbic acid is one of the most susceptible to losses during processing due to its solubility in water and highly oxidized nature. In processed foods most significant losses occur as a result of chemical degradation. Several researchers have studied the mechanism of ascorbic acid loss and reported that it obeys first order reaction order (Johnson, Braddock and Chen, 1995; Saguy, Kopelman and Mizrah, 1978).

2.10. Origin and economic significance of potato

The origin of potato belongs to South America. From there it spread around the world. It is a major food crop in temperate regions and is either used as staple food or simply as vegetable in tropical and sub-tropical countries. The tubers are consumed in various forms mainly after cooking or processing. The crop is an important source of energy, however, a substantial amount is required in order to meet the daily energy requirement of the body. Due to high moisture content potato is perishable and as such has to be processed or frozen to extend the shelf life. A part from water, carbohydrates form the major chemical constituent of the crop. They represent about 63-86% of the total solid. A large amount of potato's carbohydrate is in the form of starch, which is the main source of sugars composed of amylose and amylopectine in a 3:1 ratio. The total sugar content ranges from 0.1 to 0.7% in fresh weight basis. The protein content of potato is relatively small about (2%fwb) but of a high biological value comparable to soybean. The crop is a good source of ascorbic acid, thiamin and pyridoxine. The amount of ascorbic acid in fresh potato ranges between 15-19 mg per 100g edible portion (Nourian, 2003). However, the amount is significantly affected by storage duration and cooking methods. Potato is processed in different ways. The most important methods of processing include, chips making, frying (French fries), dehydration, cooking and canning. During canning potatoes are excessively soften and as a result, several methods were tested to increase the firmness of canned potatoes.

White potatoes are practically canned in all the major growing areas of the United States. Annual production of canned potatoes was estimated about 6 million cases in the early 1970s in the United States. Since then production fluctuates from year to year. Potato is widely used in research due to it is uniformity in nature compared to many vegetables. It is also cheap and readily available in many places. Consequently the crop was selected in this study.

Chapter 3

KINETICS OF QUALITY ATTRIBUTES OF VEGETABLES

3.1. Abstract

Kinetics of thermal softening, color change and loss of ascorbic acid in potato (*Solanum tuberosum*) were studied at selected temperatures (70-100°C). Cut samples of potatoes were heated in a constant temperature water bath at various temperatures. Samples were removed from the water bath at selected time intervals and immediately cooled in ice water. Heat-treated samples as well as the untreated control were evaluated for texture, color and ascorbic acid. The softening of these vegetables followed a pseudo-first-order reaction kinetics as has been reported in some earlier studies, while the color change and loss in ascorbic acid obeyed a simple first order. The temperature dependence of rate constants obeyed Arrhenius relationship and the process activation energy were determined. It could be concluded that thermal processing as applied to vegetables affect substantially on texture, color and ascorbic acid content. The kinetic data gathered could be used in predicting the vitamin loss, color change and texture softening of potato during thermal processing. Characterization of thermal softening is an essential step for the optimization of textural firmness and other quality attributes during thermal processing of vegetables.

3.2. Introduction

Softening of vegetable tissue, color degradation and nutrient loss during cooking are major constraints facing thermal processing. This has considerable bearing on the principal task of food processors, which is to develop processing techniques and produce products of high and uniform quality. The significance of the challenge is more realized as consumers have become more demanding as a result of increased nutritional information and change in lifestyle and eating behavior. Quality attributes of food that are more susceptible to heat damage are texture, color and vitamins.

3.2.1. Texture

Texture is an important quality parameter of vegetables, and its protection or modification is desirable (Mittal, 1994). It can be characterized as the "group of physical characteristics that arise from the structural elements of the food, sensed by the feeling of touch, related to the deformation, disintegration and flow of the food under a force and measured objectively by functions of mass, time and distance" (Bourne, 1982). Excessive softening during processing may render the food unacceptable, as texture is an important overall quality parameter that affects consumer acceptability of food. A knowledge of physical changes that occur as a function of temperature and time is crucial for optimizing process conditions. As success of thermal process design depends on relevant and accurate kinetic information for quality evaluation. Kinetic parameters can supply useful insight into understanding and predicting changes that occur during processing. A number of parameters have been tested as indicators of textural quality. Thybo and Martens (1998) developed a sensory quantitative descriptive texture profile of cooked potatoes covering nine textural attributes in terms of geometrical, mechanical and moisture characteristics. These include firmness, gumminess and adhesiveness, however firmness has been used more often in quantifying texture degradation of vegetables by virtue of its closeness to the consumer perception. Other parameters suffer from poor correlation to consumer acceptance.

Kinetic studies have been carried out on a variety of vegetables and numerous instrumental methods have been used for testing firmness. Huang et al. (1990) measured firmness of potato by puncture test and Watson and Jarvis (1995) tested firmness by force required to cut sweet potato tissue by a thin wire. Irrespective of the various methods developed fundamental methods such as compression test of uniform samples have been reported to yield better correlation to perceived sensory quality.

With regard to the mode of compression a single uniaxial test is widely used for texture measurement. However, use of double uniaxial compression test of texture profile analysis was also reported to imitate first and second bite in the mouth (Szczesniak 1963;

Bourne 1978). Many vegetables such as carrots (Paulus and Saguy, 1980) mushrooms (Anantheswaran et al., 1986) pears (Rao et al., 1981), regular turnips and beet roots (Taherian, 1995; Nourian, 2003) have been evaluated by uniaxial single cycle compression tests. The majority of theses studies indicated that time-temperature dependency of thermal softening of vegetables can be satisfactorily described applying reaction kinetic laws and Arrhenius equation. Loh and Breene (1981, 1982) reported that the first order kinetic model was applicable for many vegetables. Harada et al. (1985) mentioned that for process time beyond the optimal time, textural softening was best described by a second order kinetic equation.

Bourne (1989) showed that the rate of thermal softening of vegetable tissue is in agreement with two simultaneous pseudo first order kinetic mechanisms. Alvarez et al. (2001) indicated that the rate of thermal softening of potato tissue by water treatment at 50, 90 and 100°C was consistent with one pseudo first order kinetic mechanism, while at 70 and 80°C the rate of softening was consistent with two simultaneous pseudo first-order kinetic mechanism.

First order kinetic model is characterized by a straight line when the logarithm of the texture property under investigation is plotted against time. It is important to note that most of these studies used relatively short heating time. The classical work of Huang and Bourne (1983) was the first reported evaluation of texture degradation kinetics of vegetables using prolonged heating time. Consequently, they formulated the dual mechanism first order kinetic theory. The model was described as having a linear part with a steep slope (mechanism 1) followed by another linear region with a shallow slope (mechanism 2).

Due to the failure of simple first-order model to describe all data points, the authors postulated that two concurrent first order reactions take place when vegetables are heat treated. They hypothesized that mechanism 1 was due to a substrate "a" and mechanism 2 was due to substrate "b" which resulted into the creation of two-substrate theory. The same authors further theorized that substrate "a" on which mechanism 1 acts could be the pectic substrate undergoing changes in the inter-micellar region during processing. The chemical basis for mechanism 2 remains unknown, but could be due to the moderation of starch gelatinization, cell compaction etc.

Tissue softening induced by thermal treatments in different media depends on the temperature reached at the thermal center of the product in the heating medium, and on the heating rate attained (Alvarez et al., 2001). Different authors have used several mechanical procedures as an indicator of product texture. Kozempel (1988), Huang and Bourne (1983), and Bourne (1987) used back-extrusion test cell, taking maximum force readings as a texture measurement. Paulus and Saguy (1980) expressed the kinetic softening of cooked carrots using compressive maximum stress as a measure of the texture degradation.

The mechanism of vegetable softening during thermal processing is a complex one and many chemical components are believed to involve in the process. Mittal (1994) mentioned that the softening occurs partly due to loss of turgor, but also as a result of complex chemical changes in the cell wall matrix polysaccharides. The edible parts of a variety of vegetables are composed mainly of parenchmatous tissue characterized of thin cell wall cemented together by pectic substances of the middle lamella. The change of the chemistry of cell wall and middle lamella hydrophilic polymer material during cooking affect the physical properties Bourne (1989) and Van Buren (1979) and the resultant is decreased in textural integrity due to the breakdown of the cellular materials. The uptake of water by polysaccharides is also reported to have reduction effect on the cohesiveness of the cell matrix as it soften the cell wall and decrease the intercellular adhesion.

Textural qualities of potato are described by both the starch content in the cells and cell wall components (McComber et al., 1994). Potatoes high in sugar taste sweet and develop poor texture after cooking. The poor final texture is related to the low starch content associated with high sugar content. High contents of pectin, divalent ions (Mg, Ca), high activity of pectin methyl-esterase have been reported to be in favor of firmness in potato during processing. Calcium is reported to act in two ways. One involves regulation of cell function, such as changes in cell wall structure and membrane permeability and the other is the interaction with pectin to form a cross-linked network that increase mechanical strength (Poovaiah, 1986; Glen and Poovaiah, 1990). Pectin methyl-esterase demethylates the pectins making free galacturonic acids available for Mg and Ca-crosslinking of cells resulting in increased firmness (Bartolome and Hoff, 1972). In contrast, high content of monovalent ions (K, Na) and high activity of organic acids (citric and phytic acid) reduce adhesion between cells and thus resulting in decreased firmness. Monovalent ions replace the divalent ions while phytic acid forms complex with divalent ions making them less available for cross-linking.

3.2.2. Color

Color is an important quality attribute of foods. It represents the overall appearance of foods in the eyes of consumers, and as such many purchasing decisions are based on color. Several investigators have looked into the color of foods instrumentally (Nagle et al., 1979; Hunt, 1991; Shin and Bhowmik, 1994; Weemeas et al., 1999; Ahmed et al., 2000a; Gunawan and Barringer, 2000; Nourian, 2003) and concluded that both pigment and color degradation during thermal processed can be adequately described by first order reaction kinetics. The kinetics parameters such as rate constant and activation energy provide useful information on the quality changes that occur during thermal processing. Bright green vegetables turn olive brown during thermal processing. This change happens as a result of conversion of chlorophyll into pheophytin. A range of factors has been reported to influence the process. They include, cooking method, pH of the medium, processing temperature and duration of exposure. Other chemical reactions such as Millard reactions and enzymatic browning are also implicated in color build up. Color measurement in food is usually carried out in terms of three dimensions in the color space using the Hunter values L, a and b. The L values represent light-dark spectrum ranging from 0 (black) to 100 (white) as the eye would evaluate it. The 'a' value is for the green-red spectrum being –60 (green) to +60 (red). Similarly, b values represent blue-yellow spectrum for –60 (blue) to +60 yellow.

3.2.2. Ascorbic acid

Ascorbic acid is soluble in water, making it prone to loss with poor methods of cooking. The vitamin is generally used as research indicator of the severity of food processing. It is presumed that if ascorbic acid is well retained, all other nutrients are equally or even better retained (Selman, 1994). The principal mechanism of ascorbic acid losses during blanching is by diffusion. Anderson (1994) reported that diffusion would be increased when the potato tissue is subjected to high temperature (55-90°C). This effect is believed to be due to denaturation of membranes, which allow ascorbic acid to freely diffuse from the cells. As a result, it can be postulated that higher losses will occur when potato tissues are exposed to sterilization temperatures. Several researchers have studied degradation kinetic of ascorbic acid in citric juices under pasteurization conditions and reported that it follows a first order reaction mechanism (Johnson, Braddock and Chen, 1995). Therefore, the objectives of this study were to investigate the effect of cooking temperature on kinetics of selected quality attributes of potatoes and to establish a kinetic model to be used for predicting the loss of texture, ascorbic acid and color degradation in canned potatoes.

3.3. Materials and methods

Potato samples (*Solanum tuberosum*) of variety (Red Shef) were purchased from a local market. These were stored refrigerated (4°C) in a plastic bag with few perforations for about 4 days during which all cooking trials were completed. Using a cork borer and a sharp knife, test samples of potatoes were prepared as cubes (15 mm x 15 mm x 15 mm) to more closely simulate the practice followed in commercial canning. In an earlier study (Nourian, 2003), they were prepared as cylindrical samples (20mm diameter × 20mm height). A thermocouple (T-type) was inserted at the center of the particles with the aid of tooth pick and epoxy glue to measure the internal product temperature at the geometric center of the product. A data logger model (HP34970A, Hewlett Packard, Loveland, CO) was used to record the temperature signals at regular interval of 10 s

3.3.1. Thermal treatment

Test samples (8 pieces of 15mm potato cubes) weighing approximately 40g were spread and held in place in a small perforated basket and cooked in a water bath at selected temperatures (70 -100°C) for various times (1-50 min). Each treatment was given separately in order to prevent a large temperature change in the bath. Water temperature was monitored while heating and showed a maximum variation of ±1°C from the set point. After the heat treatment, the cooked product was cooled immediately to 3°C using iced water and drained. Cooking and texture evaluations were performed on the same day.

3.3.2. Texture measurement

Cooked samples were subjected to a single cycle compression test using a texture-testing machine (Lloyd model LRX-2500 N; Lloyd Instruments Ltd., Fareham, Hans, UK) (Figure 3.1a). A crosshead speed of 10 mm/min and chart speed of 100 mm/min were used. Similar procedures have been used in previous studies (Taherian, 1995; Nourian, 2003). Each test was repeated individually on 8 cubes and their mean values were used as indicators of the textural properties of cooked potatoes. The parameters were derived from the deformation curve as indicators of physical properties of the samples Figure (1b):

$$Firmness = \frac{Maximum\ \ force\ (N)}{Maximum\ \ deformatio\ n\ (mm)} \tag{3.1}$$

$$Stifness = \frac{Stress}{Strain} = \frac{Force/Cross\ \mathrm{sec}tional\ area}{Deformation/Initial\ length} = \frac{(F/A_0)}{(D/L)} = (N/mm) \tag{3.2}$$

$$Hardness = slope\ of\ the\ linear\ portion\ (N/mm) \tag{3.3}$$

3.3.3. Color measurement

The color characteristics were assessed using a Tristimulus Minolta Chroma Meter (Minolta Corp, Ramsey, NJ) to determine L, a and b values of cooked samples. The colorimeter was calibrated with a white standard. L, a and b measurements were evaluated from 10 samples and the values were averaged. Color was also evaluated as the total color difference (ΔE):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \tag{3.4}$$

where, L_0, a_0 and b_0 represented the readings at time zero, and L, a and b represented the instantaneous individual readings during cooking.

3.3.4. Ascorbic acid estimation

50 g potato sample was blended with an equal weight of 6% metaphosphoric acid (HPO_3) for 1 min. An aliquot (5ml) was made up to 100 ml by adding 6% (HPO_3). The solution then was centrifuged at 4000 rpm for 15 min. 5ml of the supernatant was toped with 10 ml of 2,6-Dichlorophenol-Indophenol dye at appropriate concentration and shaken. 3ml of the mixture was pipetted to a cuvette and placed in a spectrophotometer. The absorbance at 518 nm was measured within 15 to 20 s and related to the concentration using a standard curve.

3.3.5. Estimation of kinetic parameters

As indicated by Huang and Bourne (1983), the conventional chemical kinetic theory can be adopted to describe thermal softening of vegetable tissue. Hence, the time and temperature dependencies of the softening of potato tissue during cooking were described using kinetic laws and Arrhenius equations. Thermal softening of potato tissues was assumed to be first order, which is represented by the basic equation

$$\frac{dA}{dt} = -k_a \cdot A \tag{3.5}$$

where k_a is the apparent first-order softening rate constant (min^{-1}), A is the total firmness at time t (min). Integration of this equation gives the linear form of the first order model:

$$\ln A = \ln A_o - k_a.t \qquad (3.6)$$

where A_o is the initial firmness at time zero. The dependence of a reaction rate constant on temperature can be expressed by the Arrhenius model:

$$k = k_o e^{-E_a / RT} \qquad (3.7)$$

$$\ln k = \ln k_o - E_a / RT \qquad (3.8)$$

where k is the reaction rate constant (min-1), k_o is the frequency factor which is the rate constant of the reaction at $T = \infty$ (min^{-1}), E_a is the activation energy (kJ $mole^{-1}$), R is the universal gas constant, 8.314J $(mole\ K)^{-1}$ and T is the absolute temperature (K). A plot of ln (k) vs (1/T) yields a straight line of which the slope (E_a/R) can be used to obtain a value of the activation energy.

D value, which is the time required at a particular temperature to reduce the quality factor to one-tenth of the original value, was calculated as:

$$D = 2.303/k \qquad (3.9)$$

The temperature dependence of a first order rate constant can also be obtained by the z-value model:

$$\text{Log}\,(D_1/D_2) = (T_2 - T_1)/z \qquad (3.10)$$

where D_1 and D_2 are the decimal reduction times at temperatures T_1 and T_2, respectively and z is the temperature change needed for a decimal change in D values. The value of z was obtained as the negative reciprocal slope of the log D vs T curve.

The kinetic theory for two separate first order processes can be expressed as:

$$-dA/dt = k_a\, t \qquad \text{and} \qquad -dB/dt = k_b\, t \qquad (3.11)$$

where A is the texture contributed by the first mechanism, B is the texture contributed by the second mechanism, t is the time, k_a and k_b are the apparent rate constants for softening mechanism 1 and 2, respectively. These yield the following equations for the two mechanisms:

Mechanism 1 $$\ln A = \ln A_o - k_a.t \tag{3.12}$$

Mechanism 2 $$\ln B = \ln B_o - k_b.t \tag{3.13}$$

where A_0 and B_0 are the initial firmness due to substrate a and b respectively in the uncooked samples. Based on the assumption that the textural properties of cooked potatoes followed two separate first order reactions, the two reaction rate constants can be obtained from the linear portions of the two straight lines on the semi-logarithmic plots (ln C vs t) [steeper (first) line of the curve for the more rapid mechanism and the less steeper (second) line for the slower mechanism). Since most of the texture qualities of the rapid mechanism are likely to be lost during commercial canning operations, the second mechanism plays a more prominent role. The intercept from the second curve (slower) was considered an important characteristic of the product texture and named as "thermal softening index (Huang and Bourne,1983; Bourne, 1987).

Contrary to most studies on color changes in cooked potatoes, it was observed there was a quick drop in color parameters with the application of heat and then the values progressively increased with respect to heating time. This minimum value was characteristic of the treatment and so is the maximum or an equilibrium value. The color change was modeled between this minimum and the equilibrium value using a fractional conversion model: The changes in color parameters were modeled using a modified first-order model based on changes occurring between the initial and a maximum value as follows (sometimes referred to as fractional conversion model):

$$k = - [\ln (C_{max} - C_t)/(C_{max} - C_0)] / t \tag{3.14}$$

where, C_t is the color value after a given time, C_0 is the initial color value, C_{max} is the maximum value (or C_{min}, minimum value) of the color parameter, t is the time (min), and k is the reaction rate constant at a particular temperature, calculated as the negative slope of the $\log_e [(C_{max} - C_t) / (C_{max} - C_0)]$ vs. time (t).

3.3.6. Correction of thermal lag

Heat transfer from cooking medium to the center of the particle is a gradual process that faces different resistant; hence the surface and the center of the particle are not heated at the same time. Correction of the resulting thermal lag is essential to avoid overestimation of the cooking time. In this experiment, the temperature profile at the center of the particle was monitored by copper constantan thermocouples in order to calculate the effective portion of the come-up time. The procedure reported by Awuah et al. (1993) has been used in the correction of the come – up time as simplified in the following equation, which is commonly used, for calculation of process lethality.

$$t_{effective} = \int_0^t 10^{(T-T_{ref})/z} dt \quad (3.15)$$

Since z value is required for the above equation, which can only be obtained after knowing the D values, an estimate of z is initially made from the uncorrected values. Using this estimate, the heating times are corrected using Equation (3.15) and then the more accurate D values are computed. These D values are used to get a more accurate z and the process is repeated until the difference in the two z values is less than 0.5.

3.4. Results and discussions

3.4.1. Texture softening kinetics

Figure 3.1a and 3.1b show a Lloyd texture machine used in the study and a typical force deformation curve produced. The texture parameters were derived from this curve. A linear graph of different texture parameters of potato as a function of time at the different temperatures employed is presented in Figure 3.2. All texture parameters (firmness, stiffness and hardness) were found to decrease with an increase in temperature and heating time, and they all showed a somewhat similar trend. As typical of any first order rate degradation, the principal feature on the graphs is the rapid degradation of textural properties at the beginning of the heating process indicating that the softening rate is much faster in the beginning of the process and decreases as the heating time is increased. This suggests that the softening mechanism may involve different components that contribute to the firmness of the material in the raw and processed forms. Figure 3.3 compares the changes in firmness of potatoes as a function of time as influenced by temperature. The progressive softening with respect to heating time, and the increase in its severity at elevated temperatures is clearly evident from this figure.

Figure 3.4 illustrates the semi-logarithmic plot of log firmness ratio, (A/A_o) against heating time. A first look at the figure tends to indicate that the texture change can be described by a simple first order softening kinetics. This figure is obtained from the uncorrected heating time with the contribution of come-up lag included as part of the heating time. Typical heating curve during the come-up period is presented in Figure 3.5 at the temperature employed. The come-up time varied between 192 – 171 s depending on the temperature selected. While the come-up contribution could be small and neglected at lower temperatures, it accounts for 6.4-19% of heating time (15-25 min) at 90-100°C. Hence, it was found necessary to correct heating times to account for the come-up lag as detailed in the methodology. The corrected and uncorrected semi-logarithmic plots of D values is shown in Figure 3.6 more clearly indicating need for such treatment of data when the associated treatment times are short (as in HTST processing conditions).

What is also more clearly obvious from Figure 3.5 is the fact that, in contrast to the apparent simple first order rate model plots which yielded single straight lines (Figure 3.4), the time corrected texture softening was characterized by two simultaneous first-order kinetic models, one taking place at a rate faster (more sensitive to thermal destruction) than the other. Huang and Bourne (1983) were probably the first researchers to recognize such thermal softening behavior, which has been later, confirmed by several others (Anderson *et al.*, 1994; Taherian, 1995; Alvarez and Canet, 2002; Alvarez *et al.*, 2001, Nourian, 2003).

Kinetic parameters of thermal softening of potatoes estimated using the bi-phasic mode (mechanism 1 and 2) are summarized in Table 3.1. The parameters listed are the rate constant (k and D values) at different temperatures together with their temperature dependence parameters (z-value and activation energy). This indicates that the pseudo-first order kinetic theory is suitable to describe thermal degradation of texture during processing. The values of apparent rate constants (k_a) obtained from mechanism 1 are much larger (likewise D values smaller) than those (k_b) from mechanism 2 suggesting that reaction rate of mechanism 2 is slower. This finding is in consistence with what is reported in many previous studies. Huang and Bourne (1983) reported constant rates of mechanism 1 as 20 times higher than constant rate of mechanism 2. Nourian (2003) reported D values associated with the slower mechanism (mechanism 2) to range from 137 and 578 min in the temperature range 80-100°C, nearly 5-10 times larger than the range of values for the rapid mechanism (mechanism 1), while our results showed associated D values from 17.5 to 515 min in the temperature range 70 –100 °C. The relatively lower D values found in this study could be because of the different variety of potatoes. Although the reaction rate constants can be used to study the effects of thermal processing on firmness of vegetable tissue, Bourne (1989) suggested that the amount of firmness that is resistant to heat degradation (intercept on the y axis) termed thermal firmness is more appropriate (Figure 3.5). The thermal firmness values obtained are also included for the two mechanisms in Table 3.1. Bourne (1989) suggested that the substrate "a" gives most of the firmness in the raw form while substrate "b" provides most of the firmness after prolonged processing. The corresponding firmness of the intercept point of mechanism 2 in figure 3.5 was calculated to be 23 (N/mm) representing 47 % of the initial firmness. The use of the ratio of final texture to the original one as a measure for the degree of cooking in potatoes also has been proposed. Kozempel (1988) reported that the rate of change of this ratio was not influenced by the variety or lot of potatoes therefore makes it suitable for meaningful comparison.

The uncorrected and corrected z value curves of potato firmness obtained for Mechanism 1 and 2 is shown in Figure 3.7(a,b) as a plot of log (D) vs temperature. The difference between corrected and uncorrected z values for Mechanism 1 were 23°C and 24°C while it was 18°C and 18.3°C for the time-corrected data for Mechanism 2 during heating potato cubes (15mm) in the temperature range studied (70 –100°C). Thus the correction was necessary more necessary for the rapid mechanism. The z values found in this study are nearly comparable to those (17.2 and 20.4 °C) reported by Harada et al. (1985).

Figure 3.8 compares the time corrected Arrhenius plots for thermal softening of potatoes by the two mechanisms. The activation energies ranged from 104 to 131 kJ/mole. Nourian (2003) reported activation energies associated with cooking of potatoes to be in the range 79-108 kJ/mole, somewhat lower than found in this study. However, she did not account for the correction of come-up period, which can increase the E_a values by a 10-20% margin. The other parameters gave similar results.

3.4.2. Color change kinetics

For color degradation kinetics, the behaviors of the color indicators were a bit complex. All color parameters measured were found to decrease immediately after cooking (the first time interval used depending on the temperature) as compared to the color of uncooked potato. However, the L value increased again as the cooking time is increased (Figures 3.9). The extent of decrease was higher at higher temperature. Semi-logarithmic plot of the change in L value using a fractional conversion model equation (3.14) is presented in Figure 3.10, which indicated that it also followed first order. The minimum and maximum values of L values, computed by regression techniques, and the associated first order rate parameters are given in Table 3.2. The change in color was also reflected in the total color change presented as ΔE in Figure 3.11. It can be seen that as the temperature is raised the total color change also increased. The semi-logarithmic version is shown in Figure 3.12 while the reaction rate kinetic data are summarized in table 3.2 as well. The "a" and "b" values were relatively stable, their variations were small and no clear trend was established.

3.4.3. Kinetics of ascorbic acid loss

With respect to ascorbic acid loss / degradation, a plot of log concentration vs time resulted in a straight line indicating that the loss / degradation with respect to time at a specific temperature followed the simple first order (Figure 3.13). Accordingly, reaction rate constants, D-values and the temperature dependence z-value were calculated and presented in Table 3.3. The decimal reduction times at different temperatures varied from 36 min at 100°C to 181 min at 70 °C giving a z value of 44°C and activation energy of 56 kJ/mole. The values obtained are comparable to those reported in literature. Holsworth (1992) reported E_a between 30.6 and 49.9 kJ/mol while Esteve et al. (1999) studying samples of asparagus, found an E_a of 51 $kJ.mol^{-1}$. Ascorbic acid is known to be thermolabile. Several researchers have studied its thermal degradation kinetics in citric juices under pasteurization conditions and reported that it obeys a first order reaction model (Johnson, et al., 1995).

3.5. Conclusions

The results obtained showed that texture (firmness, stiffness and hardness), color (L value and ΔE) parameters and ascorbic acid content during heat treatment of potatoes changed significantly and that the kinetics of changes in these quality attributes followed first order rate (or its variation). The consistency of our findings with earlier reports subscribes to the hypothesis that thermal softening of vegetable tissues is a complex process and involves two simultaneous first order mechanisms. The apparent rate constant of the first mechanism was found to be much grater than that of second mechanism. The rapid mechanism 1 involves substrate 'a', which is the major contributing component in the firmness of the vegetable in fresh state while the slower mechanism 2 involves substrate 'b' which is more important in the firmness of the vegetables in processed form. With respect to color indicator, the increase in L values followed a simple first order relationship after an initial drop. However, none of "a" and "b" values followed a clear trend within the temperature range and time of which the study was carried out. Ascorbic acid loss also followed the first order model. The E_a were found to be 104 – 131 kJ/mole for texture, 49 – 45 kJ/mole for L and ΔE respectively. Activation was 56 kJ/mole for ascorbic acid. The corresponding z values were, 23 – 18 °C for texture, 52 - 57 °C for L values and ΔE and 44 °C for ascorbic acid, respectively

Table 3.1: Effects of temperature and time on thermal softening of potato samples

	Mechanism 1				Mechanism 2			
Temperature (°C)	**A_o (N/mm)**	**D (min)**	**k_a(min^{-1})**	**R^2**	**B_o (N/mm)**	**D (min)**	**k_b(min^{-1})**	**R^2**
Firmness								
70	48.71	113.2	0.0203	0.85	36.5	515	0.0045	0.85
80	46.79	50.5	0.0456	0.89	33.22	145.3	0.0158	0.97
90	47.84	15.6	0.1475	0.88	22.96	63.7	0.362	0.99
100	50.9	9.8	0.2346	0.92	20.36	17.5	0.1313	.99
z (°C)		**23**	**0.1000**	**0.99**	**18**		**0.1300**	**0.96**
E_a (kJ/mole)			**104.9**	**0.99**			**131.4**	**0.99**
Stiffness								
70	40.79	113.3	0.0303	0.85	502	26.1	0.0046	0.79
80	39.18	50.5	0.0457	0.89	144.2	24.68	0.0160	0.97
90	40.06	22.8	0.1008	0.94	41.2	14.9	0.0559	0.94
100	42.62	9.8	0.2345	0.99	17.5	13.02	0.1314	0.99
z (°C)		**26**	**0.0935**	**0.97**	**17**		**0.1321**	**0.99**
E_a (kJ/mole)			**97.95**	**0.99**			**138**	**0.99**
Hardness								
70	49.03	115	0.020	0.85	523	33.9	0.0044	0.96
80	48.04	47	0.0485	0.89	175	31.7	0.0131	0.96
90	48.24	16	0.1440	0.89	59	19.2	0.0392	0.99
100	50.9	9.37	0.2456	0.92	19	17.8	0.1247	0.99
z (°C)		**27**	**0.101**	**0.99**	**18**		**0.1279**	**0.97**
E_a (kJ/mole)			**105**	**0.99**			**134**	**0.99**

Table 3.2: Effects of temperature and time on L and ΔE values in potato

Temperature (°C)	t_{max} (min)	L_{max}	L_o	D value (min)	K (min^{-1})	R^2
L- value						
70	50	63	59.15	77	0.299	0.99
80	40	66	60.11	63	0.364	0.99
90	25	66	60.39	46	0.0505	0.96
100	15	66	60.81	20	0.1180	0.96
z (°C)					**52**	**0.89**
E_a (kJ/mole)					**49**	**0.84**
	t_{max} (min)	**ΔE_{max}**	**ΔE_o**			
ΔE value						
70	50	17	12.30	69	0.0333	0.95
80	40	17	13.18	42	0.0541	0.98
90	25	18	13.3	31	0.0752	0.94
100	15	18	13.49	20	0.1149	0.98
z (°C)					**57**	**0.99**
E_a (kJ/mole)					**45**	**0.99**

Table 3.3: Effects of temperature and time on ascorbic acid loss in potato

Temperature (°C)	Time (min)	% Ascorbic acid loss	D value (min)	K (min^{-1})	R^2
70	50	40	181	0.0127	0.96
80	40	60	89	0.0258	0.96
90	25	53	59	0.0390	0.93
100	15	56	36	0.0639	0.97
z (°C)			**44**		**0.99**
E_a (kJ/mole)			**56**		**0.99**

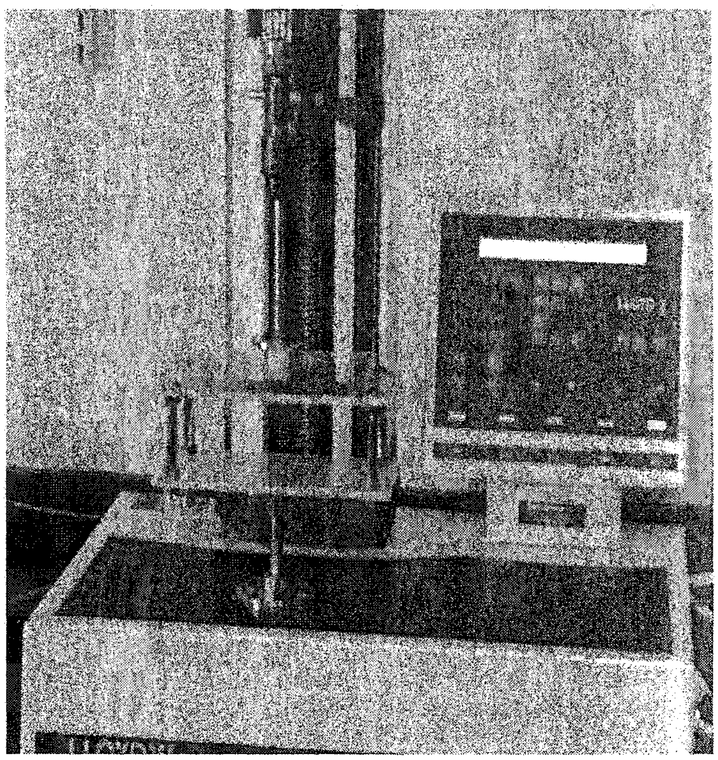


Figure 3.1a: Lloyd texture testing machine

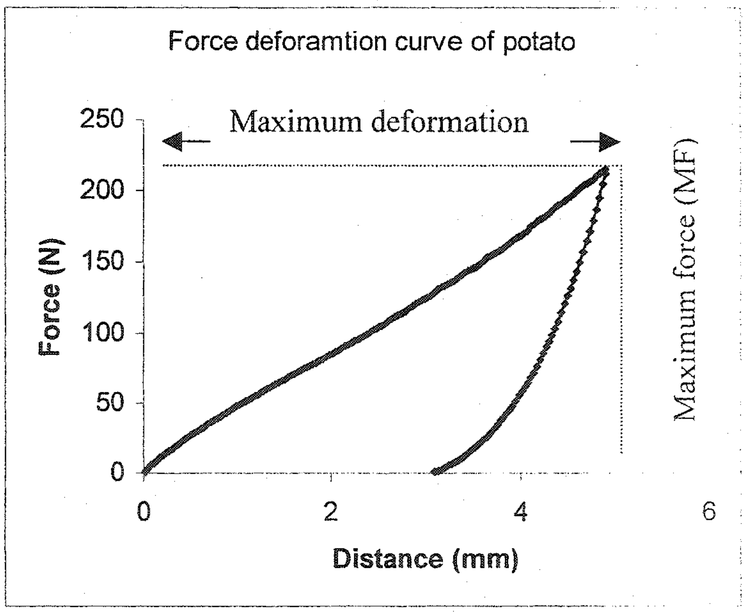


Figure 3.1b: A typical force deformation curve of potato

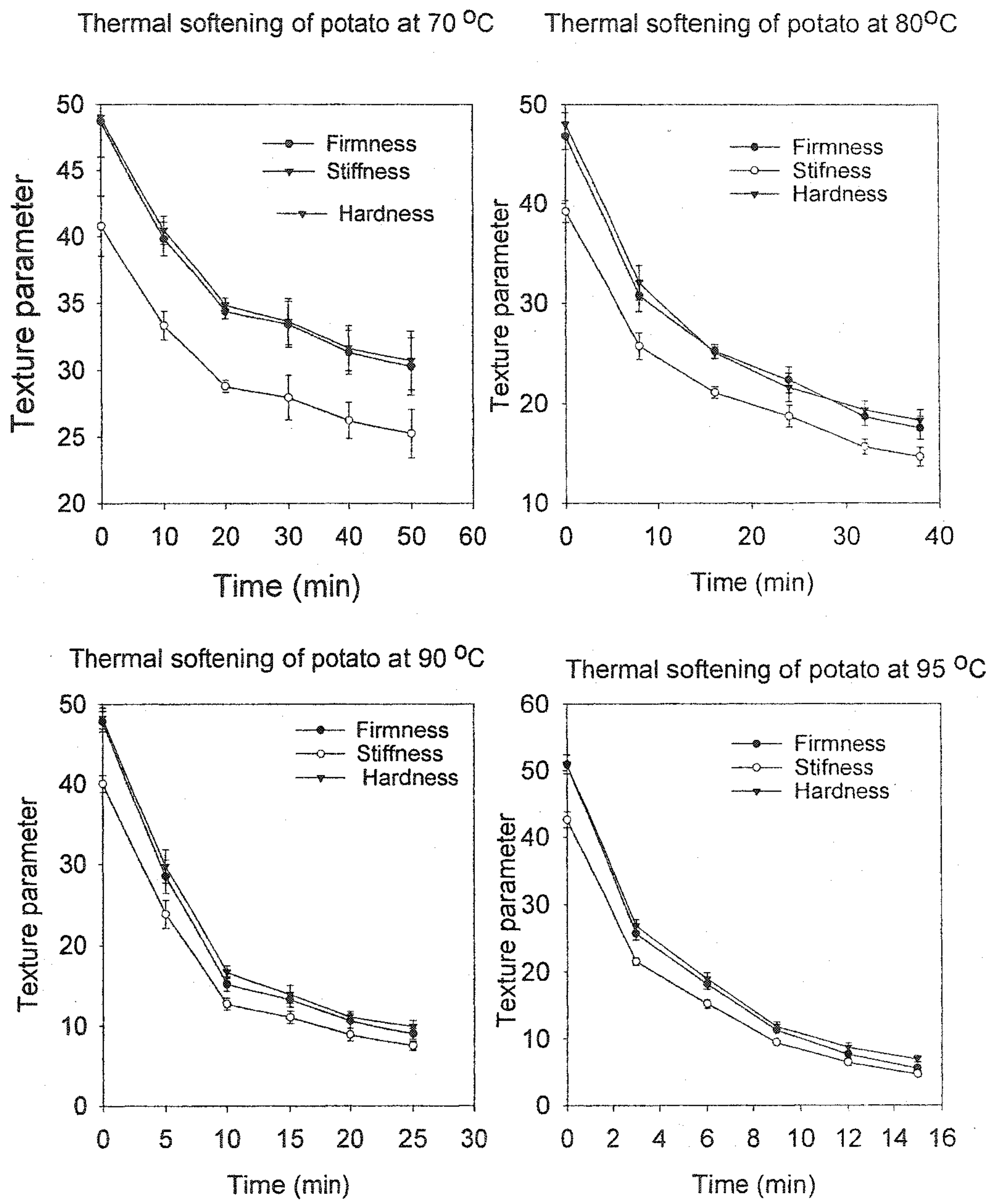


Figure 3.2:Linear plot of softening curves at various temperatures

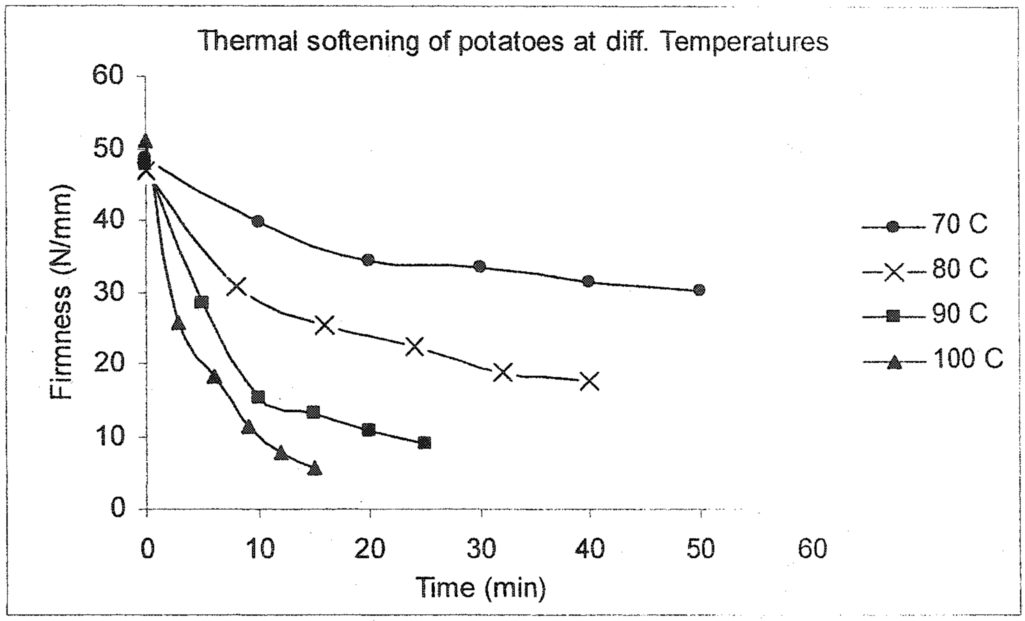


Figure 3.3: Thermal softening of potato at different temperatures

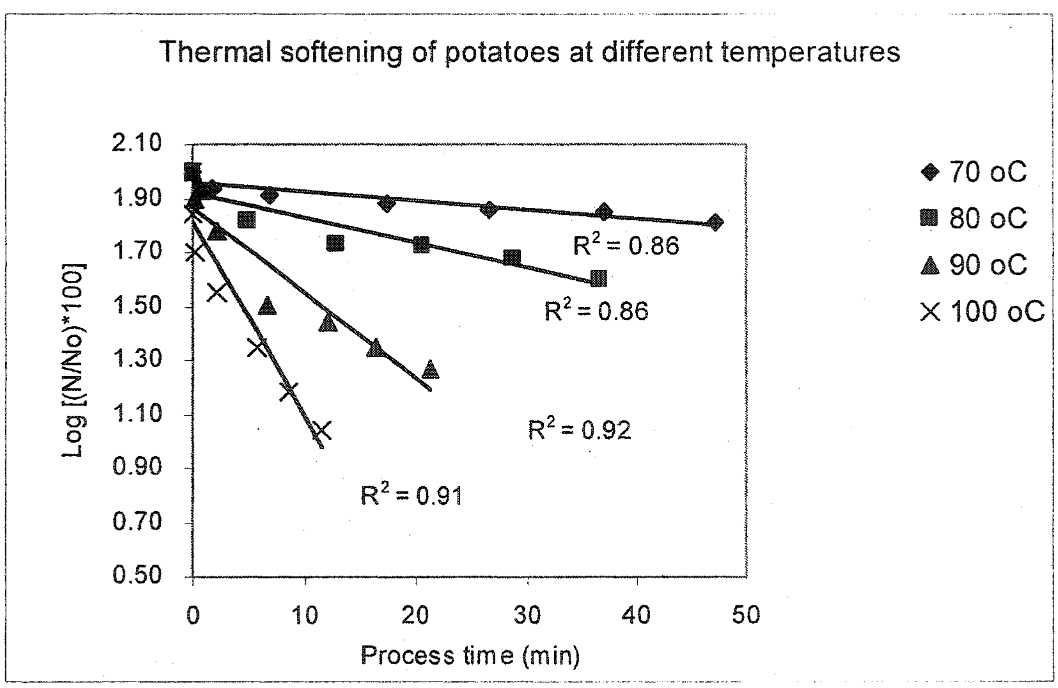


Figure 3.4: Plot of log ratio of firmness of potato at different temperatures (°C)

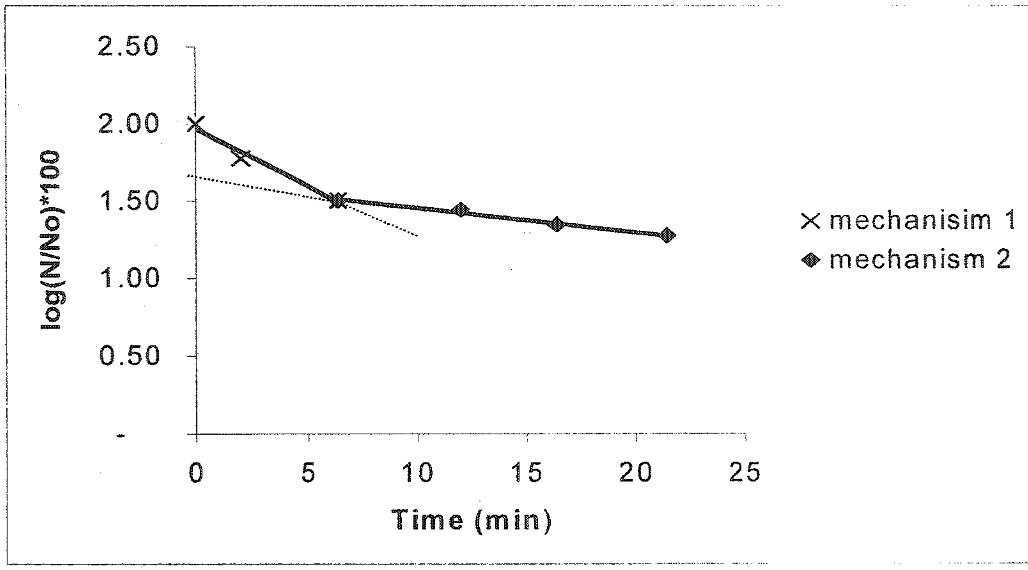


Figure 3.5: Plot showing tow mechanisms of softening of potato at 90 °C.

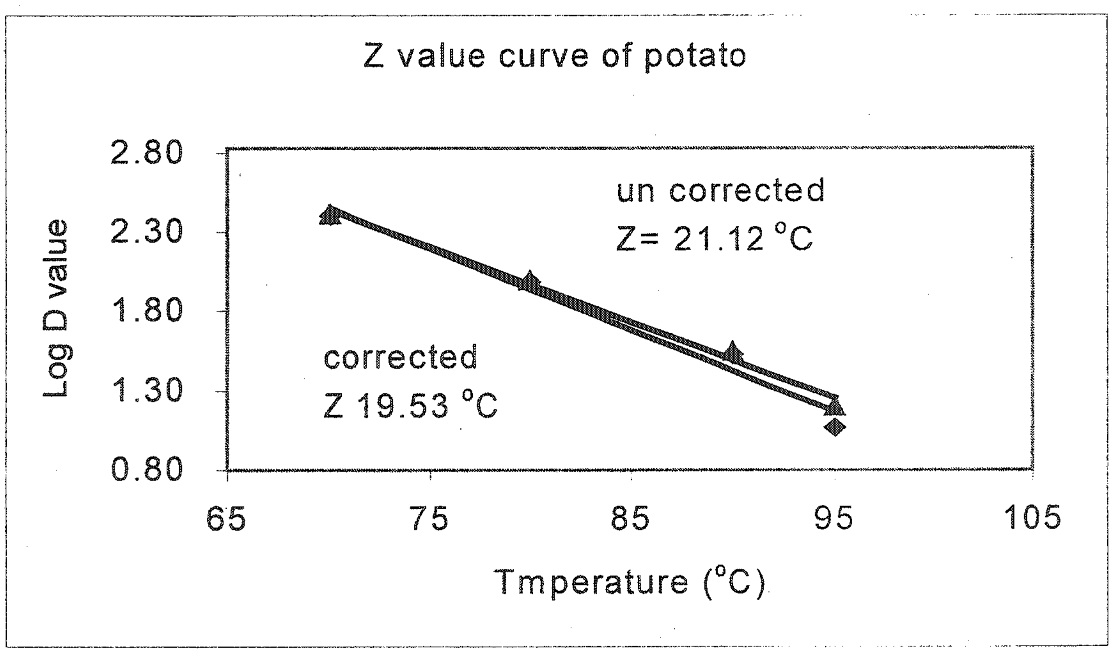


Figure 3.6: Log D value plot of potato vs temperature

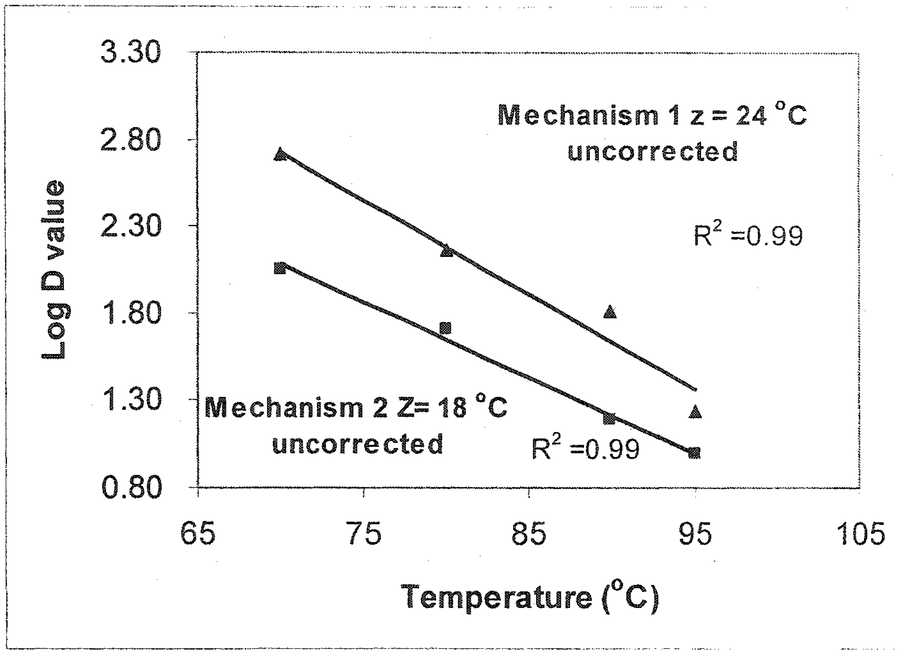


Figure 3.7 a: Uncorrected z value curve of 2 mechanisms

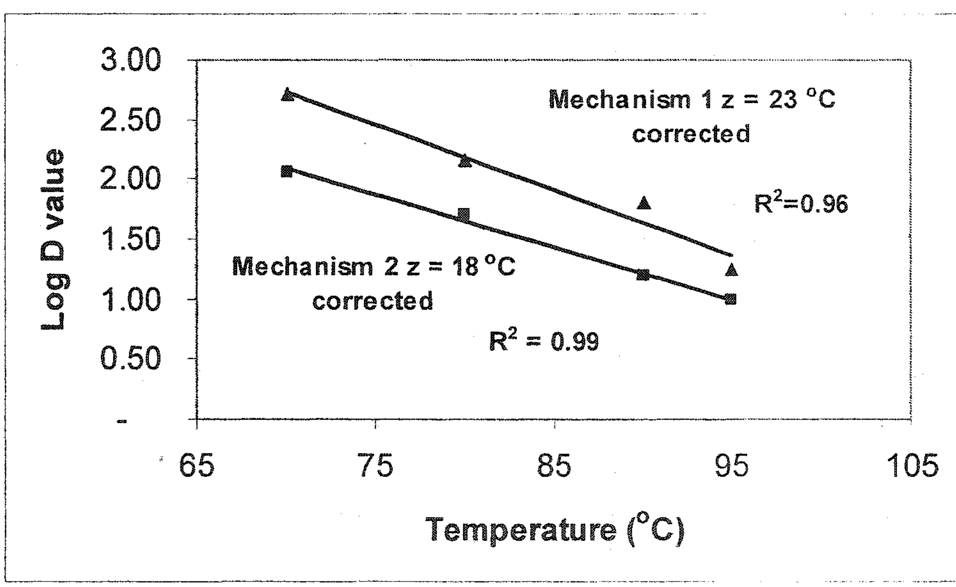


Figure 3.7 b: Corrected z value curve of two mechanisms

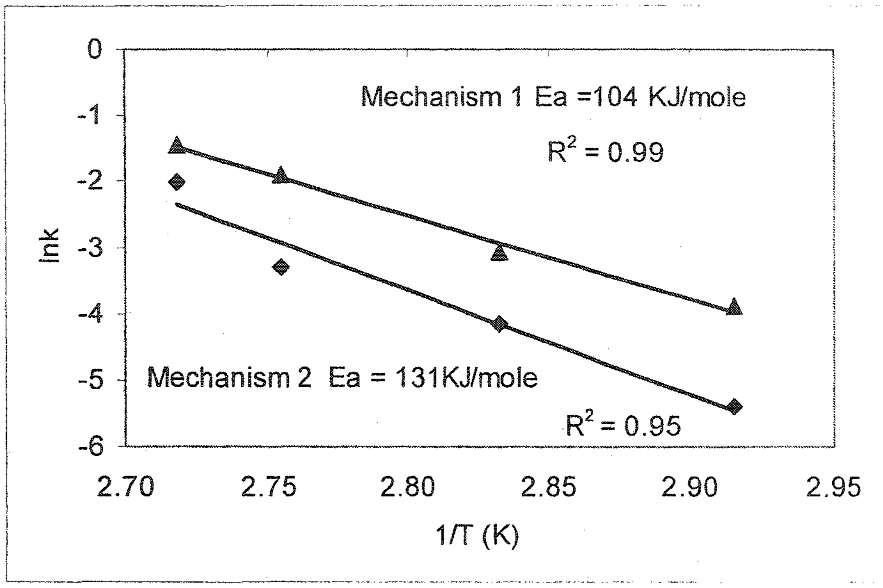


Figure 3.8: Arrhenius plot of two mechanisms of potato firmness

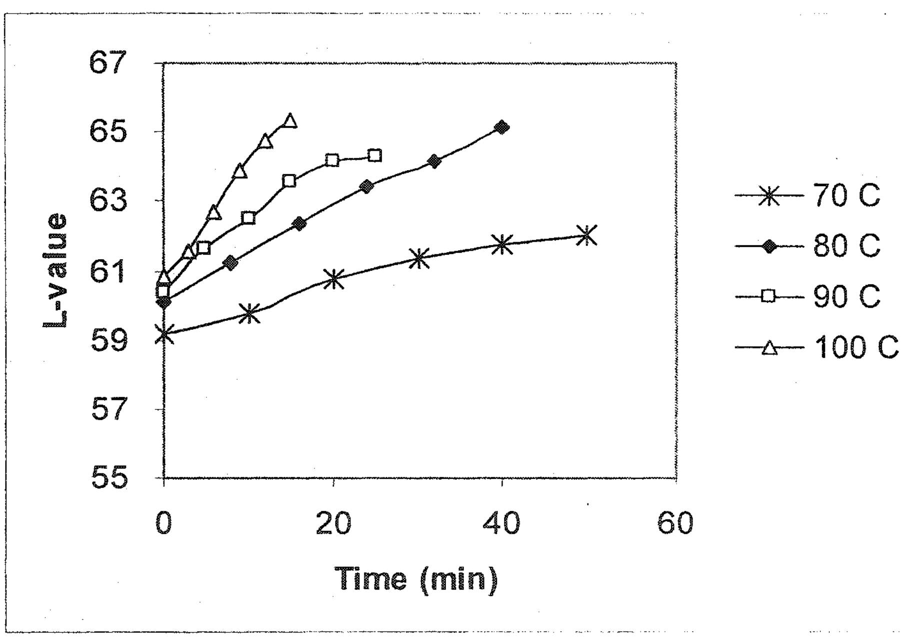


Figure 3.9: Linear plot of L value change of potato samples at different temperatures

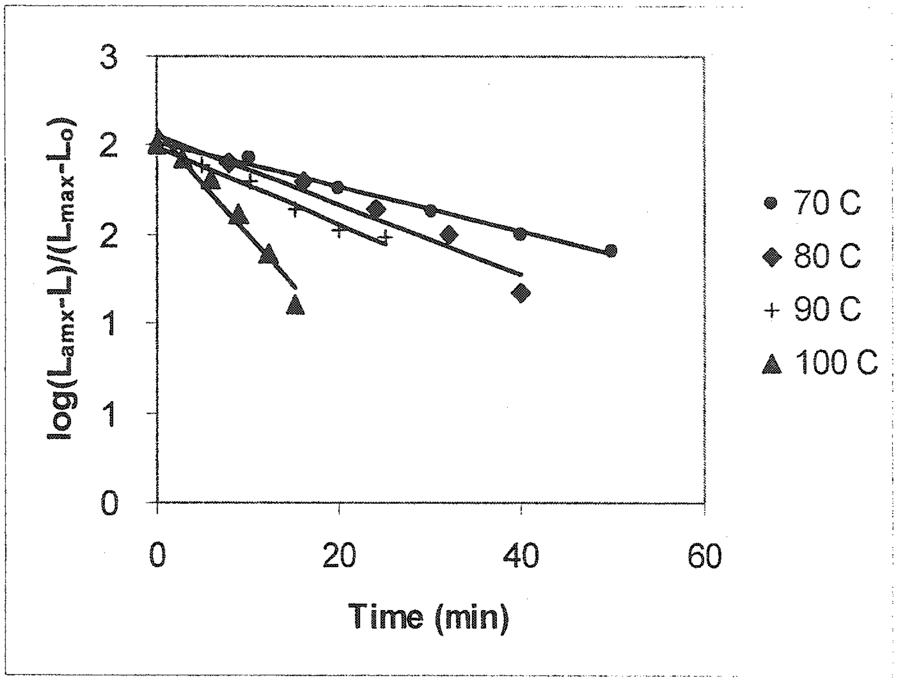


Figure 3.10: Semilog plot of L value change in potato samples at different temperatures and times

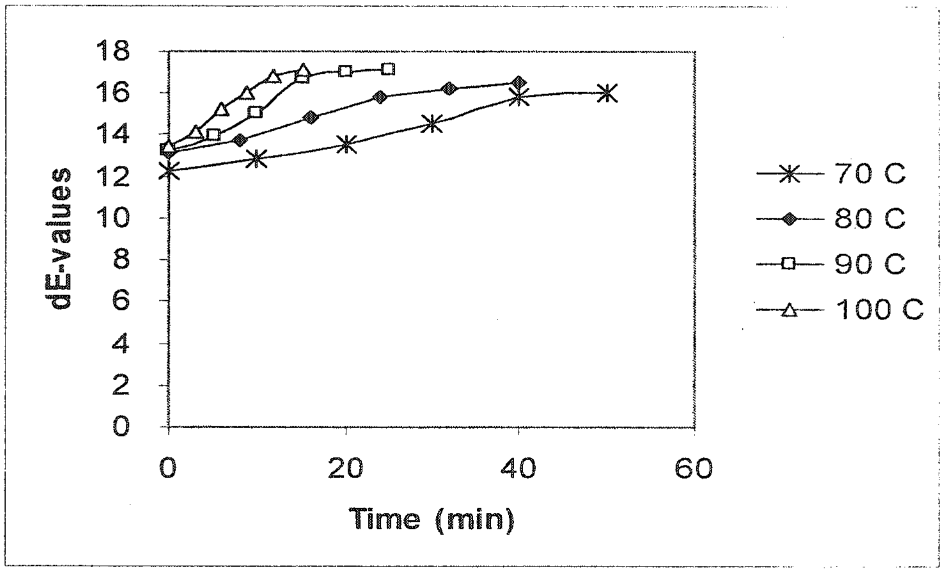


Figure 3.11: Linear plot of total color change of potato samples at different temperatures and times

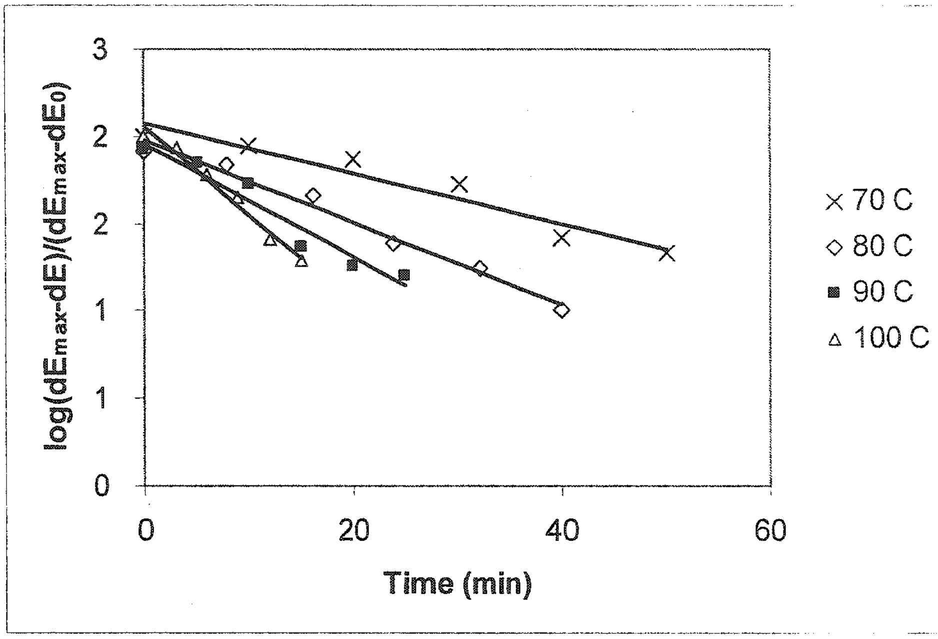


Figure 3.12: Semilog plot of ΔE value fraction of potato samples at different temperatures

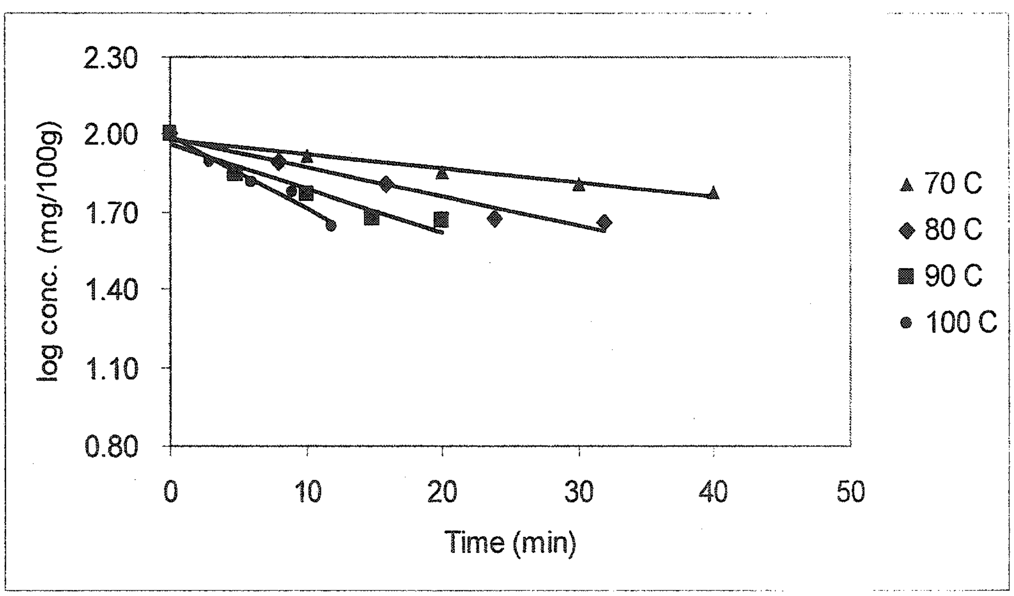


Figure 3.13: Semilog plot of ascorbic acid loss with time and temperature

CHAPTER 4

EFFECTS OF PROCESSING VARIABLES ON HEAT PENETRATION PARAMETERS OF CANNED POTATOES UNDER END-OVER-END AGITATION PROCESSING

4.1. Abstract

The effects of temperature, can size and rotational speed on heating behavior of potato have been evaluated using a 3 x 3 factorial design of experiments. Potatoes were cut into cubes (15mm x 15 mm x 15 mm), filled in to cans (68.5% w/w), covered with water or 1% aqueous solution of carboxy methyl cellulose (CMC), sealed and subjected to thermal processing in a pilot scale full water-immersion rotary retort. End-over-end (EOE) agitation in a continuous and oscillatory fashion was employed. Three retort temperatures (110, 120, 130°C), three rotational speeds (0, 10 and 20 rpm) and three can sizes were employed as process variables in addition to water and CMC as covering liquid. A thermocouple probe was fitted at the geometric center of each can to measure the temperature of the liquid medium while an additional flexible copper-constantan thermocouple was attached to the center of a potato cube to measure particle center temperature. Heating rate index (f_h), heating lag factor (j_{ch}), cooling rate index (f_c), cooling lag factor (j_{cc}), process lethality (F_o), cook value (C_o) and C_o/F_o ratio of potato samples were determined for each processing condition. Higher rotational speed, smaller can size and higher temperature significantly ($p<0.05$) generally improved the heating and cooling rates and reduced the lag factors in both continuous and oscillatory modes of rotation. These conditions generally resulted in an increase in F_o and C_o values; however the C_o/F_o correlated well high-temperature short time principles. No significant difference is observed between continuous and oscillatory rotation.

4.2. Introduction

Conduction and convection are the principal modes of heat transfer in thermal processing of foods, the former being the predominant mechanism in solid and highly viscous foods, while the latter is characteristic of fluid foods. Liquid food containing particulate matters, on the other hand, make use of both transfer mechanisms. These mechanisms need to be considered in the design and evaluation of scheduling thermal processes. The effect of process variables on the microbiological safety and quality of the food product is important as continuous change in consumer demand calls for developing new technologies and procedures to minimize thermal degradation during sterilization of low acid foods.

Research has shown that agitation during processing is an effective means for producing foods that are microbiologically stable and are of high quality. It creates induced-convection, which results in enhanced heating rates and better heat distribution. This will result in considerable reduction in process time and hence better retention of product quality. Furthermore, agitation of the can inhibits separation of different ingredients and phases in a food product during thermal processing (Rao and Anantheswaran, 1988). There are several factors that affect heat transfer rate to canned food under agitation. Early studies have indicated that with agitation it is possible to apply higher temperatures and reduce the process time in favor of quality (Clifcorn et al., 1950). Berry and Kohnhort (1985) described rotational speed as a critical factor in the case of canned homogeneous-milk-based formulas thermally processed in a Steritort.

There are several advantages of rotational processing over still processing. It creates induced convection heating in canned foods that are subjected to mechanical agitation during processing. The products that benefit most from the technique include semi-solids and viscous foods such as sauces and soups containing meat or vegetable particles. Commercial sterilization of particulate foods calls for the delivery of adequate predetermined heat at the slowest heating point usually the geometric center of the particle. Achieving this requirement could take prolonged exposure time of heat on the outer surface of the food while the center of the particles remained under processed.

Mechanical agitation during processing could be considered as an improved thermal process technique with the ability to enhance heat transfer rates to liquid particle mixture, especially when the covering liquid is viscous or semi-viscous in nature. In addition, agitation processing has the potential of substantially reducing energy consumption during processing.

CMC is a derivative of cellulose, an insoluble homopolymer of repeating β-D-glucopyranosyl units joined by (1-4) glycosidic linkages (BeMiller and Whistler 1996). The homopolymer exists in different degrees of polymerization (DP), which is the average number of anhydroglucose units per molecule, and different degree of substitution, or the average number of carboxymethyl groups per anhydroglucose unit (Elliot and Ganz 1974). Due to electrostatic repulsion the molecules are extended in solution and adjacent chains repel each other. Consequently, CMC solutions tend to be highly viscous and stable in nature (BeMiller and Whistler 1996). CMC is widely used as a viscosity modifier and as a carrier fluid for low acid particulate foods in aseptic processing and a comprehensive study on the reological properties is detailed in Abdelrahim and Ramaswamy (1995).

Numerous studies on the influence of agitation on heat transfer rate have been reported. Heating characteristics of different food system have been investigated. Berry and co-workers (Berry et al., 1979; Berry and Bradshaw, 1980, 1982; Berry and Dicherson, 1981) have studied heating characteristics of considerable range of food systems. Fernandez et al. (1988) evaluated heat transfer in canned snap beans in steritort. Similarly, substantial efforts have been devoted to studying heat transfer coefficients for liquid foods containing particles in axially rotating cans (Lenz and Lund, 1978; Fernandez et al., 1988). The majority of these studies were carried out under restricted particle movement mounted on rigid thermocouple. In recent years, several studies have been conducted at McGill University (Sablani and Ramaswamy, 1995, 1996, 1997,1998, 1999; Ramaswamy and Sablani, 1997a) using a flexible thermocouple approach as a new technique for measuring the convective heat transfer coefficients associated with end-over-end rotational mode in processing canned particulate liquids. Abbatomarco and

Ramaswamy (1993, 1994), Ramaswamy et al. (1993) and Taherian (1995) also have shown the end-over-end agitation processing to offer considerable quality advantages over the static mode for processing of vegetables.

Several factors are reported to have influence on heat penetration rate into the food particles during agitation processing. The most significant ones include rotational speed, mode of rotation, radius of rotation, can head space, product viscosity, liquid to particle ratio, particle size and shape and can size (Ramaswamy et al., 1993). Several of these factors have been studied while information on some of them is not readily available. The effect of headspace on heating rate is controversial. Some researchers found it to reduce the heating rates while others found it to have a desirable effect (Tan and Ling, 1988; Joseph et al., 1996; Robertson and Miller, 1984).

The index commonly used to measure the rate of heat transfer into conduction heating products is the f_h value. For conduction-heating products, the f_h is a function of container size and shape and thermal conductivity (k) of the product. For a finite cylinder can, this relationship is expressed as

$$k = \frac{0.398}{(\frac{1}{a^2} + \frac{0.427}{b^2}) x f_h} \tag{4.1}$$

where a is the radius and b is the half-height of the cylindrical can (Stumbo, 1973).

For designing a thermal process regime, calculation of heat penetration parameters such as heating rate and cooling rate indices, f_h and f_c, and the lag factors j_{ch}, and j_{cc} are essential. Of recently, Sablani and Ramaswamy (1999) have conducted comprehensive study on the influencing factors. However, the influence of can size, use of a non-Newtonian covering liquid, and a large fill weight as is common in commercial practice were not considered. Therefore, the objectives of this study, among other things, included investigating and quantifying the influence of selected processing conditions (can size, rotation speed, temperature, type of medium and mode of rotation) on thermal process parameters of importance in process evaluation.

4.3. Materials and methods

Potato samples (*Solanum tuberosum*) (variety Red Shef) were purchased from a local market. These were stored refrigerated (4°C) in a plastic bag with few perforations for about one week during which all cooking trials were completed. Using a cork borer and a sharp knife, test samples of potatoes were prepared as cubes (15 mm x 15 mm x 15 mm) to more closely simulate the practice followed in commercial canning. A fill weight of 140, 250 and 380g representing approximately two thirds of the total product weight was placed in each of 211X400; 307X409 and 401X411 can, respectively.

An aqueous solution of CMC was prepared by dissolving required weight of CMC, commercial grade (Sigma; St. Louis, MO) in an appropriate volume of distilled water under constant stirring and then left for 24h to allow complete dispersion of lumps and rehydration of CMC (Awuah, 1993). Cans were closed at atmospheric pressure using a manual closing machine (National Canning Co.). Each can was topped either with water containing 2% sugar+2% salt (commonly used in commercial vegetable canning) or the prepared 1% aqueous solution of carboxymethylcellulose (cmc) solution leaving a 10 mm headspace.

4.3.1 Preparation of cans

Test cans were fitted with a needle type thermocouple probe at the geometric center of the can to measure the temperature of the liquid medium while an additional flexible wire copper-constantan thermocouple (wire diameter 0.01 mm) was fitted in to the center of the potato sample with the aid of toothpick and epoxy glue to measure the particle center temperature. The use of flexible thermocouple technique was developed by Sablani and Ramaswamy (1996) as a solution to measuring particle center temperature under relatively un-restricted particle motion. A sufficient length of the wire was allowed inside the can to ensure movement of the particle. The thermocouples wires were passed through a 32-circuit slip ring assembly using 24 AWG copper-constantan thermocouple wire (Omega Engineering Corp. Stamford, CT). Thermocouple signals were recorded at 10-s intervals using a data acquisition system (HP34970A, Hewlett Packard, Loveland, CO). The prepared cans were subjected to end-over-end rotational processing in a pilot-scale rotary, single cage, full water immersion retort (Stock rotomat-PR900; Hermann Stock Maschinenfabric, Germany, Figure 4.1). Three test cans were employed for each can size and each covering medium.

4.3.2. Heat penetration tests

Each set of cans of a given size and covering medium was subjected to agitation processing under three rotation speeds (0, 10, 20 rpm) and three different temperatures (110, 120, 130°C). The process time after the retort come-up was kept at 30 min for each run. An air overpressure of 70 kPa was maintained during the process. Cans were cooled immediately after the set time under continuous addition and circulation of cold water. The cooling was stopped when the water temperature in the retort was brought below 30°C and the product cooled to below 50°C.

4.3.3. Data analysis

Due to the daily change in temperature and preparation procedures, some variation in the initial temperature of the product was unavoidable. Accordingly, and in order to have meaningful comparison of heat penetration parameters, transient can temperatures from the test runs were normalized to an initial temperature of 18°C and respective retort temperatures of (110,120 and 130 °C) based on the equations given by Stumbo (1973). The heat penetration parameters for heating (heating rate index, f_h and heating lag factor, j_{ch}) were evaluated from the plots of logarithm of temperature difference between the retort and the particle center (or covering liquid) during the heating part of the process data. Similarly, the parameters for cooling (cooling rate index, f_c and cooling lag factor, j_{cc}) were obtained using cooling part of the process data. Process lethality (F_o) and cook value (C_o) were calculated for each run by numerical integration of time-temperature as represented in the following equations (z = 10°C for F_o and z = 33°C for C_o).

$$F_o = \int 10^{(T-121.1)/z} dt \tag{4.2}$$

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

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

4.4. Results and discussions

4.4.1. Heating penetration curves

Figure 4.1 is the Stock rotomat-PR-900 used in the study and figure 4.2 shows typical time-temperature profiles of canned potato cube and the covering liquid undergoing an agitation processing at a retort temperature of 120°C. The come-up time of the retort was found to be 4.5 min. Initially, heat flows from heating medium (water in the retort) to the can liquid through the can wall and then to the particle. From the profile, it can be seen that the liquid and particle center temperatures lag behind the retort heating medium temperature and the gap narrows down, as they get closer to the set temperature. The particle lags behind the liquid and retort temperature during both heating and cooling. The temperature gradient is due to collective effect of the conductive resistance of the potato, and the external and internal convective resistance at the can wall surface.

The logarithm of the temperature difference (T_r-T) was plotted against linear time as presented in Figure 4.3 to evaluate the heat penetration parameters. The heating rate index (f_h) was calculated as the negative reciprocal slope of the straight-line portion of the curve, while the lag factor was obtained from the intercept as: $(T_r - T_{pih})/(T_r - T_{ih})$

where T_r is the retort temperature and T_{pih} is the psedo-initial temperature (at the intercept) T_{ih} is the actual initial temperature of the particle during heating. Parameters for the liquid and those for cooling were likewise computed.

4.4.2. Effect of process variables on heating rate index

Analysis of variance of results showed that (Table 4.1a,b) all factors studied had a significant influence ($p<0.05$) (although to different extents) on the heating rate index of particles in water as well as in CMC solution. In each case the most dominant factor was speed of rotation followed by can size and temperature.

The mean effects of these process variables (together with the overall standard deviation are summarized in Table 4.1c. Increasing rotational speed from (0 to 20 rpm) resulted in 29% and 25% reduction in f_h value of potato cubes in water and CMC, respectively. The effect of rpm was much higher between 0 and 10 (21% in water and 17% in CMC) than between 10 and 20 rpm (8.4% in water and 7.4% in CMC). With respect to container size, the f_h of particles decreased by about 26% in water and 20% in CMC as the can size was changed from 401x411 (large) to 211x400 (small). With respect to temperature, the f_h of particles decreased by about 14% in water and 12% in CMC as the process temperature was increased from 110 to 130C.

Figure 4.4 and 4.5 show the 3-D bar graphs of particle f_h as influenced by rotation speed and temperature for the three can sizes in CMC and water, respectively. The decrease in f_h value could be attributed to the enhanced mixing in the can resulting in faster heat transfer rate. With respect to temperature the improving effect could be due to greater liquid convection at higher temperatures. And the improvement in f_h with respect to can size obviously is due the lowering of penetration depth, a direct effect which can easily be recognized from Equation 4.1 presented earlier. The f_h values of particle were higher at all processing conditions when CMC was used and this could be due to higher viscosity causing thicker boundary layer which act as a resistance force to heat penetration. Similar observation was reported in (Sablani and Ramaswamy, 1997).

With respect to interaction between variables no significant effect ($p>0.05$) was seen in case of water as carrier liquid; however there was significant interactions ($p<0.05$) between temperature and rotational speed, as well as temperature and can size in CMC. The lack of significance of interactions with water may be due to the low viscosity nature of water hence, bulk of the effects being accounted by main factors. The absence of interaction between can size and rotational speed in both media was expected since can size and rotational speed had antagonistic effects on f_h values, and their effect of magnitudes were somewhat similar. However, with respect to temperature - can size and temperature – rotation speed interactions, one of the factor was more dominant than the other thereby producing significant interactions.

As with heating rate index of particles, heating rate index associated with the liquid also generally decreased with rotation speed and temperature, and increased with can size (Table 4.1a-c). As compared with the f_h values for the particle, the f_h for the liquid were 17-21% lower in magnitude for water cans and 16-17% in CMC cans. These observations followed the expected trends, being associated with convective heat transfer as compared with conduction in particles. The f_h values were again 30-34% higher for CMC as compared to water because of the association of higher viscosity of CMC.

4.4.3. Effect of process variables on heating lag factor

Analysis of variance of results for the particle and liquid lag factors as influenced by process variables are summarized in Table 4.2a-b Again all factors studied had a significant influence ($p<0.05$) (although to different extents) on the j_{ch} value of particles in water as well as CMC solution. In this case the most predominant factor was the rotation speed, which explained almost 90% of the total variance (i.e. mean square value / total >0.9). Again this was followed by can size and temperature.

The mean effects of these process variables (together with the overall standard deviation are summarized in Table 4.2c. The mean j_{ch} values decreased from 1.84 to 1.34 (27%) as the rotation speed increased from 0-20 rpm. With can size it decreased about

8% from 1.61 to 1.48 between the large and small can. The temperature effect was the least, only showing a statistically significant decrease between 110 and 120C. Table 4.2a-b also show the influence of process variables on j_{ch} values of liquid portion of the cans. The trends were somewhat similar in case of CMC cans. The mean value decreased from 1.31 to 1.18 representing 12% in CMC cans as rotational speed increased from 0 to 20 rpm, but no significant difference ($p<0.05$) in water cans. The effects of can size on the liquid j_{ch} was not clear in the CMC medium but the mean value steadily decreases with the decreasing can size in water. However the statistical difference was only between the large and small cans.

Figure 4.6 and 4.7 show the 3-D bar graphs of particle j_{ch} values as influenced by rotation speed, temperature and can size in both water and CMC. As expected, j_{ch} of the particle in CMC was always higher than that of particle in water. Similarly, the j_{ch} of particle was always higher than that of liquid (Figure not shown). Except temperature, all studied factors that affected f_h were found to have similar effect on lag factor (j_{ch}) of particles. The effect of temperature was somewhat unclear. The heat transfer-enhancing trend with respect to the influence on f_h (numerically resulting in a decrease in f_h values) also resulted in a decreased lag factor values. Again the associated values were larger in CMC than in water.

With respect to j_{ch}, of liquid the behavior was not different from that of particle. The factor generally decreases with increasing rotational speed and increase with increasing can size. Increasing the rotational speed from 0 to 20 decreases the factor by 9% in CMC liquid while in water, the difference was not statistically significant but there was a clear decreasing trend. With can size, the j_{ch} of the liquid in water can was found to significantly decrease with decreasing can diameter, however the results was somehow confusing in the case of CMC liquid were the medium size can, gave smaller j_{ch} value and there was no significant difference between the small and large size can. Likewise temperature also did not show meaningful difference.

4.4.4. Effect of process variables on cooling rate index

Analysis of variance of results for the particle and liquid cooling rate index as influenced by process variables are summarized in Table 4.3a-b. Again most factors studied had a significant influence ($p<0.05$) on the f_c value of particles in water as well as CMC solution. In this case, again, the most predominant factor was the rotation speed. This was followed by can size. Temperature was significant only in CMC solution. Similar to the cooling rate index of particles, the small cans gave lower values of (f_c) indicating faster cooling rate. However the difference between the large and medium size can was not significant in water medium. With respect to rotational speed, there was no significant difference between 10 and 20 rpm in water cans but with CMC, the value decreases as rotational speed is increased. Temperature has no meaningful effect on the cooling rate index.

As the case in f_h rotational speed was found to be very significantly effective in reducing f_c. However, from thermal processing point of view this may be less important since agitation during cooling is not necessarily a common practice. It is also desirable from process calculation point of view to have $f_c > f_h$, because these are implicit assumptions in process calculations methods such as Ball and Stumbo models (Stumbo 1973). In the present studies, f_c was twice as high as f_h values. The temperature effect is obvious because during cooling is really not a variable. It is always the same cold water (~30C) that is employed for cooling. The three temperatures (110-130C) constitute to be initial of the cans, which will have a low influence on the heating or cooling rates.

4.4.5. Effect of process variables on cooling lag factor

With respect to j_{cc} overall results did not show any clear trend with any of the studied factors (Table 4.4a-b). As explained earlier with the cooling rate index, several of the variables are not really a variable during cooling (like retort temperature). The associated j_{cc} values are somewhat smaller than the j_{ch} values. Generally, lag factor is inversely proportional to the heating rate index. For a fast heating product (low f_h), the differences in lag factor becomes easily noticeable with respect to process variables. For slow heating products, the rate factor accommodates most of the variation, that the changes in lag factor become less significant. Although there is significant difference it is difficult to attribute it to any variable since it is not systematic.

4.4.6. Effect of process variables on F_0, C_0 and C_0/F_0

The primary objective of rotational processing is to deliver sufficient heat at the most critical point in the food within a short time. F_0 value (process lethality) is the common parameter usually employed to measure adequacy of a thermal process with respect to microbial destruction. Other closely associated parameter is C_0 (cook value), which indicates the cumulative equivalent cooking minutes at 100°C. Obviously, higher temperature or factors that improve heat transfer such as mechanical agitation will also increase the process lethality and the cook value as well. This increase is generally accompanied by a reduction in the C_0/F_0 ratio, which could be used as a relative measure of degree of cooking especially when process time is not constant (Ramaswamy et al., 1993).

Variables investigated in this study showed significant effect on F_0, C_0 and consequently on the C_0/F_0 ratio (Table 4.5a,b,c). However, the influence of temperature was most noticeable in this case than any other parameter accounting for more than 99% of the variance. Rotation speed and can size followed next. Their effects were small, but significant. The effects of variables on C_0/F_0 ratio for particle in CMC and water are illustrated in Figures 4.8 and 4.9.The mean value of the particle C_0/F_0 decreased dramatically from about 32 to 1.8 in water, and 35 to 1.99 in CMC, as temperature was raised from 110 to 130°C. This demonstrates the usefulness of high temperature short time processes for the product implying that the cook value (degree of cooking) can be significantly lowered (which will improve quality retention) as the process is carried out at 130°C as compared to 110°C. Relatively, the differences between the C_0/F_0 ratios were small with reference to can size and rotation speed. However, this can still be optimized to yield better product because higher rotation speed and small can size can improve the uniformity of heating and reduce the process time. The overall results indicated that higher liquid viscosity and bigger can size increase the C_0/F_0 ratio while higher rotational speed and higher temperature have decreasing effect. As expected, the behavior of the indicative parameter in the liquid media was not different. Except can size and high liquid viscosity, all factors studied resulted in smaller C_o/F_o ratio and the influence of temperature was again the overriding factor. Increasing temperature from 110°C to 130 °C reduced the ratio almost from 30 to 1.5 in both liquids representing about 2000 folds while changing rotational speed from 0 to 20 rpm brought it down from 14 to 12.5 in CMC and from 13 to 12 in water cans.

4.4.7. Continuous vs. oscillatory end-over-end processing

From mechanical perspective, rotational processing can be accomplished in different modes. Most common are end-over-end and axial modes. End-over-end is reported to be more effective and can be carried out either in continuous or oscillatory fashion. Like the case in continuous rotation, heating rate index of particle as well as that of liquids, cooling rate factor and C_o/F_o all were found to decrease with rotational speed and increase with can size. For example increasing the oscillation speed from 0 to 20 rpm resulted in about 30 and 24% reduction in particle f_h in CMC and water respectively, while processing in small cans instead of large ones resulted in 31 and 26% reduction in particle f_h in CMC and water respectively. Similarly, the liquid f_h of CMC reduced by 15% while that of water reduced by 21.5%. As expected, the improvement attained in heat transfer during oscillatory processing correlates well with the C_o/F_o ratio. Although the oscillation runs were carried out at single temperature (120°C) it can be reported that the influence of temperature is expected to be much greater than changing rotational speed or reduced can size as indicated by the continuous mode of rotation.

With respect to the comparison between continuous versus oscillation the overall results are summarized in table (4.6). By comparing mean values none of the heating parameters (f_h &J_{ch}) showed significant difference ($p<0.05$) between oscillatory and continuous mode. However, oscillatory mode gave slightly lower figures.

Since any improvement in heat transfer system is expected to give higher sterilization (F_o) and cook values (C_o), accompanied by lower (C_o/F_o) ratio, the little decrease in the f_h values are also reflected in the indicative parameter for conditions promoting better quality (C_o/F_o). Although some earlier studies reported that continuous rotation is superior to oscillatory fashion, our overall results obtained from the 9 runs do not contribute to that suggestion.

4.5. Conclusions

In both water and cmc media, rotational speed and liquid viscosity showed greater effects on f_h and j_{ch} values followed by can size, while the effect of temperature was more dominant with the C_o/F_o ratio. Results indicated that, higher rotational speed gave considerably lower f_h and j_{ch} values while increasing can size exhibited the opposite effect. The influence of mode of rotation (continuous versus oscillation) on the heating rate index f_h and the lag factor j_{ch} was marginal in cmc cans and insignificant in water cans. F_h and j_{ch} values of liquid were found to be always lower than that of particles in both water and cmc cans. None of the factors investigated showed meaningful influence on the j_{cc} values although an increasing trend with increasing rotational speed was obvious. All factors that improve heat transfer rate were found to give lower C_o/F_o ratio a good indicator of condition promoting better quality. Effects of reduction achieved in process time on the quality attributes are discussed in chapter 5.

Table 4.1a: Analysis of variance for (f_h) of potato cubes in water

	Particle				Liquid		
Source of variation	D. F.	M. S.	F-value	P-value	M. S.	F-value	P-value
Can	2	29.19	82.4	0.0001**	18.89	115.25	0.0001**
Temp.	2	6.84	19.3	0.0001**	5.77	35.25	0.0001**
RPM	2	40.93	115.53	0.0001**	19.85	121.17	0.0001**
Can*Temp.	4	0.27	0.78	(ns)	0.46	2.80	0.0333*
Can*RPM	4	0.71	2.01	(ns)	0.87	5.34	0.0009*
Temp*RPM	4	0.28	0.81	(ns)	0.63	3.85	0.0007*
Error	62	0.35			0.16		
Total	80						

** highly significant, * significant

Table 4.1b: Analysis of variance for (f_h) of potato cubes in CMC

	Particle				Liquid		
Source of variation	D. F.	M. S.	F-value	P-value	M.S.	F	P-value
Can	2	22.51	92.81	0.0001**	16.55	72.78	0.0001**
Temp.	2	5.74	23.64	0.0001**	6.87	30.22	0.0001**
RPM	2	46.82	193.03	0.0001**	38.48	169.24	0.0001**
Can*Temp.	4	0.74	3.06	0.028	2.28	10.03	0.0001**
Can*RPM	4	0.51	2.11	(ns)	0.25	1.1	(ns)
Temp*RPM	4	1.97	8.14	0.0001**	0.35	1.56	(ns)
Error	62	0.24			0.23		
Total	80						

** highly significant, * significant

Table 4.1c: Effects of process variables on (f_h) values

Variable		Water (LSD 0.32,0.22)		CMC (LSD 0.27,0.26)	
		Particle	Liquid	Particle	Liquid
Can size					
	401x411	7.80a	6.62a	9.87a	8.20a
	307x309	6.51b	5.53b	8.83b	7.22b
	211x400	5.54c	4.97c	8.05c	6.66c
Temp.					
	110	7.27a	6.23a	9.41a	7.79a
	120	6.38b	5.54b	8.84b	7.48b
	130	6.42c	5.35b	8.49c	6.8c
RPM					
	0	8.05a	6.78a	10.37a	8.72a
	10	6.34b	5.40b	8.57b	6.85b
	20	5.66c	5.04c	7.80c	6.51c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 4.2a: Analysis of variance for (j_{ch}) of potato cubes in water

	Particle				Liquid		
Source of variation	D.F	M.S.	F-value	P-value	M.S	F-value	P-value
Can	2	0.11	13.17	0.0001**	1.22	3.36	0.04*
Temp.	2	0.04	4.61	0.0136*	1.69	4.64	0.01*
RPM	2	1.87	215.90	0.0001**	0.68	1.88	(ns)
Can*Temp.	4	0.003	0.39	(ns)	0.99	2.71	0.03*
Can*RPM	4	0.012	1.34	(ns)	0.78	2.14	(ns)*
Temp*RPM	4	0.018	0.211	(ns)	0.89	2.44	(ns)
Error	62	0.008			0.36		
Total	80						

* significant

Table 4.2b: Analysis of variance for (j_{ch}) of potato cubes in CMC

	Particle				Liquid		
Source of variation	D.F	M.S.	F-value	P-value	M.S.	F-value	P-value
Can	2	1.91	51.13	0.0001**	0.12	11.94	0.0001**
Temp.	2	0.43	11.60	0.0001**	0.50	50.38	0.0001**
RPM	2	7.71	206.20	0.0001**	0.12	12.54	0.0001**
Can*Temp.	4	0.03	0.81	(ns)	0.02	1.73	(ns)
Can*RPM	4	0.17	4.75	0.002*	0.03	3.83	0.007*
Temp*RPM	4	0.11	3.00	0.02*	0.01	1.17	(ns)
Error	62	0.037			0.01		
Total	80						

** highly significant, * significant

Table 4.2c: Effects of process variables on (j_{ch}) values

Variable		Water (LSD 0.05, 0.32)		CMC (LSD 0.1, 0.05)	
		Particle	Liquid	Particle	Liquid
Can size	401x411	1.61a	1.46a	2.33a	1.26a
	307x309	1.54b	1.1b	2.14b	1.17a
	211x400	1.48c	1.07b	1.8c	1.29
Temp.	110	1.5b	1.5a	1.98b	1.39a
	120	1.57a	1.07b	2.21a	1.22b
	130	1.7a	1.06b	2.11a	1.12c
RPM	0	1.84	1.16a	2.69a	1.32a
	10	1.45	1.39b	1.93b	1.22b
	20	1.34	1.08a	1.65c	1.19c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 4.3a: Analysis of variance for (fc) of potato cubes in water

Source of variation	Particle				Liquid		
	D. F.	M .S.	F-value	P-value	M. S.	F-value	P-value
Can	2	57.05	87.59	0.0001**	34.13	45.59	0.0001**
Temp.	2	1.51	2.33	(ns)	8.43	11.27	0.0001**
RPM	2	301.68	463.13	0.0001**	227.14	303.45	0.0001**
Can*Temp.	4	1.14	1.75	(ns)	1.95	2.61	0.0439*
Can*RPM	4	3.95	6.07	0.0003*	12.59	16.82	0.0001**
Temp*RPM	4	2.53	3.90	0.0069*	3.54	4.73	0.0021*
Error	62	0.65			0.74		
Total	80						

** highly significant, * significant

Table 4.3b: Analysis of variance for (fc) of potato cubes in CMC

Source of variation	Particle				Liquid		
	D. F.	M.S	F	P-value	M.S.	F	P-value
Can	2	68.06	57.46	0.0001**	43.22	20.93	0.0001**
Temp.	2	81.23	68.58	0.0001**	50.16	24.29	0.0001**
RPM	2	1036.76	875.32	0.0001**	942.96	456.76	0.0001**
Can*Temp.	4	2.54	2.15	(ns)	9.27	4.49	0.003*
Can*RPM	4	10.60	8.96	0.0001**	8.83	4.28	0.004*
Temp*RPM	4	22.38	18.90	0.0001**	12.10	5.86	0.0005*
Error	62	1.18			2.06		
Total	80						

** highly significant, * significant

Table 4.3c: Effects of process variables on (fc) values

Variable		**Water (LSD 0.43, 0.47)**		**CMC (LSD 0.59,0.78)**	
		Particle	Liquid	Particle	Liquid
	401x411	13.43a	11.17a	16.86a	14.26a
Can size	307x309	11.76b	10.70b	14.76b	13.08b
	211x400	10.53c	9.03c	13.75c	11.73c
	110	12.13a	10.69a	17.02a	14.59a
Temp.	120	11.66b	10.55a	14.74b	12.40b
	130	11.95ba	9.66b	13.61c	12.09b
	0	15.7a	13.65a	22.13a	19.80a
RPM	10	10.66b	8.76b	12.86b	10.36b
	20	9.38c	3.49b	10.36c	8.92c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different (p<0.05)

Table 4.4a: Analysis of variance for (jcc) of potato cubes in water

Source of variation	Particle				Liquid		
	D.F.	M.S.	F	P-value	M.S.	F	P-value
Can	2	0.20	15.39	0.0001**	0.98	0.99	(ns)
Temp.	2	0.03	2.29	(ns)	1.56	1.59	(ns)
RPM	2	1.50	114.85	0.0001**	1.46	1.48	(ns)
Can*Temp.	4	0.09	7.37	0.0001**	0.82	0.84	(ns)
Can*RPM	4	0.06	4.64	0.0024*	1.33	1.36	(ns)
Temp*RPM	4	0.05	3.90	0.0069*	1.86	1.89	(ns)
Error	62	0.01			0.98		
Total	80						

** highly significant, * significant

Table 4.4b: Analysis of variance for (jcc) of potato cubes in CMC

Source of variation	Particle				Liquid		
	D. F.	M.S	F value	P-value	M.S	F value	P-value
Can	2	0.06	5.08	0.0091*	0.27	23.35	0.0001**
Temp.	2	0.07	5.51	0.0063*	0.09	8.50	0.0005
RPM	2	1.39	106.47	0.0001**	0.30	26.33	0.0001**
Can*Temp.	4	0.21	16.15	0.0001**	0.13	11.72	0.0001**
Can*RPM	4	0.02	1.76	(ns)	0.13	11.89	0.0001**
Temp*RPM	4	0.03	2.36	(ns)	0.04	3.83	0.007*
Error	62	0.01			0.01		
Total	80						

** highly significant, * significant

Table 4.4c: Effects of process variables on (jcc) values

Variable		**Water (LSD 0.06, 0.53)**		**CMC (LSD0.06, 0.05)**	
		Particle	Liquid	Particle	Liquid
	401x411	1.14c	1.1a	1.11c	0.73b
Can size	307x309	1.3a	0.88a	1.21a	0.88a
	211x400	1.22b	0.71a	1.18a	0.69b
	110	1.21ba	0.74a	1.2a	0.7b
Temp.	120	1.26a	0.76a	1.11b	0.81a
	130	1.19b	1.17	1.19a	0.8a
	0	0.94b	0.67a	0.91b	0.64b
RPM	10	1.36a	1.13a	1.31a	0.83a
	20	1.35a	0.87a	1.28a	0.82b

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different (p<0.05)

Table 4.5a: Analysis of variance for (Co/Fo) ratio of potato cubes in water

Source of variation	Particle				Liquid		
	D. F	M. S	F-value	P-value	M. S.	F value	P-value
Can	2	9.00	24.4	0.0001**	21.11	84.92	0.0001**
Temp.	2	7024.23	19024.6	0.0001**	6160.0	24771.5	0.0001**
RPM	2	11.33	30.68	0.0001**	5.52	22.21	0.0001**
Can*Temp.	4	3.58	9.72	0.0001**	6.37	25.64	0.0001**
Can*RPM	4	1.19	3.23	0.0179*	0.37	1.52	(ns)
Temp*RPM	4	0.64	1.75	(ns)	0.87	3.52	0.01*
Error	62	0.36			0.24		
Total	80						

** highly significant, * significant

Table 4.5b: Analysis of variance for (Co/Fo) ratio of potato cubes in CMC

Source of variation	Particle				Liquid		
	D. F.	M. S	F	P-value	M. S.	F	P-value
Can	2	29.2	9.84	0.0002*	39.14	275.57	0.0001**
Temp.	2	8336.6	2807.9	0.0001**	6658.35	46879.5	0.0001**
RPM	2	58.41	19.68	0.0001**	19.18	135.01	0.0001**
Can*Temp.	4	1.11	0.37	(ns)	13.18	92.78	0.0001**
Can*RPM	4	0.8	0.27	(ns)	1.5	10.59	0.0001**
Temp*RPM	4	19.18	6.46	0.0002*	4.46	31.44	0.0001**
Error	62	2.96			0.14		
Total	80						

** highly significant, * significant

Table 4.5c: Effects of process variables on (Co/Fo) ratio

Variable		**Water (LSD 0.33, 0.53)**		**CMC (LSD0.93, 0.2)**	
		Particle	Liquid	Particle	Liquid
Can size	401x411	14.16a	13.34a	15.77a	14.35a
	307x309	13.18b	12.27b	14.23b	12.9b
	211x400	13.14b	11.59c	13.80b	11.95c
Temp.	110	31.9a	29.64a	34.67a	30.97a
	120	6.75b	6.1b	7.13b	6.56b
	130	1.83c	1.46c	1.99c	1.64c
RPM	0	14.15a	12.91a	16.25a	14.03a
	10	13.48b	12.23b	14.12b	12.71b
	20	12.85c	12.05b	13.43b	12.46c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 4.6: Comparison of the mean effects of continuous vs oscillation on process parameters

Parameter	Water continuous		Water oscillation	
	Particle	Liquid	Particle	Liquid
f_h	6.37a	5.54a	6.36a	5.64a
j_{ch}	1.56a	1.07a	1.56a	1.3b
C_o/F_o	6.75a	6.1a	6.67a	6.13a
	CMC continuous		**CMC oscillation**	
f_h	8.2a	7.5a	8.0a	7.1b
j_{ch}	2.08b	1.2b	2.38a	1.7a
C_o/F_o	7.1a	6.59a	6.9b	6.57a

Numbers in a row for a given variable not sharing the same letter are significantly different ($p<0.05$)

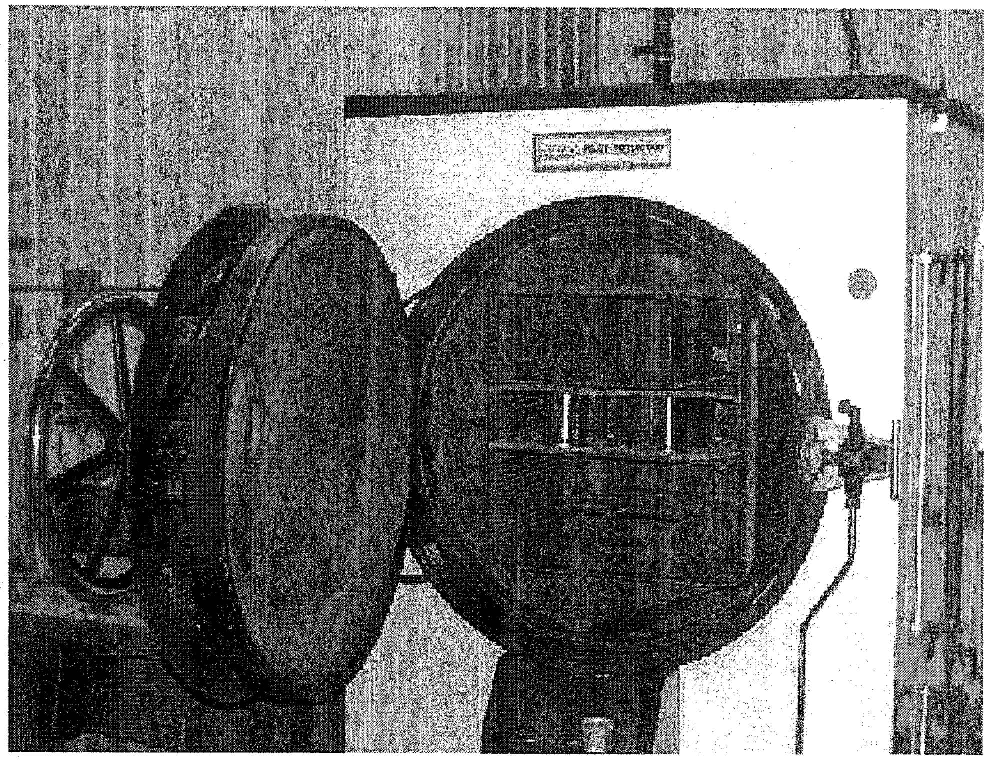


Figure 4.1: Picture of Stock rotomat-PR900

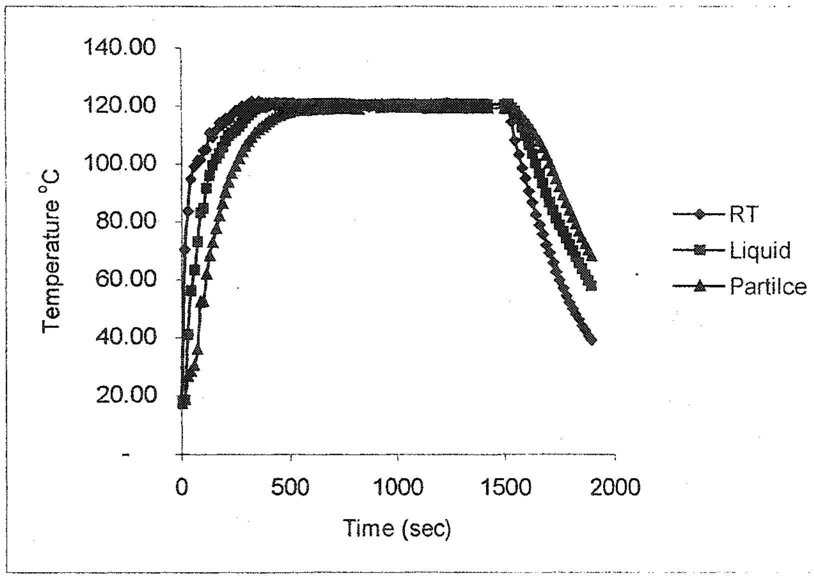


Figure 4.2: Typical heating and cooling curve of potato cubes

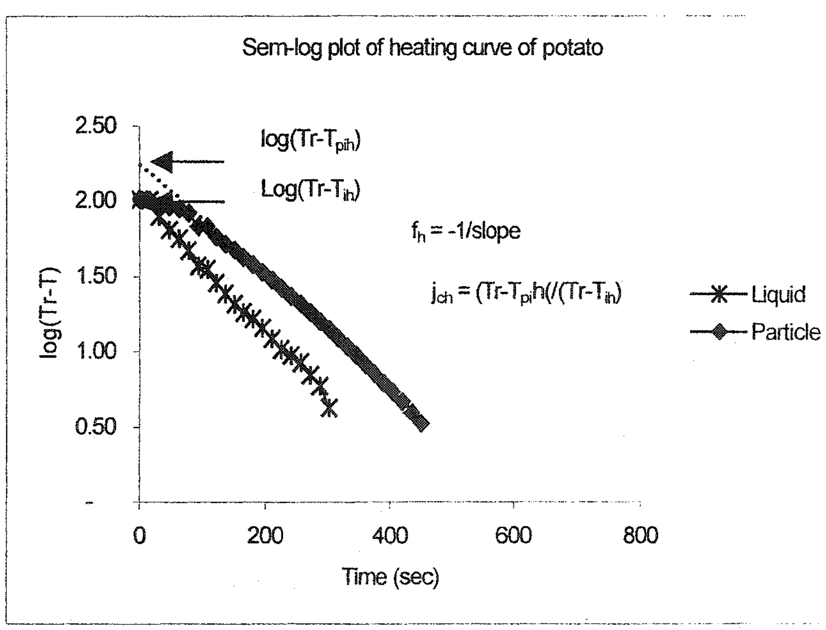


Figure 4.3: Typical semi-log heating curve of potato samples

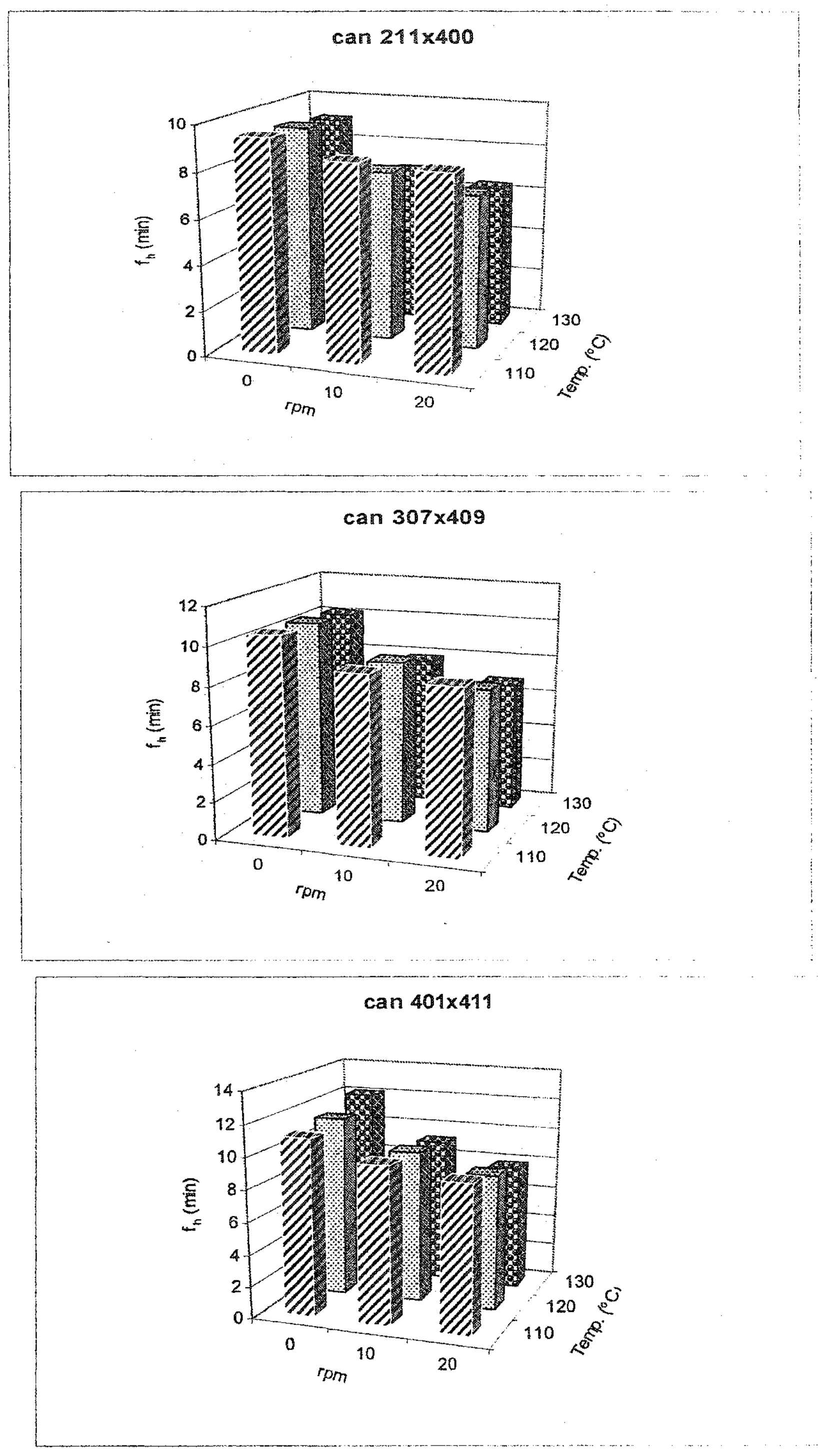


Figure 4.4: Effect of rotational speed and temperature on particle heating rate index (f_h) in CMC

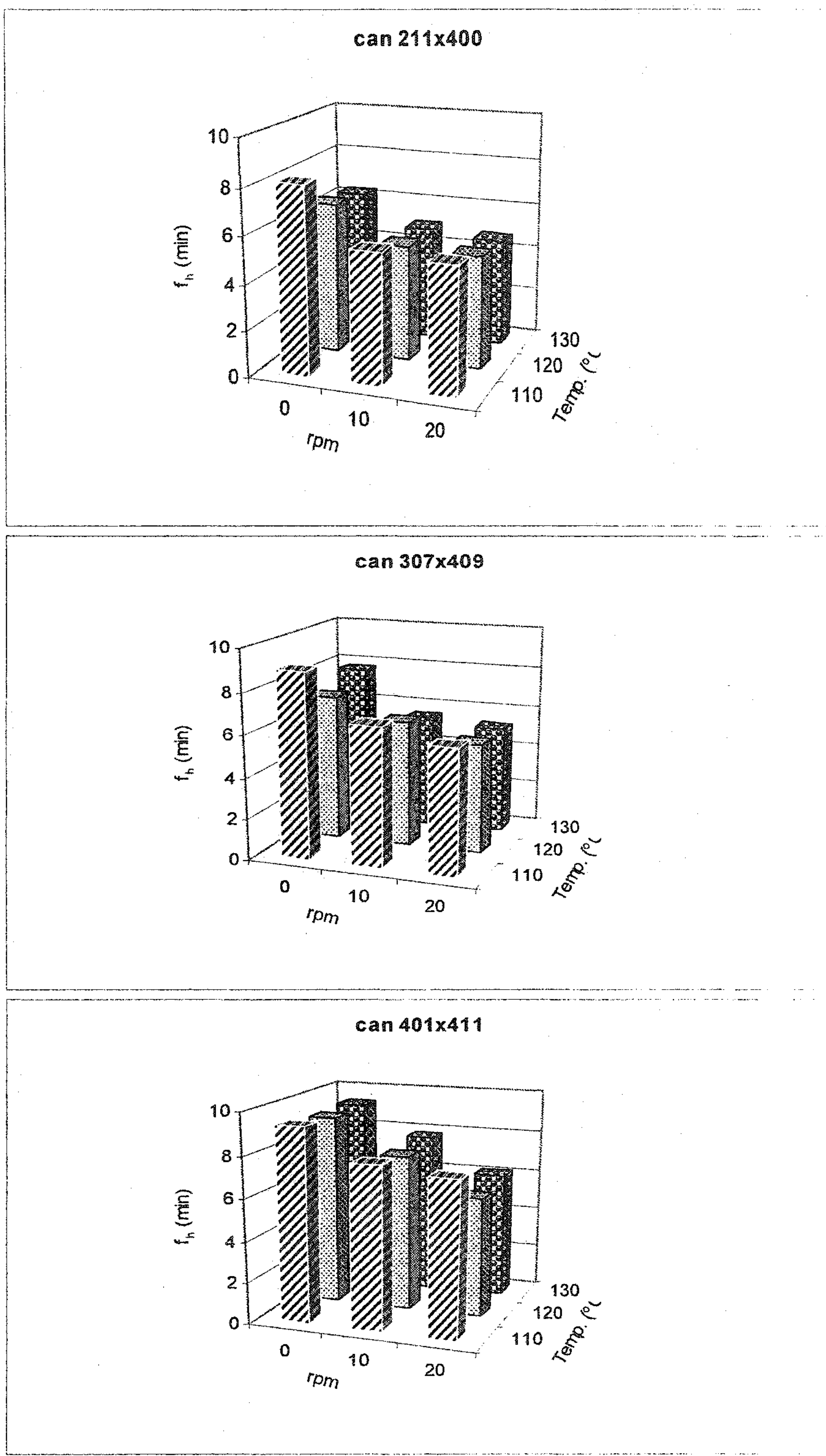


Figure 4.5: Effect of rotational speed and temperature on particle heating rate index (f_h) in

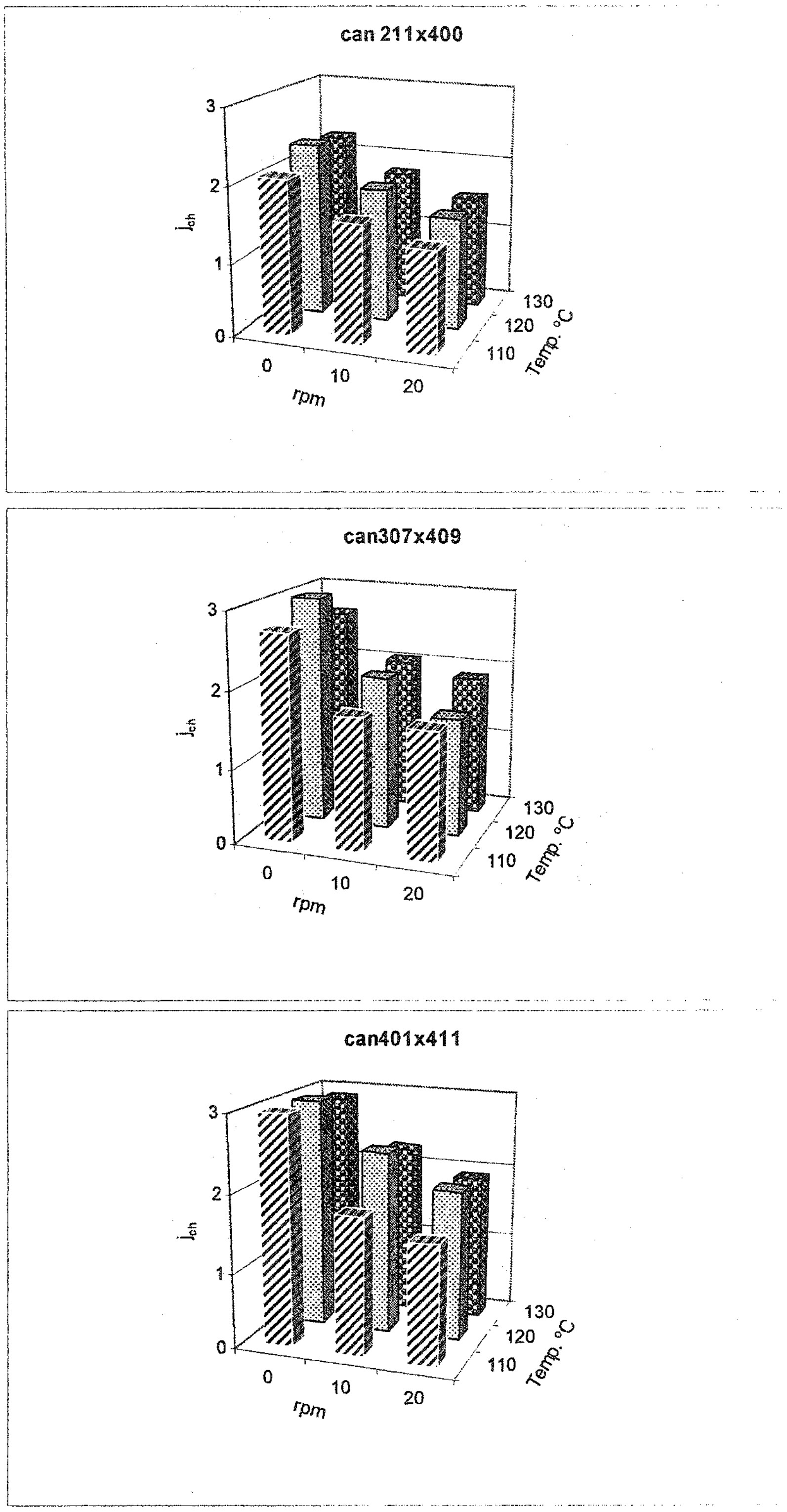


Figure4.6: Effect of rotational speed and temperature on particle heating lag factor (j_{ch}) in cmc

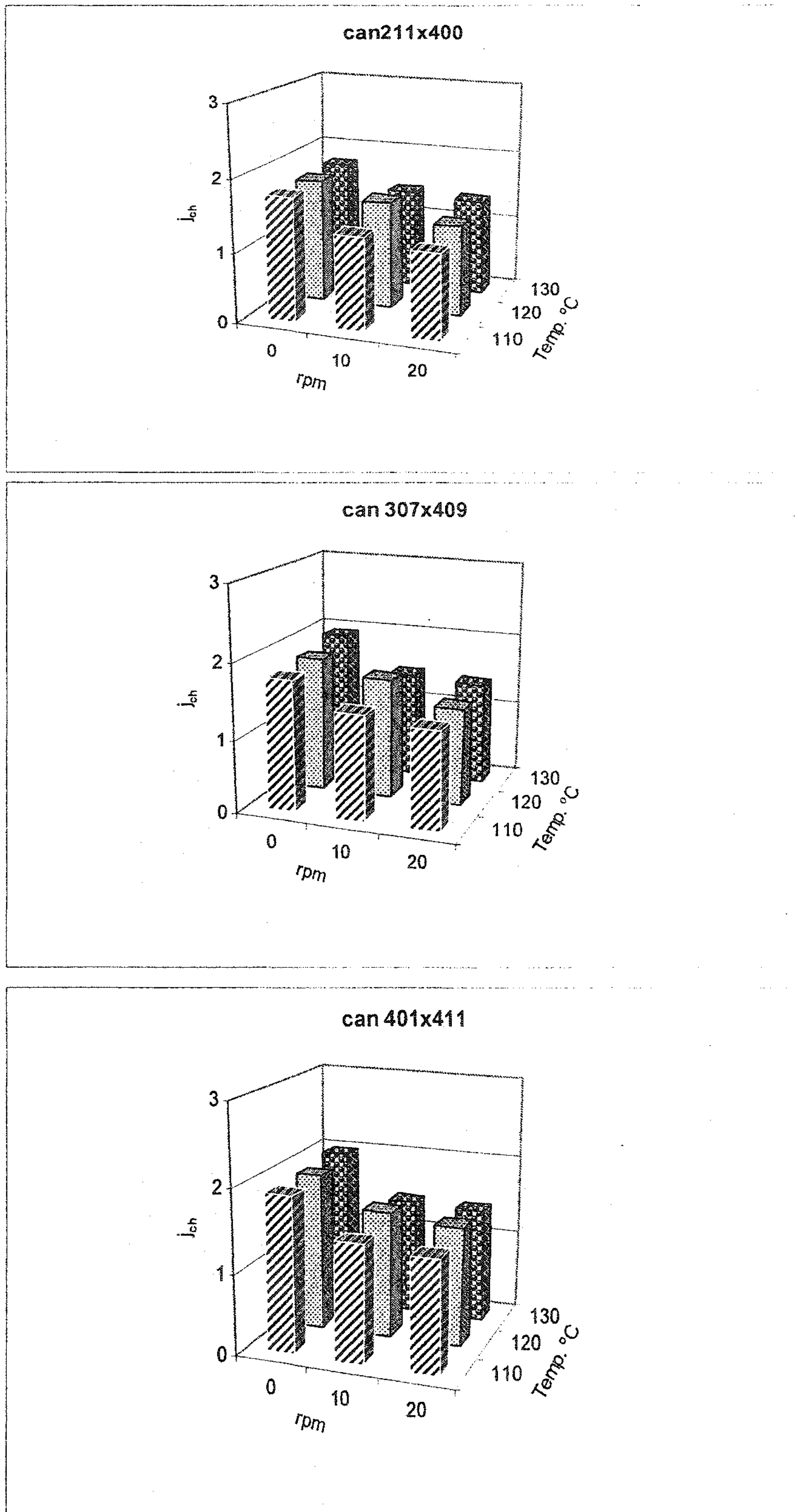


Figure 4.7: Effect of rotational speed and temperature on particle (j_{ch}) in water

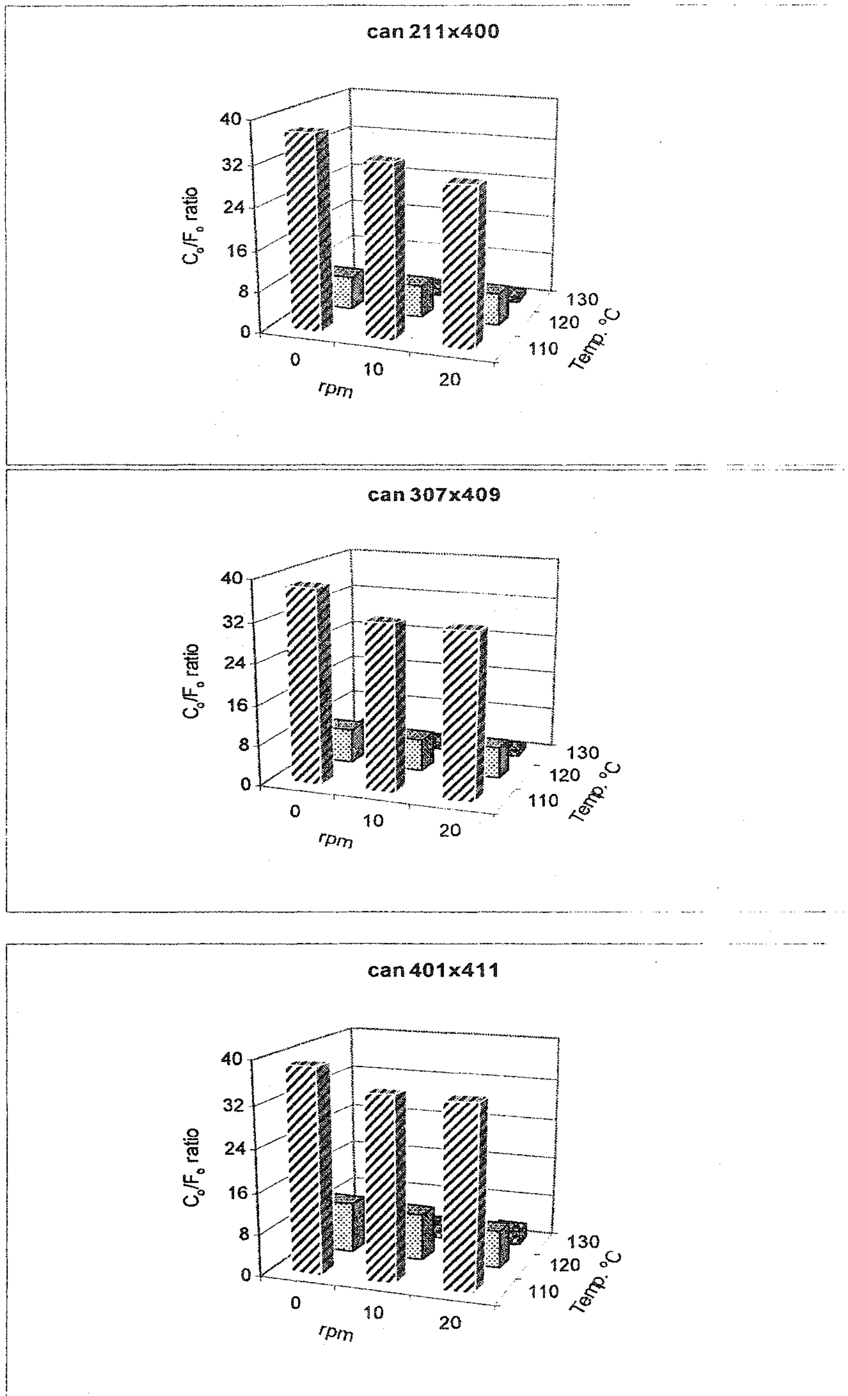


Figure 4.8: Effect of rotational speed and temperature on particle C_o/F_o ratio in cmc

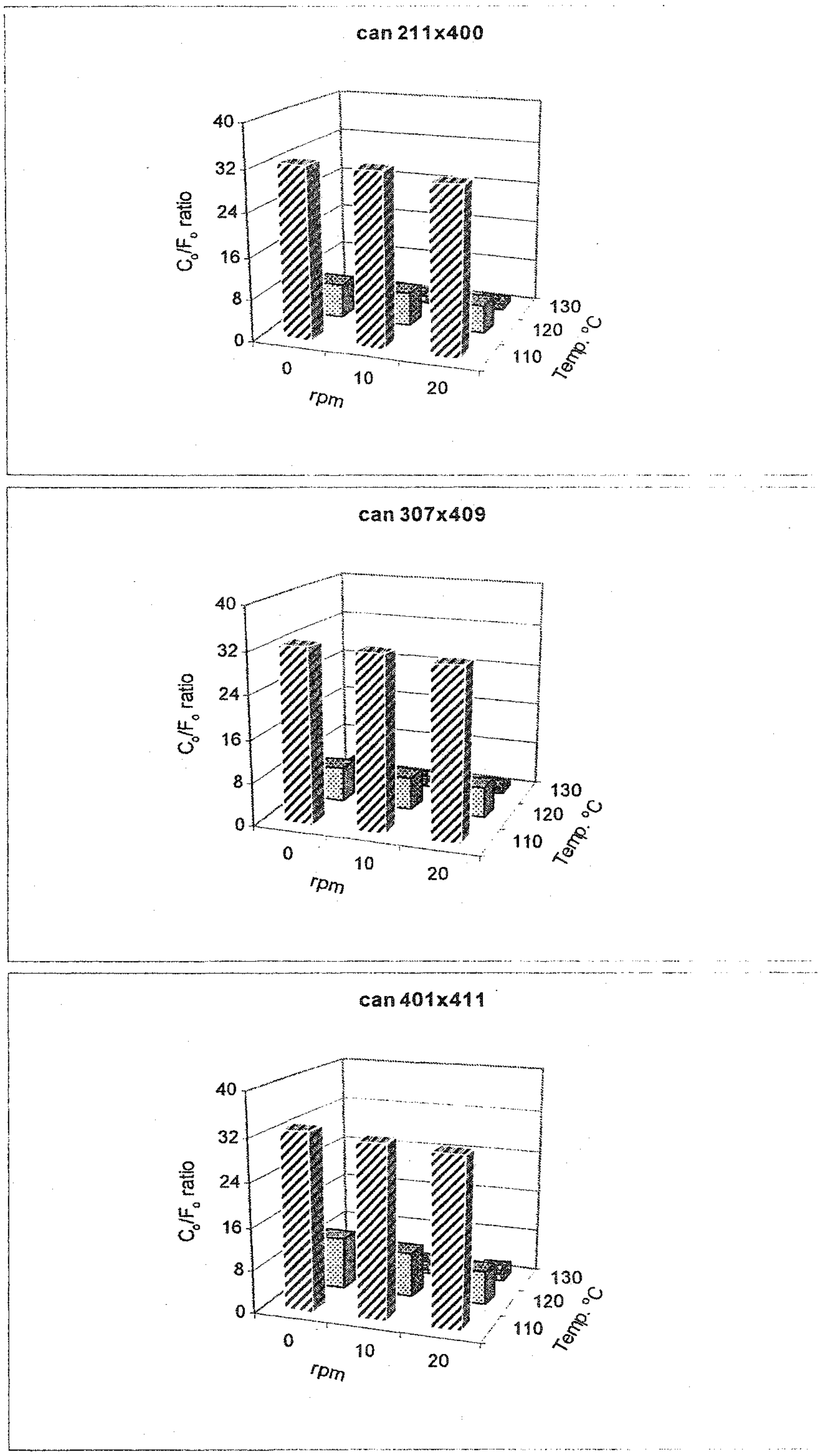


Figure 4.9: Effect of rotational speed and temperature on particle C_o/F_o ratio in water

CHAPTER 5

EFFECTS OF PROCESSING VARIABLES ON TEXTURE AND COLOR OF CANNED POTATOES UNDER END-OVER-END AGITATION PROCESSING

5.1. Abstract

The effects of temperature can size rotational speed and processing liquids on texture and color of canned potatoes have been evaluated. Potatoes were cut into cubes, 15 mm x 15 mm x 15mm, filled in to cans (68.5% w/w), covered with water or 1% aqueous solution of carboxy methyl cellulose (CMC), sealed and subjected to thermal processing in a pilot scale full water-immersion rotary retort as described in the previous chapter. Texture parameters, firmness, stiffness and hardness as well as color indicators L, 'a' and 'b' were evaluated for each processing condition. Under constant processing conditions, higher rotational speed and temperature and smaller can size generally resulted in significant ($p<0.05$) decrease in texture and L-values indicating softer and darker products. Both "a" and "b" values were found to increase with a rise in temperature or rotational speed while the effect of can size on these two parameters was not uniform. Following normalization of process time, an increase in temperature and rotational speed or processing in small cans produced canned potatoes with firmer texture and better color.

5.2. Introduction

A variety of low acid vegetables are thermally processed in order to destroy microorganisms, prolong shelf life and provide a reliable supply of processed foods. The required lethal effect can be delivered over a wide range of combinations of processing times and retort temperatures. With a decrease in processing time the retort temperature has to be increased in order to achieve a desired lethality. During processing, the physical, chemical and sensory characteristics of the food are modified. Thus, rapid and uniform heating is required to achieve the target lethality with minimum damage of food quality attributes such as color, texture and nutrients. In addition to that, rapid heating leads to an increase in the overall process equipment output and thus increased efficiency and reduced costs. Although HTST processing or even more extreme UHT methods are known to offer several quality advantages, both techniques suffer from certain limitations for in-package sterilization. Very high temperatures will inflict severe damage of the food near the container wall, long before the food at the center of the container experience a rise in temperature. Similarly, a very low retort temperature will result in substantial loss in quality because of adverse chemical reactions due to prolonged heating. Consequently, there is a need to achieve a trade off between the beneficial and the destructive effects of the heat processing of foods, to reach a heating temperature profile that ensures a pre-defined final microbial safety while maximizing the final nutritional or organoleptic quality of the product (Canto et al., 2002).

Optimization of processing conditions becomes more important due to the fact that acceptance or rejection decisions of certain foods are largely based on texture and external appearance. Therefore, provision of safe foods, which are attractive in color and texture, remains to be the major challenge of the food industry. At present, based on consumers increased awareness, there is a strong incentive to minimize thermal damage of processed canned foods, prompting many studies on innovative technologies for enhancing quality.

Traditionally, the adverse effect of cooking on quality and nutritive values of food had been receiving a lot of attention from those in industry and consumers as well. More than 200 hundred years a go Count Rumford mentioned that "it seems to be unanimous opinion of those who are most acquainted with these useful vegetable that the best way of cooking them is to boil them simply, and their skin on, in water" (Anon, 1875). A decade later, Snyder *et al.* (1897) reported that for maintenance of highest food value potatoes should not be peeled before cooking. These statements are clear indications that maintenance of nutritional quality of foods had ever been a great concern for many people since two centuries ago. Many thermal processes that are carried out in industry are associated with undesirable effects on food. Kozempel et al. (1982) found that hot water blanching caused significant losses of glutamic acid, aspartic acid, valine, phenylalanine, arginine, methionine, tryptophan and ϒ-amino-butric acid from potatoes. Some of these amino acids are essential for maintaining good health and can only be found in foods. A significant reduction in water- soluble vitamins including ascorbic acid was also observed. Hence a leaching model, with diffusion as the rate-controlling parameter was developed to predict losses of these vitamins as a function of process parameters. Although nutrient losses are important, their influence on consumer acceptance or rejection of food is less significant compared to color and texture. The color of food contributes immensely to its esthetic application. In addition to giving pleasure, the color of foods is associated with other attributes. For example, the ripeness of fruits such as bananas and strawberries is judged by color. Hence color is used as an index to the quality of a number of foods. It is also used as an indicator of the brown pigments formed during non-enzymatic browning and caramelization process (Ibanoglu, 2002).

As very important external quality attributes for processed vegetables, color and texture have attracted lot of attention from various researchers in recent years and thus have been extensively studied (Hayakawa & Timbers, 1977; Paulus & Saguy, 1980; Rao et al., 1981; Abou-Fadel & Miller, 1983; Huang & Bourne, 1983; Rao et al., 1985; Anantheswaran et al., 1986; Abbatemarco & Ramaswamy, 1994). Ahmed and Shivhare 2001 studied the effect of temperature on color change, and rheology of garlic and reported considerable loss of quality due to high temperature. Shin and Bhowmik (1995) studied thermal kinetics of color changes in pea puree and reported that retention of food color after thermal processing can be used to evaluate the extent of damage due to heat exposure. Therefore, the objective of this research was to investigate the effect of selected thermal process variables on texture and color of potato samples under various retort conditions with end-over-end rotational processing.

5.3. Materials and methods

Test material, potato samples (*Solanum tuberosum*) (variety Red Shef) were purchased from a local market in Sainte Anne. These were store refrigerated (4°C) in a plastic bag with few perforations for a bout three weeks during which all cooking trials were completed. Using a cork borer and a sharp knife, test samples of potatoes were prepared as cubes (15 mm x 15 mm x 15 mm) to more closely simulate the practice followed in commercial canning. A fill weight of 140, 250 and 380g representing approximately two thirds of the total product weight was placed in each of 211X400, 307X409 and 401X411 can respectively. Cans were sealed and subjected to thermal processing in a pilot scale full water-immersion retort as outlined in the previous chapter. Textural analysis and color measurements were performed on raw and cooked samples as detailed in the kinetic studies (chapter three). The ascorbic acid content of the process potatoes was also examined. However, during the heat treatment, vitamin content of the cooked product becomes so low and sometimes undetectable unless a very sensitive method is used. Because of these problems the vitamin test was discontinued.

5.3.1 Statistical analysis

The effects of temperature, rotational speed, can size and natures of carrier liquid were statistically tested using ANOVA of the SAS program.

5.4. Results and discussions

5.4.1. Cook quality

Rotational processing (end-over-end) creates a stirring of the contents in the can and by so doing improves heat transfer. The out come from this type of agitation is to shorten the process time that promotes improved quality characteristics of the food. Tables (5.1 & 5.2) show Ball process time in minutes to deliver an equivalent lethality of 10 in water and CMC respectively. From the two tables it can be seen that increasing the temperature and rotational speed significantly ($p<0.05$) reduce the process time and this is expected to give significant improvements in the quality. Contrary to that, increasing can size was found to give the opposite effect (i.e., larger cans take longer time to process). The influence of the enhanced heat transfer on the process lethality (F_o) and cook value (C_o) and the associated C_o/F_o ratio as mentioned in the previous chapter is reproduced in Table (5.3 &5.4) for comparison.

5.4.2. Color

In addition to heat penetration information, Table 5.3 and 5.4 also show the effects of process variable on the quality parameter (L- value) of the processed samples. The most striking feature of these tables is the fact that all factor that promote enhanced heat transfer also gave quality advantage which confirms our findings in the previous chapter. Analysis of variance of the L values are displayed in table 5.5 (a) and the corresponding figures for water and CMC are shown in Figure (5.1 & 5.2). To a different extent, all variables studied showed significant effect on the L-value an indicator of brightness of the final product. The mean comparison and the standard deviations are given in table 5.5 (b). From this table it can be seen that temperature is the most important variable followed by rotational speed while can size has minimal effect. For example, increasing the temperature from 110 to 130°C resulted in 20% and 14% decrease in brightness of the processed samples in water and CMC respectively, while increasing rotational speed resulted only in 5 and 4% decrease in water and CMC respectively. The effect of can size was in the opposite direction and small in magnitude representing only about 3% in CMC and less than 1% in water between the large and medium size can. No difference was noticed between medium and small can

The influence of process variables on the degree of redness or greenness (a-values) is shown in table 5.6 (a,b) with corresponding figures for both water and CMC in descending order (Figure 5.3 & 5.4). Again the influence of temperature was the overriding factor in color degradation followed by rotational speed and can size. Comparison of the mean effect showed that increasing the temperature from 110 to 130°C resulted in 200 and 150% increase in the a values towards red spectrum in water and CMC respectively while increasing the rotational speed push it about 87 and 56% in the same direction for water and CMC respectively. Can size did not show any effect in water but surprisingly showed 36% decrease in a values as one would vary the can size from small to large can.

The effects of process variables on b values were similar to that of 'a' values and are shown in tables 5.7 (a,b) and Figures (5.5 & 5.6) for water and CMC respectively. From the tables as well as in the figures it is clear that increasing the temperature from 110 to 130°C accounts for the 75 and 85% increase in 'b' values in water and CMC respectively indicating more yellow product. This was followed by rotational speed representing 24 and 27% increase in the 'b' values in water and CMC respectively. Can size showed no effect in water but showed about 5% decrease in 'b' value as the can is varied from small to large size in CMC. Certainly, the highly significant of temperature is due to the faster heat transfer that will eventually result into overcooking of the product with extended cooking time. In general all the variables studied showed very significant effect ($p<0.05$) on the L-values in both water and CMC cans, however the effect of can size was less significant compared to that of temperature and rotational speed. Therefore, it can be concluded that as temperature and the rotational speed are increased at constant process conditions, the samples become darker (i.e., lower L values) more reddish (i.e., higher a values) and more yellow (i.e., higher b values). The observed changes in color indices are probably due to the increased amount of brown pigments due to the Maillard reaction. The L values of the samples changed from 71 (raw) to around 50 in water and 54 in CMC over the temperature range and rotational speed studied respectively. All cans processed in CMC gave better color compared to those processed in water.

5.4.3. Texture

Analysis of variance of firmness in form of texture value for both water and CMC cans are shown in tables (5.8a,b). From practical point of view texture value is more meaningful than simple firmness as it relates to the fresh condition of the material. It is calculated as firmness of the finished product divided by firmness of the raw samples. Obviously under constant processing conditions, increasing the temperature and rotational speed produced softer potato samples in both water and CMC cans as shown in figures (5.7 & 5.8). Similar to 'a' and 'b' values in color the effect of can size on texture value was less evident. Prolonged heating induces complex chemical changes in the cell matrix polysaccharides, which results in more damage on the cell wall components resulting to a softer product. The behavior of stiffness and hardness were found similar to firmness (i.e., higher temperatures and rpm resulted in softer and less stiff products), while increasing the can size showed the opposite (data not shown).

However, it is worth noting that subjecting all cans of different sizes to the same processing conditions is not realistic. Therefore, several time-temperature combinations with different rotational speed and can sizes were tested.

Following the Application of the appropriate times, for each condition, processing at higher temperature for example increasing the temperature from 110 to 130 °C reduces the process time from 136 min to only 10 min. The sharp reduction in process time is accompanied by a remarkable increase in L values indicating brighter products (Table 5.9). Similarly, the influence of process variables on a and b values after adjusting the process time are shown in tables (5.10 & 5.11) while their effect on texture values is given in table (5.12).

5.4.4. Ascorbic acid

With respect to ascorbic acid, the test was discontinued due to the fact that the vitamin residue was very low in the final product and therefore, undetectable. This could be associated to the susceptibility of ascorbic acid to diffusion and oxidation, which may be much higher at sterilization temperatures. Whatever the case might be, the high destruction of ascorbic acid was not a surprise considering that more than 56% of the initial content was destroyed within 15 minutes at 100°C in the kinetic studies in water bath. A second probable reason for ascorbic acid loss in these cans is the lack of vacuum because the product was cold filled and not exhausted.

5.5. Conclusions

The results suggest that texture and color indices of canned potatoes during end-over-end processing changed significantly ($P>0.05$). However, statistical analysis of the results showed that temperature was the primary driving force followed by rotational speed while can size has minimal effect.

Under constant processing conditions, texture value was found to be significantly decreasing with an increase in temperature and rotational speed. Similarly, the L-values were found to behave in the same way. The effect of temperature and rotational speed was found to be in the increasing side with both 'a' and 'b' values indicating poorer quality. However, when process time is adjusted appropriately, all factors that enhance heat transfer (high temperature, fast rotation speed, less viscous medium) were found to give lower C_o/F_o values and better quality.

Table 5.1: Ball process time (minutes) to deliver an equivalent lethality of 10 in water

Temperature (°C)	Can size	Rotational speed (rpm)		
		0	10	20
110	211x400	142	135	133
110	307x409	143	136	134
110	401x411	145	140	139
120	211x400	26	22	21
120	307x409	27	24	22
120	401x411	31	27	24
130	211x400	12	9	8
130	307x409	14	10	9
130	401x411	16	13	11

Table 5.2: Ball process time (minutes) to deliver an equivalent lethality of 10 in cmc solution

Temperature (°C)	Can size	Rotational speed (rpm)		
		0	10	20
110	211x400	144	141	140
110	307x409	148	143	141
110	401x411	151	145	143
120	211x400	32	28	26
120	307x409	35	31	28
120	401x411	38	33	30
130	211x400	17	13	11
130	307x409	19	14	12
130	401x411	22	16	14

Table 5.3: Effect of process variables on quality indices in water cans

Variable	Process time (min)	F_0 (min)	C_0 (min)	C_0/F_0	Texture value	L value
Effect of temperature						
110	136	10.09	269.41	26.70	0.08	52
120	24	10.76	78.19	7.27	0.08	60
130	10	13.42	37.14	2.77	0.09	61
Effect of rpm						
0	27	11.97	95.62	7.99	0.08	57
10	24	11.13	83.52	7.50	0.08	60
20	22	10.53	77.91	7.40	0.1	61
Effect of can size						
211x400	22	12.44	81.3	6.54	0.11	62
307x409	24	11.13	83.52	7.50	0.08	61
401x411	27	13.32	89.34	6.71	0.09	59

Table 5.4: Effect of process variables on quality indices in CMC cans

Variable	Process time (min)	Fo (min)	Co (min)	Co/Fo	Texture value	L value
Effect of temperature						
110	143	10.15	273	26.90	0.08	57
120	31	12	80	6.67	0.09	61
130	14	14.95	45.61	3.05	0.1	62
Effect of rpm						
0	35	12.19	85.39	7.00	0.08	60
10	31	12	80	6.67	0.09	61
20	28	10.49	81.26	7.75	0.1	63
Effect of can size						
211x400	28	12.17	80.89	6.65	0.1	63
307x409	31	12	80	6.67	0.09	61
401x411	33	11.27	81.28	7.21	0.09	59.

Table 5.5a: Analysis of variance for L-value of canned potatoes in two liquids

	Water				CMC		
Source of variation	D.F.	M. S.	F value	P-value	M.S	F	P-value
Can	2	6.07	7.27	0.0015*	44.76	53.89	0.0001**
Temp.	2	1097.3	1313.8	0.0001**	632.09	761.02	0.0001**
RPM	2	68.64	82.18	0.0001**	59.13	71.19	0.0001**
Can*Temp.	4	5.25	6.29	0.0003*	2.57	3.10	0.0218*
Can*RPM	4	9.25	11.5	0.0001**	3.19	3.85	0.0074*
Temp*RPM	4	15.37	18.32	0.0001**	47.49	57.18	0.0001**
Error	62	0.83			0.83		
Total	81						

** highly significant, * significant

Table 5.5b: Effects of process variables on L-values of canned potatoes in two liquids

Variable		Water (LSD 0.49)	CMC (LSD 0.49)
Can size	401x411	54.9a	58.57a
	307x409	54.04b	56.24b
	211x400	54.57a	56.46b
Temp.	110	59.77a	60.31a
	120	56.40b	59.44b
	130	47.43c	51.53c
RPM	0	56.27a	58.73a
	10	54.19b	56.71b
	20	53.14c	55.84c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 5.6a: Analysis of variance for a-value of canned potatoes in two liquids

	Water				CMC		
Source of variation	D. F.	M. S.	F	P-value	M.S	F	P-value
Can	2	0.02	0.31	(ns)	3.09	50.73	0.0001**
Temp.	2	386.9	4875.8	0.0001**	227.62	3733.2	0.0001**
RPM	2	3.88	48.99	0.0001**	12.98	212.98	0.0001**
Can*Temp.	4	0.18	2.25	(ns)	1.03	16.94	0.0001**
Can*RPM	4	0.16	2.05	(ns)	0.09	1.63	(ns)
Temp*RPM	4	0.61	7.73	<0.0001**	5.09	90.18	0.0001**
Error	62	0.07			0.06		
Total	81						

** highly significant, * significant

Table 5.6b: Effects of process variables on a-values of canned potatoes in two liquids

Variable		Water (LSD 0.15)	CMC (LSD 0.13)
Can size	401x411	-0.18a	-1.79c
	307x409	-0.17a	-1.59b
	211x400	-0.23a	-1.13a
Temp.	130	4.02a	1.81a
	120	-1.34b	-2.81b
	110	-3.28c	-3.53c
RPM	20	-0.08a	-1.00a
	10	-0.05a	-1.22b
	0	-0.62b	-2.29c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 5.7a: Analysis of variance for b-value of canned potatoes in two liquids

	Water				CMC		
Source of variation	D. F	M. S.	F	P-value	M. S.	F	P-value
Can	2	0.47	2.05	(ns)	6.3	13.20	0.0001**
Temp.	2	1687.5	7318.1	0.0001**	1745.21	3653.6	0.0001**
RPM	2	95.02	412.11	0.0001**	73.60	154.09	0.0001**
Can*Temp.	4	0.98	4.26	0.004	1.69	3.55	0.011
Can*RPM	4	0.24	1.08	(ns)	0.61	1.29	(ns)
Temp*RPM	4	29.48	125.78	0.0001**	53.48	111.97	0.0001**
Error	62	0.23			0.47		
Total	81						

** highly significant, * significant

Table 5.7b: Effects of process variables on b-values of canned potatoes in two liquids

Variable		Water (LSD 0.26)	CMC (LSD 0.37)
Can size	401x411	12.52ba	9.88b
	307x409	12.39b	9.55b
	211x400	12.65a	10.5a
Temp.	130	20.83a	18.66a
	120	11.62b	8.50b
	110	5.10c	2.78c
RPM	20	13.78a	11.14a
	10	13.41b	10.71b
	0	10.36c	8.09c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

Table 5.8a: Analysis of variance for texture value of canned potatoes in two liquids

	Water				CMC		
Source of variation	D. F.	M. S.	F value	P-value	M. S.	F value	P-value
Can	2	0.00100	21.68	0.0001**	0.0017	14.67	0.0001**
Temp.	2	0.00207	44.7	0.0001**	0.0039	33.62	0.0001**
RPM	2	0.00068	14.68	0.0001**	0.0025	21.4	0.0001**
Can*Temp.	4	0.00041	8.82	0<.0001**	0.0003	2.68	0.039
Can*RPM	4	0.00001	0.42	(ns)	0.0001	0.74	(ns)
Temp*RPM	4	0.00004	0.86	(ns)	0.0024	2.11	(ns)
Error	62	0.0004			0.0001		
Total	81						

** highly significant, * significant

Table 5.8b: Effects of process variables on texture values of canned potatoes in two liquids

Variable		Water (LSD 0.003)	CMC (LSD 0.49)
Can size	401x411	0.08b	0.09b
	307x409	0.09a	0.1a
	211x400	0.07c	0.08c
Temp.	110	0.09a	0.1a
	120	0.07b	0.09b
	130	0.07b	0.08c
RPM	0	0.08a	0.1a
	10	0.08b	0.09b
	20	0.07c	0.08c

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different (p<0.05)

Table 5.9 Effect of process variables on L-values after adjusted process time

Variable		Water	CMC
		LSD 0.83	**LSD 2.21**
	211x400	61.85a	62.76a
Can size	307x409	60.59b	61.00ba
	401x411	59.75c	59.05b
		LSD 1.57	**LSD 0.56**
	130	60.69a	62.01a
Temp.	120	60.59a	61.00b
	110	51.89b	56.72c
		LSD 1.22	**LSD 0.41**
	20	60.61a	62.62a
RPM	10	60.59a	61.00b
	0	57.16b	59.8c

Table 5.10 Effect of process variables on a-values after adjusted process time

Variable		Water	CMC
		LSD 0.38	**LSD 0.06**
	211x400	-2.23ab	-2.87c
Can size	307x409	-1.98a	-2.51a
	401x411	-2.37b	-2.77b
		LSD 1.64	**LSD 0.23**
	110	1.86a	1.32a
Temp.	120	-1.98b	-2.51b
	130	-2.99c	-3.162c
		LSD 0.51	**LSD 0.21**
	0	-1.84a	-2.33a
RPM	10	-1.98a	-2.51a
	20	-2.42b	-2.76b

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)

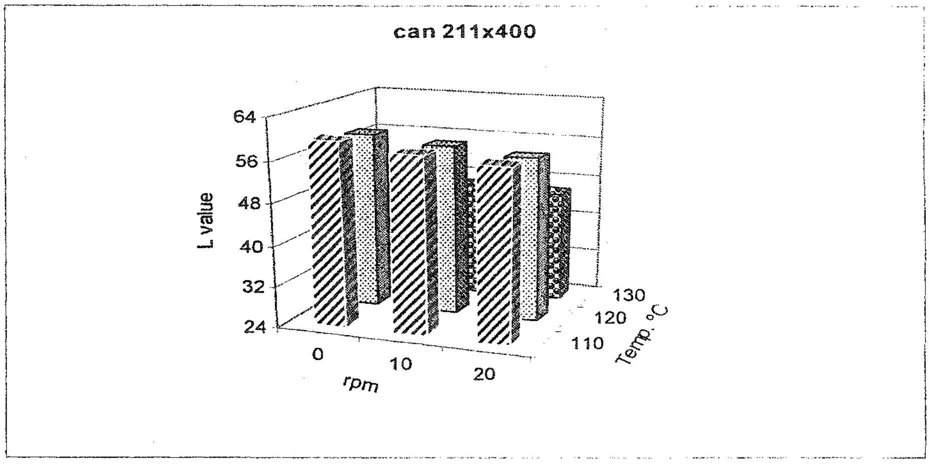
Table 5.11 Effect of process variables on b-values after adjusted process time

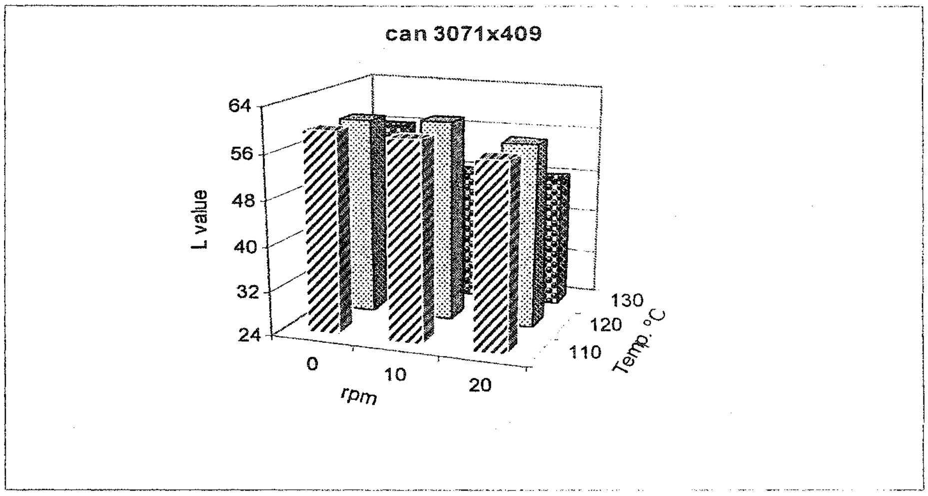
Variable		Water	CMC
		LSD 0.79	**LSD 0.9**
	401x411	14.13a	13.18a
Can size	307x409	11.71b	10.45b
	211x400	10.95b	9.70b
		LSD 2.01	**LSD 1.16**
	110	19.18a	14.78a
Temp.	120	11.71b	10.45b
	130	11.60b	9.49b
		LSD11.02	**LSD 0.96**
	0	14.06a	13.02a
RPM	10	11.71b	10.64b
	20	11.54b	10.45c

Table 5.12 Effect of process variables on texture values after adjusted process time

Variable		Water	CMC
		LSD 0.01	**LSD 0.006**
	211x400	0.1a	0.1a
Can size	307x400	0.08b	0.08b
	401x411	0.09b	0.09b
		LSD 0.0	**LSD 0.006**
	130	0.9a	0.1a
Temp.	120	0.08b	0.086b
	110	0.08b	0.08c
		LSD 0.51	**LSD 0.01**
RPM	0	.0.08c	0.08c
	10	0.08b	0.86b
	20	0.1a	0.1ac

No of replicates cans 27; numbers in a column for a given variable not sharing the same letter are significantly different ($p<0.05$)





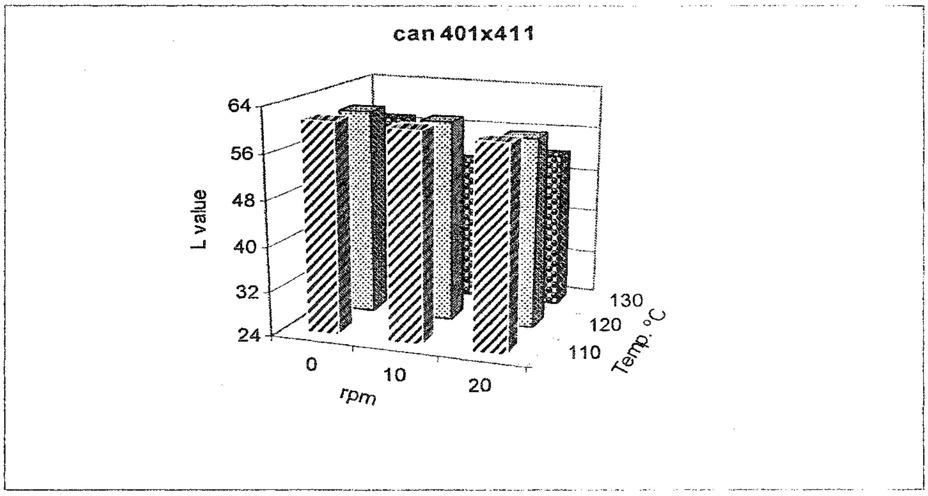


Figure 5.1: Effect of temperature and rotational speed on L value of canned potatoes in water

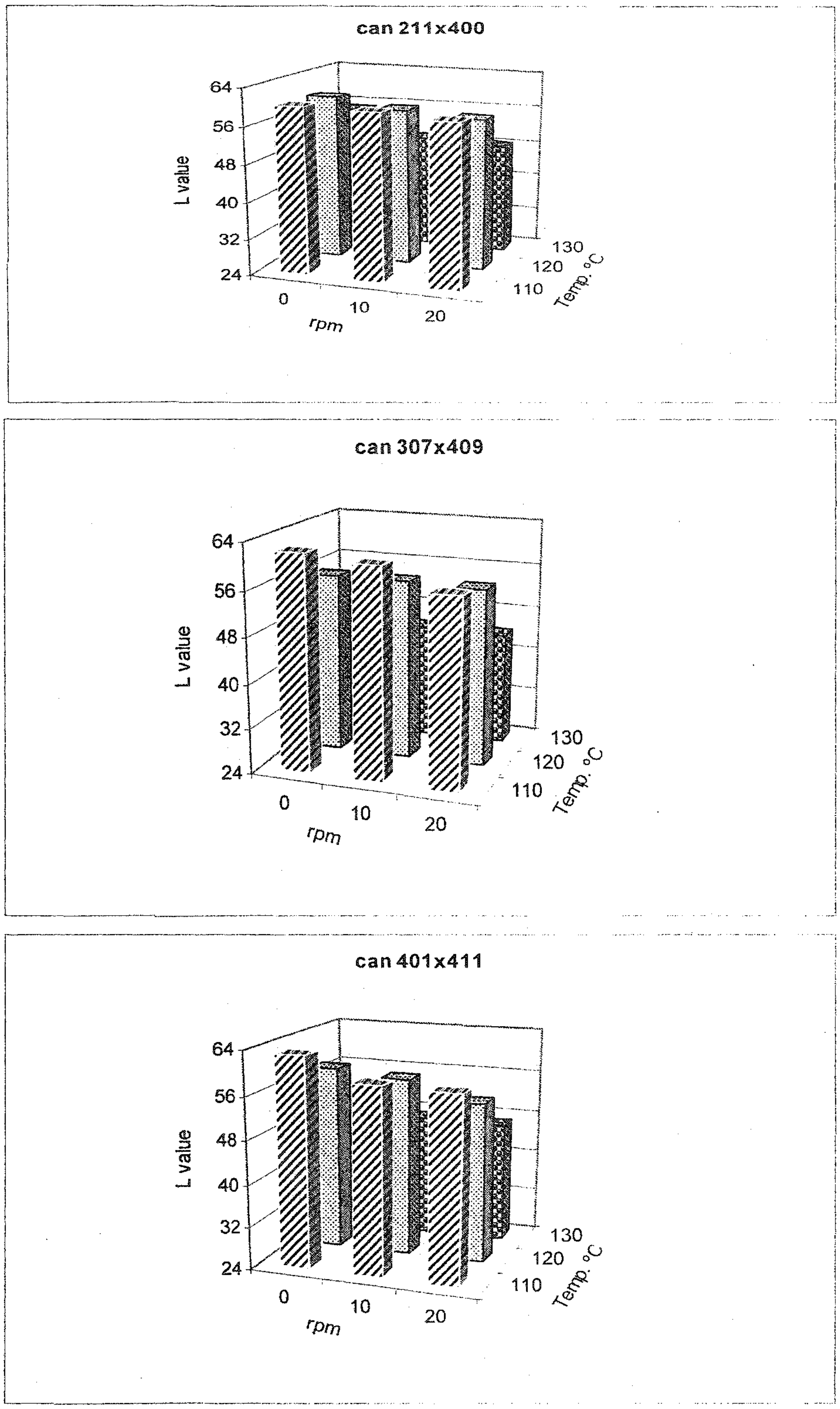


Figure 5.2: Effects of temperature and rotational speed on L values of canned potatoes in CMC

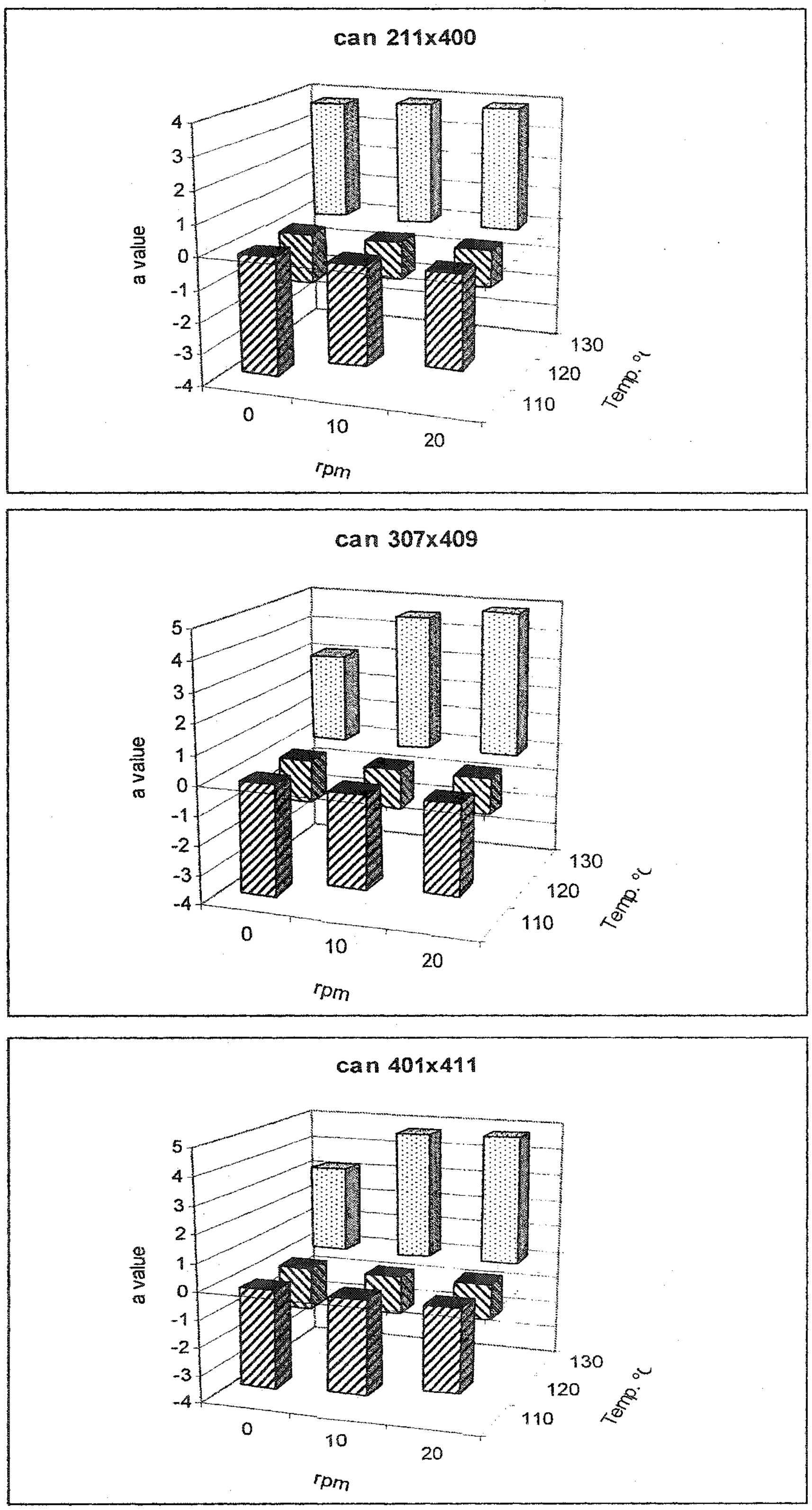


Figure 5.3: Effects of temperature and rotational speed on 'a' values of canned potatoes in water

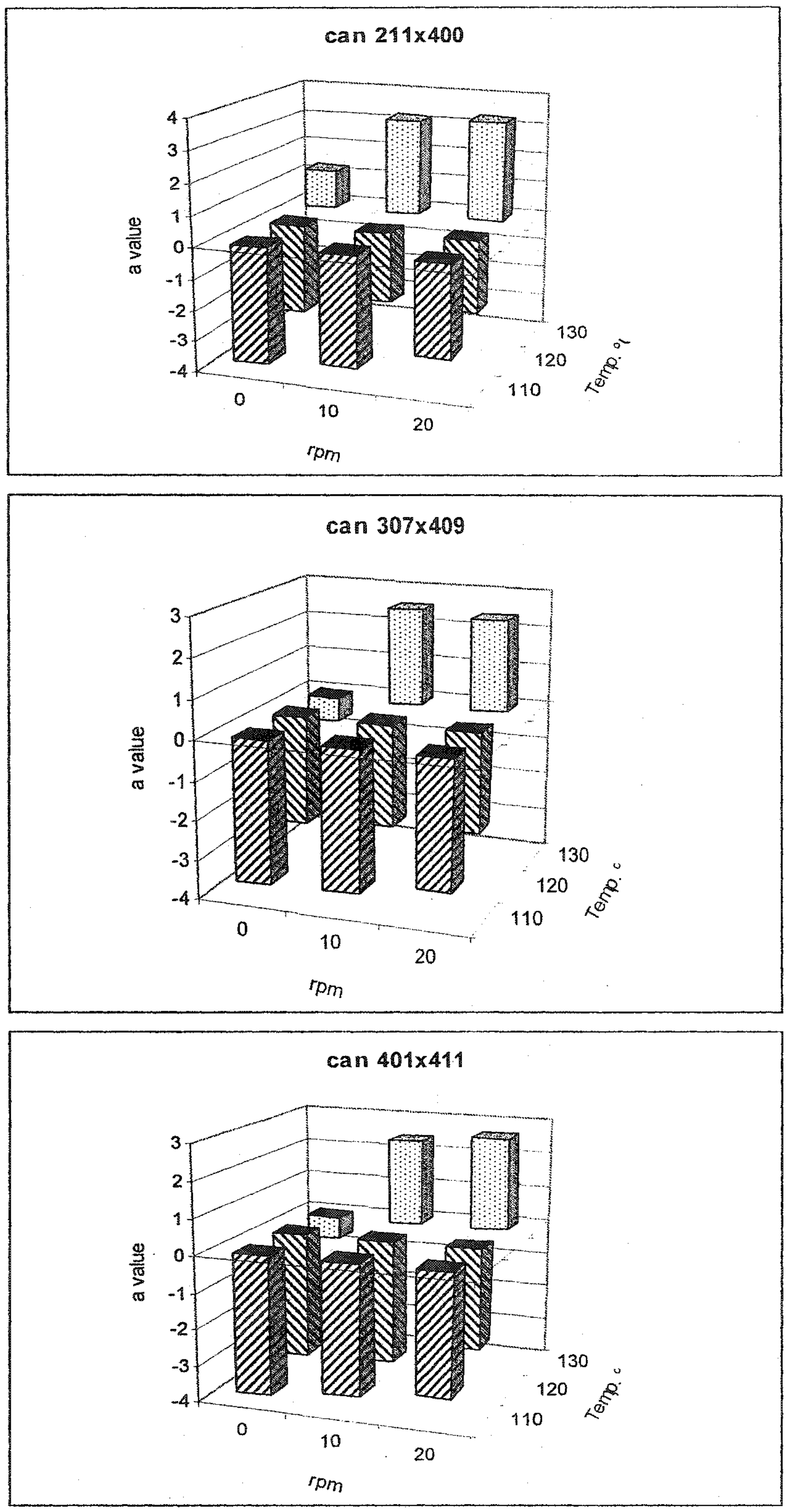


Figure 5.4: Effects of temperature and rotational speed on 'a' values of canned potatoes in CMC

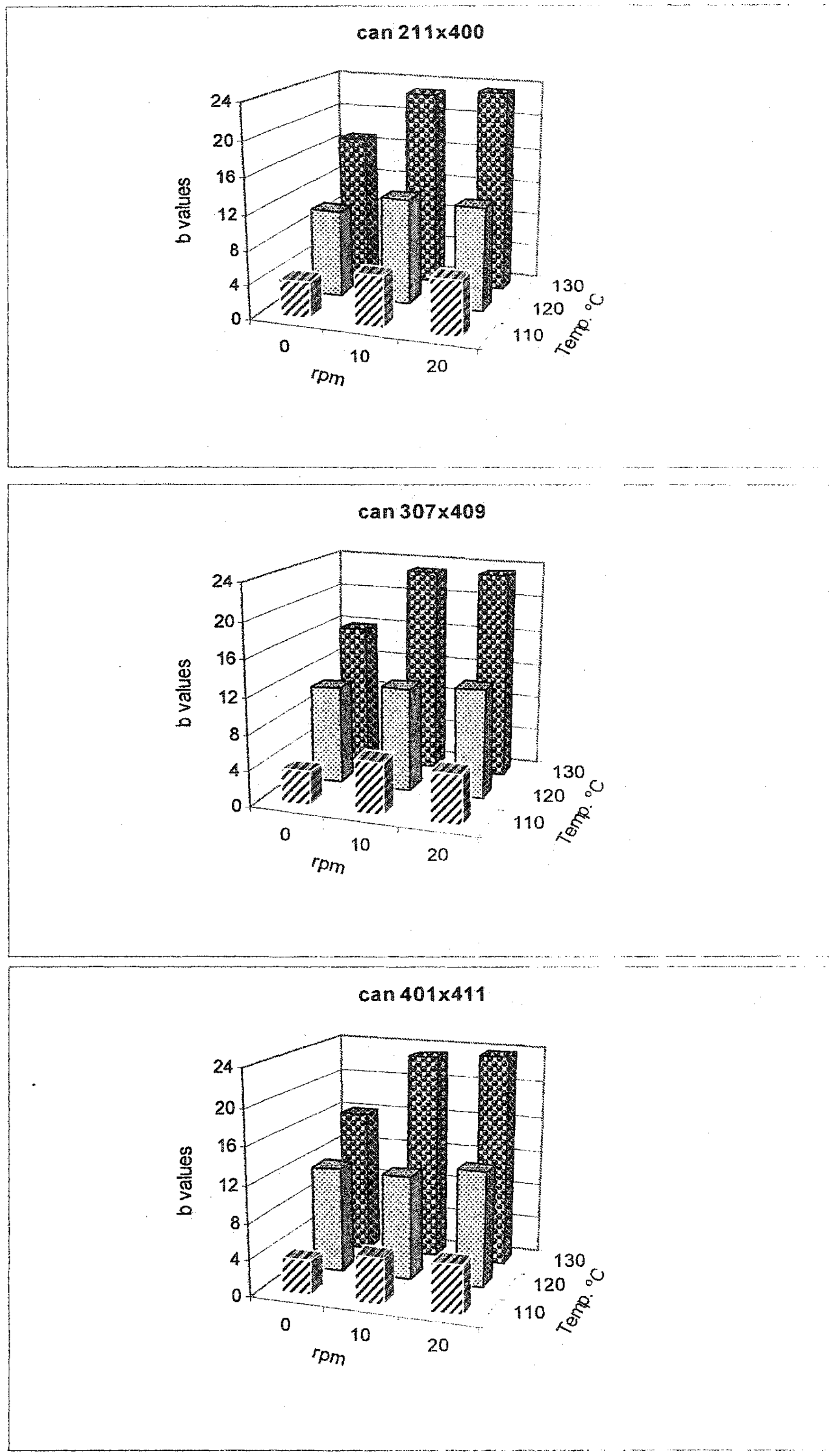


Figure 5.5: Effects of temperature and rotational speed on b values of canned potatoes in water

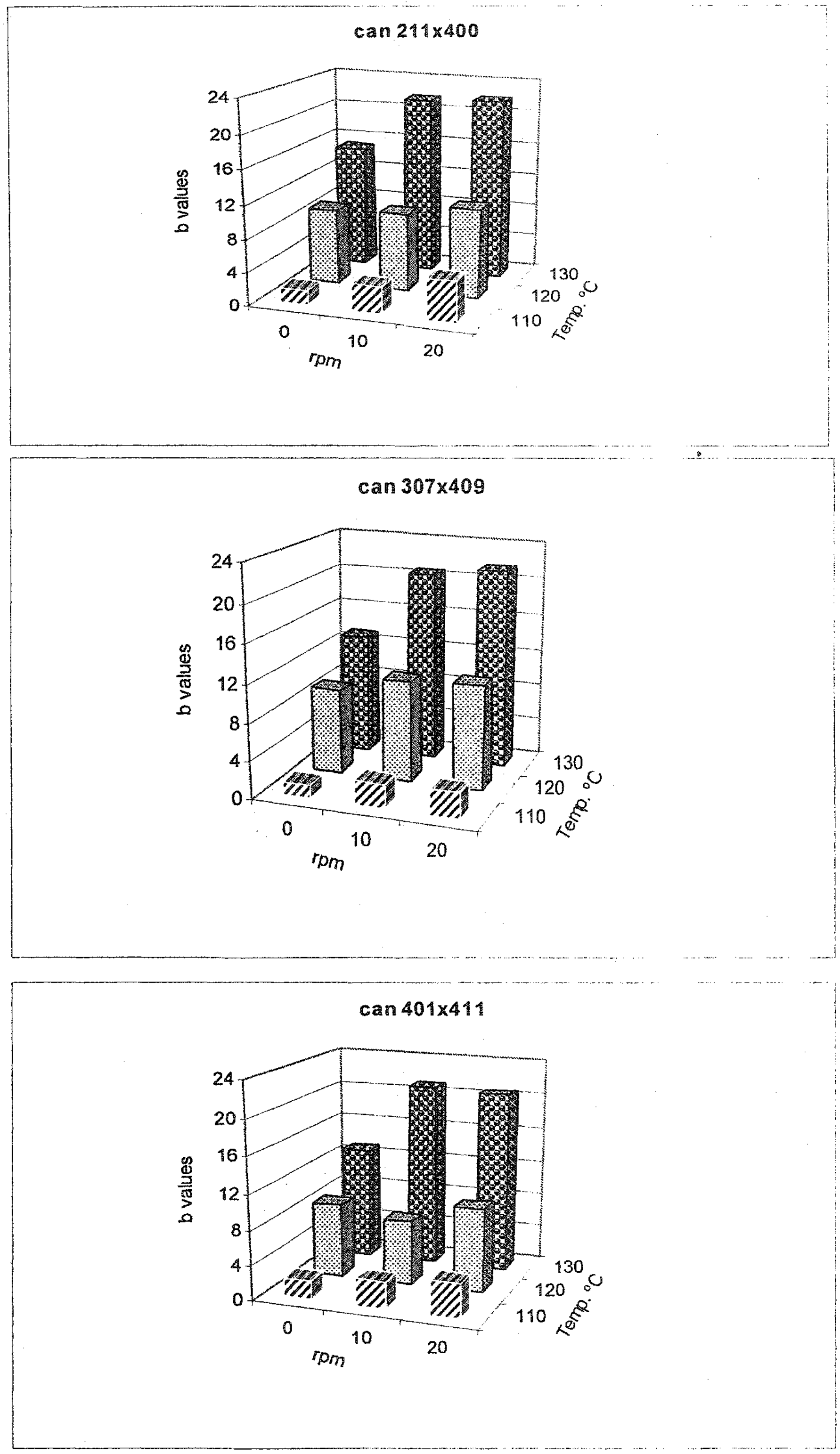


Figure 5.6: Effects of temperature and rotational speed on b values of canned potatoes in CMC

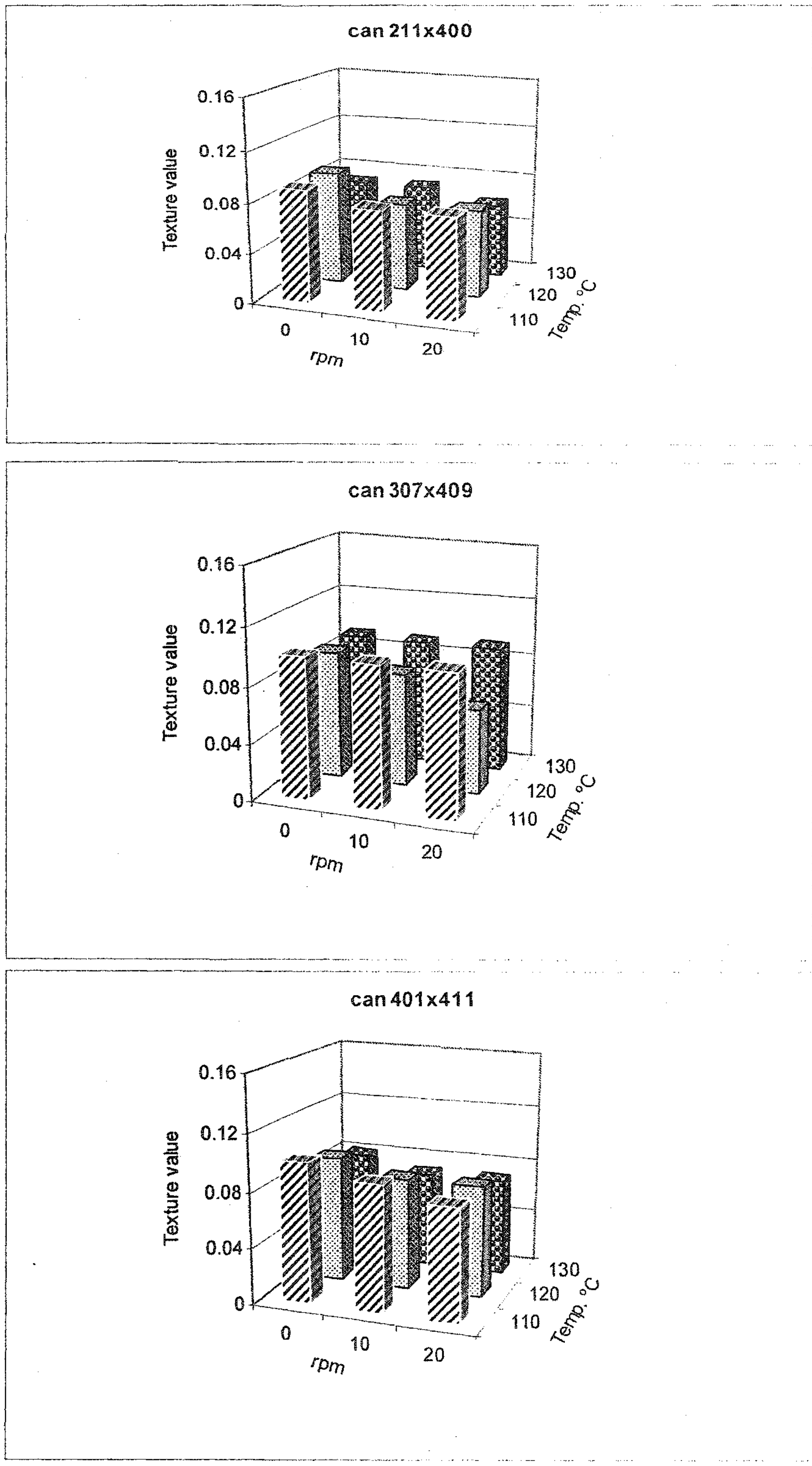


Figure 5.7: Effects of temperature and rotational speed on texture value of canned potatoes in water

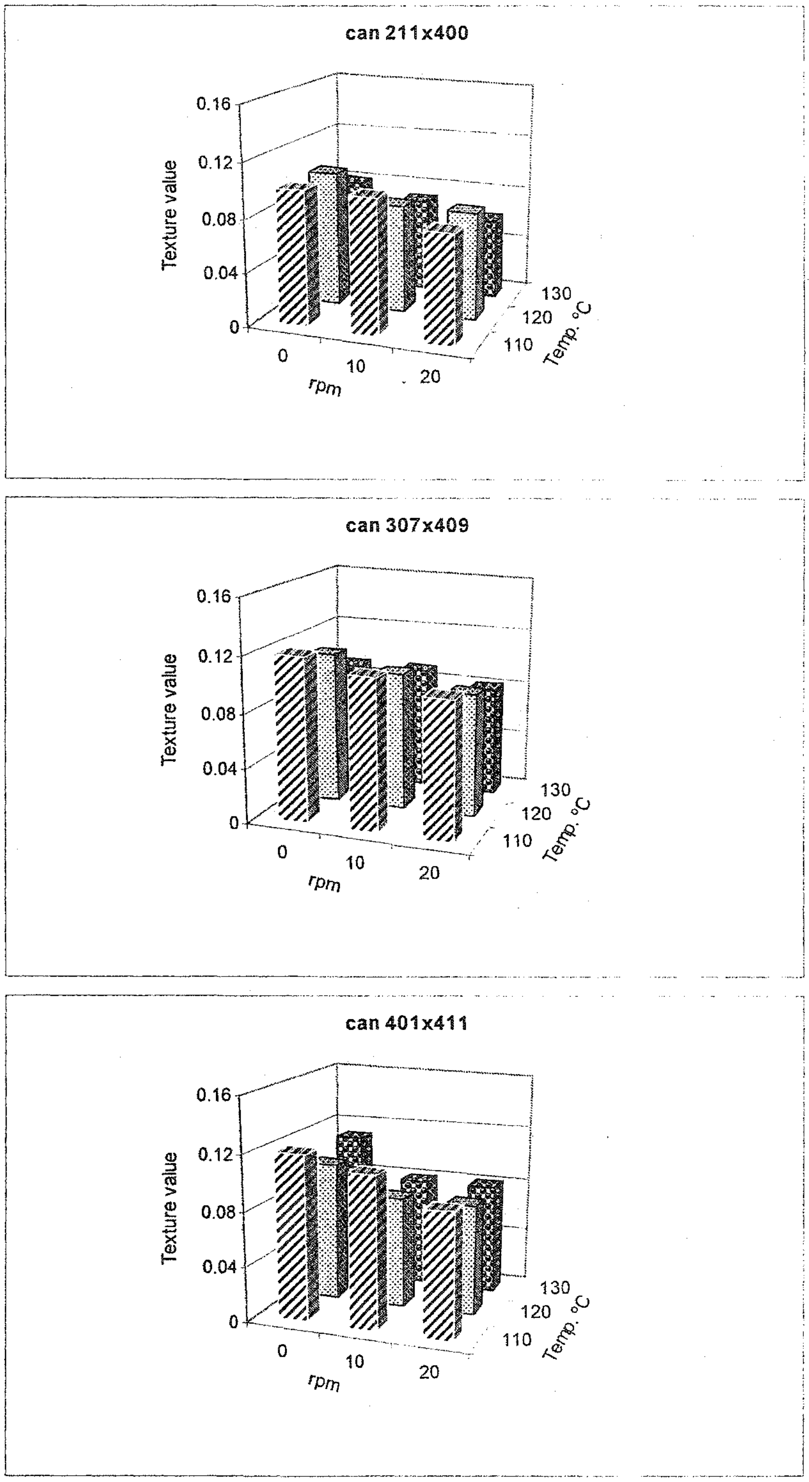


Figure 5. 8: Effects of temperature and rotational speed on texture value of canned potatoes in CMC

6. General Conclusions

Thermal processing is an important technique for extending storage life of foods and has been used extensively in industrial scale to produce safe foods. The technique is also associated with considerable degradation of taste, color, texture, flavor and nutritional quality of processed foods, and hence the process needs to be optimized in order to deliver the required lethality with minimum damage to desirable quality attributes is essential. Data on kinetics of changes in quality factors and their temperature dependence, as well as the heat penetration behavior of the food during processing are necessary to predict and optimize the extent of quality retention. The objectives of this study were: a) to evaluate the kinetics of thermal softening, color degradation and loss of ascorbic acid in potato (*Solanum tuberosum*) at selected temperatures (70-100°C) and to evaluate their temperature dependence; b) to evaluate the effect of process variables (temperature, rotational speed, can size and nature of the covering fluid) on heating behavior of canned potatoes and c) to determine the influence of the above process variables on process time and product quality.

Results of the study indicated that softening of potatoes followed pseudo-first order reaction kinetics, while the color change and ascorbic loss obeyed a simple first order. The temperature dependence of rate constants obeyed the Arrhenius relationship. The kinetic data gathered could be a useful tool to better understand the mechanism of quality changes that may occur during processing of foods.

Heat penetration tests were carried out employing end-over-end agitation processing in continuous and oscillatory fashion using a pilot-scale rotary, single cage full water immersion retort to determine the effect of can size (211x400, 307x409 and 401x411), temperature (110, 120 and130C), rotation speed (0, 10 and 20 rpm), covering medium (water or 1%CMC) on the heating rates of both liquid and particle in the can. Results indicated that, higher rotational speed gave considerably lower f_h and j_{ch} values, while increasing can size showed the opposite effect. The effect of temperature on f_h was not uniform throughout the experiment, however, there was an overall clear and significant decreasing trend in f_h values with increasing temperature. Higher rotational speed, smaller can size and higher temperature significantly ($p<0.05$) improve the thermal process parameters and that in general, all factors that enhance heat transfer were found to have increasing effect on the process lethality (F_o) and cook values (C_o) accompanied by a decrease in process time and Co/Fo ratio an indicator of conditions promoting better quality. Increasing the rotational speed resulted in considerable reduction in process time. The achieved reduction resulted better quality retention in texture and color indicator (L, a and b values).

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