Heat Treatment of Soybean in a Continuous Particulate Medium Processor

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Abstract

Full-fat soybeans require heat treatment to denature trypsin inhibitors which interfere with proper digestion of the soybean protein. This study examines the heat treatment of soybeans in a continuous particulate-medium conduction processor.

Whole soybeans at 13% and 23% moisture were roasted at salt temperatures of 225, 250 and 275°C for residence times of 15, 30 and 60 seconds. The soybeans reached temperatures ranging from 107°C to 134°C, after which they were maintained in an insulated container for 0, 5, 10 or 15 minutes. Salt temperature, residence time, and moisture content were found to significantly affect final temperature, temperature change, moisture loss and total heat transfer. Moisture losses in the processor were very high, indicating that combining the processes of heat treatment and drying may provide a high combined efficiency.

Analysis of trypsin inhibitor activity and soluble protein indicated that all three factors likely affect soybean quality, and the soybean quality achieved in these tests is likely to be sufficient for livestock feeding, although this remains to be confirmed through feeding trials.

Resumé

Les fèves de soya entière requièrent un traitement à haute température pour dénaturer les inhibiteurs de trypsine, afin de faciliter la digestion des protéines. Cette étude examine le traitement dans un appareil à conduction en procédé continu. Des fèves de soya entières, avec 13 et 23% d'humidité ont été rôties dans le sel chauffé à 225, 250 et 275°C pour des périodes de 15, 30 et 60 secondes. Les fèves attaignèrent des températures de 107°C à 134°C, après quoi elles ont été maintenues dans un contenant isolé pour 0, 5, 10 où 15 minutes. La température du sel, le temps du procédé et l'humidité influencent la température finale, le changement de température, la baisse d'humidité et le transfert de chaleur. La baisse d'humidité grâce à ce procédé s'est avérée très efficace et prometteuse pour un procédé combinant traitement à haute température et séchage.

Une analyse d'inhibiteur de trypsine et protéine soluble à indiqué que tous les trois facteurs ont probablement un effet sur la qualité des fèves de soya, et que la qualité des fèves de soya obtenue dans ces tests est probablement adéquate pour l'alimentation animale, néanmoins ceci devrais être confirmé par un test *in vivo*.

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List of Symbols

Symbol	Definition	Units
A	area	m^2
C	heat capacity	J/kg°C
d	diameter of particulate medium	m
D	diameter of suspended particle	m
Fo	Fourier number ($\alpha t/D$)	-
h	heat transfer coefficient	$W/m^2{}^\circ C$
Δh_v	heat of vaporization of water	J/kg
Δh_p	heat of combustion of propane	J/kg
H	height	m
k	thermal conductivity	W/m°C
l	film layer width	m
L	length (plate)	m
m	mass	kg
M	moisture content (wet basis)	%
Nu	Nusselt number (hd/k)	-
Pe	Peclet number (UL/α)	-
q	heat transfer rate	W/m^2
Q	total heat transfer per unit mass of grain	J/kg
r	radius	m
SGMR	salt to grain mass ratio	-
t	time	s
T	temperature	°C
U	average velocity	m/s
v	velocity	m/s
V	volume	m^3
α	thermal diffusivity	m^2/s
ε	porosity	%
ρ	density	kg/m^3
χ	effective film layer ratio (l/d)	-

Subscripts

b	stagnant bed
c	contact
e	effective
f	final
g	grain (soybean)
i	initial
m	medium (salt)
N	surface
O	outside
s	sliding layer

I. Introduction

1.1 Background

Soybean production in Canada and Quebec has been increasing considerably. In the 15 years from 1976 to 1991, Canadian land in soybean production increased almost four-fold from 154 000 ha to 598 000 ha, about 95% of that land being in the province of Ontario. In the province of Québec, land area in soybean production increased from 4 400 hectares to 25 300 ha in the period 1986-1991 (Canadian Census, 1991) and can be expected to continue to increase. The increasing importance of soybean is due to its high value as a source of edible oil for human consumption, as well as a major source of protein for livestock, and to a lesser extent, human diets.

The soy industry originally developed in North America with the edible oil as the main focus, and the high protein de-fatted meal left over was considered a low value by-product. However, this soybean meal has become very important in livestock diets, and it has become common for livestock to be fed whole soybean, with the soy oil replacing another energy source such as corn. In order to feed whole soybean to non-ruminant livestock, the soy must first be heat treated. This treatment, which occurs incidentally when fat is extracted from soy, de-natures proteins in the soy which are anti-nutritive. These proteins bind with the digestive enzyme trypsin in the stomach, rendering the enzyme ineffective and thus hampering digestion, and are referred to as trypsin inhibitors.

Several methods exist for effecting this heat treatment, each based on a different means of heat transfer. One method of heat transfer which is not currently used for soybean roasting is immersion in a particulate medium. This method has been studied for its potential in drying and other agricultural heat treatment applications. One study is known to have been done on soybean roasting in a particulate medium (Raghavan, 1974). This study showed promising results, and with the further development of the understanding of particulate medium heat transfer since that time, and the development of a prototype machine for particulate medium heat transfer (Raghavan and Pannu, 1986), it is appropriate to examine the potential of this machine to process soybean effectively and efficiently.

1.2 Objectives

The objective of this study is to examine the process of roasting soybean in a particulate medium using the prototype machine developed by Raghavan and Pannu (1986), both to develop a better understanding of the process, and to determine the potential usefulness of this particular machine design. The heat transfer within the machine is examined and compared to empirical results from previous studies. The nutritive quality of the soybean, treated at several levels, will be examined to determine the optimum level of treatment and to ensure that soybean treated in this manner is of sufficient quality for livestock feeding. The overall performance of the machine, including energy efficiency, is examined. Finally, the design of the prototype processor is examined from the experience of this study, and improvements in the design are proposed.

1.3 Scope

Due to the fact that the experimental machine being used in these experiments is a prototype for a practical machine, conditions cannot be controlled as well as would be the case in a machine developed for experimental investigation. As well, the machine is not designed for close observation of the roasting process, or for easy measurement of temperatures while processing. This study is therefore limited in terms of its ability to contribute to a detailed understanding of heat transfer in a particulate medium. The results from this study are nevertheless compared with the predictions from previous empirical studies, and thus provide an evaluation of the predictive ability of these studies. Examination of the precise biochemical processes which occur during soybean roasting is also outside the scope of this study.

II. Literature Review

2.1 Soybean Quality

Soybean meal contains several anti-nutritive components, the most important of which are the trypsin inhibitors. The two main groups of trypsin inhibitors are known as the Kunitz and Bowman-Birk trypsin inhibitors. These trypsin inhibitors bind with the digestive enzyme trypsin, and in the case of the Bowman-Birk inhibitor, the enzyme chymotrypsin as well. This then interferes with the proper digestion of foods, causing low weight gains in livestock. It has also been observed that the presence of trypsin inhibitors in feed causes hypertrophy of the pancreas, the gland which is responsible for producing trypsin.

It is, however, possible to denature the trypsin inhibitors in the whole soybean by heat treatment. However heat treatment may also destroy, or make unavailable, other proteins in the soybean. In particular, the amino acid lysine can be made unavailable due to cross-linking of peptide chains, and cystine can be destroyed through the loss of hydrogen sulfide (Snyder and Kwon, 1987). Heat treatment must therefore carefully balance the desired destruction of trypsin inhibitor with the undesirable destruction of amino acids. There has been considerable research into preferred methods and levels of treatment in order to produce heat treated whole soybean of limited antinutritive activity and maximum protein availability.

2.2 Soybean Heat-Treatment Methods

Several heat transfer methods, other than particulate medium heat transfer, have been used for soybean treatment. Air convection heating, flame heating, extrusion and infrared heating are currently used in commercial operations. Steam cooking, dry roasting, and dielectric heating have been used experimentally, but are not in commercial use. Of concern in examining these methods, aside from the effectiveness in trypsin destruction, is the speed and efficiency, both in terms of energy and economics, of a heat-treatment process.

2.2.1 Steam Cooking

The most common method of heat treatment used in experimental work is autoclaving, or pressurized steam cooking. This is because autoclaves are readily available for experimental work and permit very precise control of experimental conditions. Although autoclaves are not suitable for large-scale production of whole soybean, they are useful in indicating the level of heating necessary for the adequate denaturation of the trypsin inhibitors.

Renner and Hill (1960) performed experiments on autoclave heating of both soybean meal and whole soybean to determine the effects of the heat treatment on nutritive value for chicks. In this study it was found that the growth of the chicks was similar for both whole soybean and soybean meal diets. Treatments consisted of holding the soybean in an autoclave at 107°C for 10, 40 or 60 minutes. No significant differences were found in weight gain or feed conversion for these different heating times, indicating that 10 minutes at 107°C would likely be adequate heat treatment.

Further experiments with autoclaving of whole soybean were performed by Rogler and Carrick (1964). In this case feeding trials were performed on laying hens rather than chicks. Heat treatment was performed at only one level, that being 115°C for 45 minutes. Egg production was similar for whole soybean diets as compared to soybean meal diets, and feed conversion was better for the whole soybean diet.

White et. al. (1967) heat treated soybeans using autoclave, infrared and extrusion methods. The autoclaved soybean was treated at 110°C (6 pounds pressure) for 30 minutes. Thirty percent moisture was added prior to heat treatment, then removed afterwards through air drying. Neither weight gain of the chicks nor feed conversion differed significantly from those of the control group.

On the basis of these studies, it appears that autoclaving of whole soybean can produce a feed of comparable value to one consisting of soybean meal and an energy source such as corn.

In the studies mentioned above, there is no discussion of the exact heat transfer processes within the autoclave; it is not clear whether, or to what extent, forced convection is used as opposed to free convection. It also appears to be assumed that temperatures within the soybean reach the temperature of the autoclave environment almost instantaneously. This is likely to be a reasonable approximation if shallow trays of ground soybean are used, but if whole soybean is placed in the autoclave, heating of the interior of the bean will require a significant amount of time.

2.2.2 Dry Air Heating

Dry air heating of soybeans is a very attractive idea since the capital costs are low and the process is not complex. Any fuel could be used to heat air, and the air has simply to be blown over the beans in order to achieve good rates of heat transfer through forced convection, or left in still air, which results in lower rates of heat transfer through natural convection.

Fritz et. al. (1947) dry air heated soybeans in a still air drying oven for one hour at 125 and 150°C. The treated beans were compared to autoclaved beans (1 hr @ 121°C) in feeding trials to chicks. Growth rates of chicks fed the dry air heated beans were poor. Weight gains were 207 and 167 g at 4 weeks for the 125 and 150°C treatments respectively, compared to 346 g for autoclaved beans. Fritz et. al. then concluded that dry air heating was clearly much more destructive than moist heat to the protein value of the beans. However, the temperatures and residence times used in this study were quite high, and subsequent researchers have been more successful in dry air heating of soybean. The fact that similar residence times and temperatures in the dry oven and autoclave give very different results does, however, indicate that moisture is an important factor in the heat treatment of soybean.

Further research in dry air heating was performed by Arnold et. al. (1971). A series of experiments was performed at oven temperatures ranging from 149 to 246°C, residence times of 3, 5 and 10 minutes, and moisture contents of 10, 12.5, and 16% (wet basis). Each moisture level was used in a different experiment; it is therefore not possible to directly compare the effect of moisture content on the feed conversion of the chicks used in the feeding trial. Each trial compared feed conversion to a control diet of soybean meal, however, and the percent difference in feed conversion between the control and the oven-heated beans can be used as an indicator. The highest feed conversion at 10% moisture was 9.6% above the control, and was achieved with a 5 minute treatment at 182°C. For 12.5% moisture, the best feed conversion was 12.3% above the control with 5 minute treatment at 171°C. For 16% moisture, the best level was 16.6% above control at 246°C for 3 minutes. This experiment clearly indicated that higher weight gains and feed conversions could be achieved with oven-heated whole soybeans than with soybean meal, in opposition to the results of Fritz et. al. (1947) discussed above. It also appears that higher moisture in the bean can lead to a better quality processed product. With increasing moisture, the temperatures and residence times for optimal results increased and decreased respectively. It is therefore advantageous to use high moisture contents with high oven temperatures and low residence times in order to achieve the best results. It should be noted that the temperatures given in this study are oven temperatures rather than temperatures of the soybean itself, which would be lower than the oven temperature, but unfortunately were not reported.

A commercial dry air roaster has been developed and is in commercial use. The Jet-Sploder is a dry air roaster which derives its name from the fact that the soybeans, after being roasted, are passed through rollers while still hot. The vapour pressure built up inside the bean during roasting then assists in the mechanical breakdown of the bean cell structure. The roasting itself uses air at 315°C which is forced through the beans passing through the roaster. Total exposure of the beans in the roaster is for slightly more than one minute, during which the beans reach a temperature of 150-160°C. The air exiting the roaster is at 120-200°C. This air is then passed through a cyclone to remove dust and fines, after which it is recycled back through the furnace and continuously used for the roast.

2.2.3 Flame Roasting

Perhaps even more straightforward than dry air heating is flame roasting. In this method, the soybean is contained in the same space as the flame, and may pass directly through the flame, depending on the design of the particular machine. Heat transfer is by convective and radiative transfer from both the flame directly, and by convection of the air in the roaster. One of the disadvantages of this process is the lack of uniformity in the level of treatment of the individual soybeans. The cascading effect will cause some of the beans to pass through the flame, while others do not, and some of the beans will therefore be under-processed while others are over-processed.

A commercially available flame roasting machine is described by McKenzie and Gottbrath (1971). This is the Roast-a-Tron, which has become quite popular. This machine moves soybeans through a flighted drum in which the flame is located. The soybeans cascade, passing through the hot air in the roaster, as well as through the flame itself. This machine is capable of processing 340 kg/hr, and consumes liquified petroleum gas with an energy content to provide 265 MJ/hr of energy.

The effectiveness of this machine in producing a product of high nutritional value has been examined by several researchers. Soybean roasted in a Roast-a-Tron were fed to broiler chicks in rations containing from 5 to 40% (in 5% increments) of the roasted soybean in a study by Waldroup and Cotton (1974). Weight gains were not significantly different from the soybean meal control, provided the roasted soybean content in the ration remained at or below 25%. Above these levels, weight gains decreased significantly, and thus the authors recommend limiting whole soybean rations to 25%.

Mitchell et. al. (1972) used a Roast-a-Tron in their examination of the effects of particle size of feed on the utilization of the soybeans by broilers. In this study weight gains were achieved with roasted beans that were higher than weight gains from soybean meal, though the difference was not significant. The main focus of the research was to determine if pelleting or mashing was important for proper utilization of the roasted soybean by the broilers. The high weight gains from whole soybean were from pelleted soybean; in experiments where the ration was mashed, weight gains from whole soybean were significantly lower than the soybean meal control. The highest weight gain was achieved with meal pelleted top the smallest particle size used in the experiment, that being 20 mm mesh. This indicates that mechanical treatments which follow heat treatment are also very important in determining the quality of the soybean.

2.2.4 Dry Roast

Badenhop and Hackler (1971) report that dry roasting of soybeans for human consumption has been a common process in Japan for centuries. Dry roasting uses primarily conduction to transfer heat from a hot metal surface to the soybean. Additional convective heat transfer will occur through the air in the roaster.

Badenhop and Hackler also studied the effect of dry roasting on protein efficiency ratios of soybean. These studies were oriented to the use of the soybean for human rather than livestock consumption, and the experimental subjects were rats. Soybeans were soaked in water prior to roasting, to bring the moisture content up to 43, 48, 53 or 59% (wet basis). They were then placed in a small tumbling roaster designed for coffee beans. The initial temperature of the roaster was 400°C, and roasting time was an average of 32 minutes. The mass of soybean placed in the roaster was adjusted to give three different final bean temperatures of 170, 180, or 185°C. The feeding trials did not compare the whole soybean to soybean meal, but simply compared different levels of heat treatment. The best weight gains were achieved with the highest moisture content and the lowest final temperature, indicating both that high moisture during roasting does improve nutritional value, and that the temperatures used were sufficiently high to be significantly reducing the protein availability of the soybean.

Leeson et. al. (1987) studied the nutritional quality of soybeans dry roasted at a core temperature of 118°C for 8.5 minutes. These beans were then included in broiler diets at levels of 0, 10, 20, or 30% of the diet. Weight gains and feed conversion significantly declined in the first 3 weeks of growth with increasing inclusion of the dry roasted beans in the diet. However, from 3-6 weeks growth and feed conversion were not significantly affected, indicating that whole soybean pose more of a problem in the earlier stages of growth.

2.2.5 Infra-Red

Infra-red radiative heating provides a very direct means of heat transfer from the heat source to the soybean.

A study by Featherston and Rogler (1966) tested the effects of different heat treatment levels on the nutritive value of infra-red heated whole soybean for chicks. The infra red roaster used in this case used a nichrome wire mesh heated by a liquified petroleum (LP) gas flame as the infra-red source. The soybeans cascaded through two successive rotating perforated cylinders parallel to which were located the infra-red sources. They were then recirculated through the system by augers until the specified end temperature was reached. In this case it was found that weight gain for chicks fed the whole soybean diets was less than that for chicks fed soybean meal. The feed conversion was, however, comparable to that of soybean meal. Heat treatments were at different temperatures (107, 113, and 118°C) and with either no moisture added, or 10% moisture added. However, there was no statistically significant difference in the effects of these different heat treatments, possibly because the temperature differences were so small.

In the study of White et. al. (1967) mentioned above in the discussion on autoclaving, infra-red treated beans were also considered. In this case the infra-red source was the burning of LP gas on the surface of an inconel metal screen. The soybeans were passed through a flighted perforated cylinder which cascaded the beans, intermittently exposing them to the infra-red radiation. The infra-red generator maintained a temperature of 800 - 1000°C, and the soybean residence time was 4-6 minutes, during which the bean temperature was raised to 113°C. Feeding trials to chicks resulted in weight gains lower than those obtained with the soybean meal control diet, but not significantly lower than those obtained with extruded or autoclaved whole soybean.

Lawrence (1978) evaluated the value of micronized soybean for growing pigs and concluded that it was quite suitable for their diets as they resulted in growth not significantly different than that resulting from soybean meal diets. The term micronization is used to refer to a process of infra-red heat treatment of soybeans. The micronizing machine contains heated ceramics which emit infra-red radiation. Soybean is passed under the heated ceramics for 90 s during which the soybean reaches a temperature of 195°C. As with the previous two studies, it is not specified whether the beans are then promptly cooled or allowed to remain at that temperature for some time. This could be important, as the experiments with autoclaving have shown that time is as important a factor as temperature in soybean heat treating.

2.2.6 Dielectric Heating

Electromagnetic radiation of higher frequencies above the infra-red range can be used in heating as is the familiar case with microwave ovens. Microwaves are electromagnetic radiation in the range $5(10^8)$ to $5(10^{11})$ Hz, while RF, or radio frequency radiation is in the range $5(10^6)$ to $5(10^8)$. In these ranges, only certain frequencies have been allocated by regulating bodies for industrial use. These are 0.915, 2.45, 5.8, and 22.125 GHz for microwaves, and 13.58, 27.12 and 40.68 MHz for radio frequency radiation. Microwaves transmit energy to a material through ionic conduction and dipolar rotation. When an electric field is produced in the material by the microwaves, ions in the material will move in the direction of the electric field. These moving ions then collide with other molecules, generally increasing the movement of the molecules, which results in a temperature rise The water molecules in the material will also be affected by the electric field. Because water molecules have a small polarity, they tend to align with the electric field. The electric field is constantly changing, however, and the water molecules are constantly agitated. This motion is then converted to heat as the agitated molecules interact with surrounding molecules. Other polar molecules are also agitated in this way. All molecules have a characteristic relaxation frequency, however, which is similar to a natural frequency. This relaxation frequency is affected by the nature of the material, its temperature, the viscosity of the material around the molecule, and the nature of its bonds with surrounding molecules. If the microwave frequency is close to the relaxation frequency, faster heating will result.

Wing and Alexander (1975) examined the conditions necessary to achieve proper heat treatment of soybean through microwave heating. Beans were first soaked in water for 125 minutes, which raised their moisture content to 48%. They were then exposed to microwave radiation at 2.45 GHz for 1 to 6 minutes. The oven used had a power rating of 1250 watts, and the size of the samples treated was 150 g. The level of heat treatment achieved was then evaluated using a cresol red absorption rate assay, which is a protein assay. Samples heated for 2 min and 3 min were found to be properly treated, as they gave similar absorption rates as that of a sample autoclaved at 120°C for 40 min, conditions considered by the authors as appropriate for proper treatment of whole soybeans. The time difference between the microwave and autoclave treatments is quite clear; microwave treatment can process beans at 20 times the rate of autoclave or steam treatment. In feeding trials to rats, the microwaved whole soybean resulted in greater feed intake, greater weight gain, and better feed conversion than the autoclaved samples. The work of Gustafson et. al. (1971) is also mentioned. In this work, chicks fed microwave processed soybean had similar feed conversion but much poorer weight gains than chicks fed commercial soybean meal. Wing and Alexander attribute this difference in results to the high moisture contents used in their study, while Gustafson et. al. used moisture contents of 15%. The significance of moisture content in the effectiveness of heat treatment is not clear; this will be discussed below.

Dielectric heating using RF frequencies was examined by Borchers and Manage (1972). In this study the frequency used was 43 MHz. Soybeans were placed in petri dishes 15 cm in diameter and 2 cm in depth. The electrodes were placed below the dish and 1.4 cm above, for a total separation between the electrodes of 3.4 cm. The average intensity of the electric field induced was calculated to be 0.65 kV/cm. The soybean was treated at this level for 0.83, 1.00, 1.67, or 2.00 minutes. In these time periods, temperatures achieved by the beans were 127,132, 146 and 168°C respectively. Similar to the study of Wing and Alexander discussed above, the resulting processed beans were compared to soybeans treated by autoclaving for 30 minutes at 120°C. It was found in feeding trials to rats that the highest growth rate was achieved with treatment for 1.67 min, although this was significantly different than results from the shorter treatments or the autoclaved beans. The trypsin levels in the soybean treated for 1.67 min was 61 units/g, compared to 193 units/g for untreated beans and 0 units/g for the autoclaved beans. This may indicate that complete trypsin destruction may not be necessary, and that the cost of overheating in terms of reducing the availability of amino acids in the soybean may be too high. It is also worth noting that higher temperatures are achieved in the RF treatment than in the autoclaving; for the sample treated for 2 min, trypsin levels were 54 units/g, but rat growth was much lower than for the sample treated for 1.67 min. The reduction in growth is more likely to be due to the higher temperature reached (168°C vs. 146°C) than to the longer time period of the treatment.

2.2.7 Extrusion

Extrusion is a common process in the food processing industry. It essentially involves using mechanical work to compress a material and force it through a die. This mechanical work heats the material, and the material may also be heated prior to extrusion, or the extruder itself may have a heating jacket to transfer heat to the material being worked.

Mustakis and Griffin (1964) describe an extruder which has been developed for use in developing countries. This extruder has an advantage over more common large scale extruders in that it is relatively small and easy to construct and operate. Their study focuses on the potential use of this extruder for producing full fat soy flour for human consumption, although the extruder was originally designed for production of animal feeds from whole soybean. The preconditioned feed, which has been steam heated and may have been moistened depending on the exact process, is fed into the extruder. The screws force the soybean through each stage of the extruder and through the die at the end of each stage. The die at the end of each of the first sections serves as an airlock to allow high pressure to build up in the last section without blowback to the earlier sections which are at lower pressures. These first two sections also have steam jackets which heat the soybean. The temperature in the final section of the extruder is considerably above the atmospheric boiling temperature; therefore, when the soybean passes through the final die to be released at atmospheric pressure, it expands. This expansion, which has led to this process also being referred to as expansion rather than extrusion, results in rupturing of the cell walls, which allows for easier digestion of the soybean. As well, in the high pressure section of the extruder, the oil in the soybean is expelled from the cell structure, but it is immediately reabsorbed by the hot meal once it has expanded after passing through the final die. This releasing of the oil can increase its digestibility.

In the experiments performed by Mustakis and Griffin, soybean was fed into the extruder at moisture contents of 15 - 22 % (wet basis) and temperatures close to 100°C. This was after preconditioning in steam for 2 ¾ min. Temperatures in the extruder reached 240 - 290°C, and residence time in the extruder was ¾ - 1 ½ minutes. Trypsin inhibitor destruction was in the range of 95%, and available lysine was in the range 5-6% of total protein. This process therefore achieved very good trypsin inhibitor destruction while retaining good availability of the important limiting amino acid lysine.

White et. al. (1967) used soybean extruded in a process similar to that described above. This soybean was then compared in chick feeding trials to autoclaved and infra-red cooked whole soybeans, as well as soybean meal, as mentioned earlier. In this case, the beans were again preconditioned to 212°C, then extruded for 60-90s to a final temperature of 115-143°C. The process of release and reabsorption of oil noted by Mustakis and Griffin was also observed in this study. The soybean produced in this manner did not result in significantly different growth or feed conversion than soybean meal.

Moran et. al. (1973) note that the sensitivity of young birds to improperly processed full-fat soybean may make it necessary to avoid the use of full fat soybean in starter diets, particularly since the total amount of feed consumed during the starter period is quite small compared to the total consumption during the lifetime of the bird. Their study focused therefore on growing and finishing large white turkeys, from 8 to 23 weeks of age, on extrusion processed full-fat soybeans, as compared to soybean meal with added oil. Weight gain was in general similar for the two diets, while feed conversion showed an interesting trend. From 8 to 12 weeks, feed conversion was better with the whole soybeans, while from 12 to 20 weeks feed conversion was better for the soybean meal. The reason for this is not clear, but does demonstrate that the discrepancy of results between researchers comparing whole soybean diets to soybean meal diets discussed in this paper so far also extends to a discrepancy within a single study. This demonstrates the fact that it is not possible to conclusively consider whole soybean either preferable or less preferable than soybean meal. Rather, results will depend on the animal being considered, other elements of the diet and the animal environment, and the age of the animal.

2.2.8 Sodium Metabisulfite

One method of enhancing the effectiveness of heat treatment of soybean may be the use of sodium metabisulfite during processing. This is because of the chemistry of the trypsin inhibitor. The two major trypsin inhibitors in soybean, the Kunitz and Bowman-Birk inhibitors, contain disulfide bonds. The inhibitors are inactivated in heat treatment through the cleaving of these bonds, but this effect could also be achieved or enhanced by chemical means. The sulfite ion in sodium metabisulfite will cleave these bonds, but this does require some heat. Herkelman et. al. (1991) examined the effect of sodium metabisulfite on the autoclave processing of whole soybeans.

Sodium metabisulfite was mixed with ground soybean at levels of 0, 1, or 2%, and the soybean was then processed in the autoclave at 121°C for 0, 10, 20 or 40 minutes. The processed soybean was then used in a feeding trial to chicks, as well as being analyzed for trypsin inhibitor activity, urease activity, and protein solubility. Of greatest significance in the results was the accelerated deactivation of trypsin inhibitor due to the sodium metabisulfite (SMBS). Trypsin levels in the soybean processed for 10 and 20 minutes with SMBS were less than half the levels of trypsin inhibitors in soybean processed without SMBS. However, this effect disappeared for the processing time of 40 minutes, and the effect was not very different between the 1 and 2% levels of inclusion of SMBS. This does present the possibility that trypsin inhibitors in soybean can be destroyed without the usual trade-off made in soybean processing between desirable trypsin inhibitor destruction and undesirable protein destruction, or at least not to the same extent. In the feeding trials of this experiment, soybean treated with SMBS increased the weight gain of birds over weight gain from soybean treated for the same time without SMBS, as could be expected from the trypsin inhibitor levels. The authors do not discuss the potential health effects of including SMBS in the diets of chicks. This author is aware of the use of SMBS as a sterilizer and de-oxidizer for food processing equipment and food products; the fact that it is used for food processing equipment may indicate that it is not seriously dangerous, but at the concentrations used in this experiment it may be a concern. The chicks in the feeding trial did not appear to suffer grave consequences however, and thus it is likely not to be a concern.

As well, the cost of SMBS in concentrations as high as 1-2% has not been stated, and is likely to be significant. The use of SMBS in conjunction with heat treatment, if it becomes common, will have considerable impact on the potential design and usefulness of certain types of heat treatment machines. If it is required that the soybean be ground and mixed with SMBS prior to roasting, the heat treatment machines must be able to process the ground soybean. Several of the existing machines, such as the Roast-a-Tron and the Jet-Sploder, as well as the processor used in this study, are designed for use with unground soybean and may not easily be adaptable to ground soybean.

2.3 Particulate Medium Heat Transfer

The use of a particulate medium for heat transfer is often seen as an extension of the use of conduction heat transfer. Conduction heat transfer is of the type discussed previously in the discussion of dry roasting of soybean, where heat transfer is from a flat heated plate to the grain. The reason for using this method is that heat transfer rates in conduction can be much higher than is possible by convection of hot gases. However, because the flat plate can only be in contact with a small portion of the grain bed, the area over which the heat transfer occurs is quite small compared to the case of convective heating. By using a particulate solid medium, the grain to be heated can be surrounded by a heated solid, and thus heat transfer can be very rapid.

The situation of practical interest in the current study is that where a grain is surrounded by smaller particles of the heat transfer medium. Heat transfer from a particulate medium to a grain can occur with or without a flow of the medium relative to the grain. Typically, prototype driers have been developed which involve relative motion between the grain and the particulate medium for some part of the drying process, and no relative motion for another period. An example of this is the rotating drum. In this case the medium in the drum rotates with the drum, and is carried by the drum through a part of its rotation. During this time there is no relative velocity between the grain and the particulate medium. After the medium has been raised some height by the drum, it will begin to tumble down over the stagnant portion of the bed. During the tumbling, some relative motion may occur, though Sibley and Raghavan (1985) have observed this process and indicate that it is minimal. Experiments have also been performed with agitators in beds of granular material, in which the material remains stationary for part of the time, but is regularly agitated and therefore mixed. It is therefore necessary to examine heat transfer from granular material for both stagnant and moving beds of granular materials.

In most cases, research in particulate medium heat transfer has focused on heat transfer from a wall to a granular bed. The results of this research should, however be applicable to the situation of grain immersed in a granular material, since the grain will behave as a wall if the particle size of the granular medium is much smaller than the size of the grain.

2.3.1 Stagnant Beds

A stagnant bed of particulate material can be modelled by assuming that the bed acts as a continuum. For any particular material, the effective thermal properties of the bed, which include the effects of conduction between contacting particles, and heat transferred through the interstitial gas, can be determined readily through experiments. Wunschmann and Schlünder (1974), presuming the bed to act as a continuum, used the following equations to describe the heat transfer from a wall to a stagnant bed. These equations are simply the equations for heat flow to a solid.

$$h = \frac{2}{\sqrt{\pi}} \frac{\sqrt{k_e \rho C}}{\sqrt{t_c}} \quad \text{(1)}$$

for short contact times, and

$$h = \frac{3k_e}{H} \quad \text{(2)}$$

for longer contact times, where;

h = heat transfer coefficient (W/m^2°C)

k_e= effective thermal conductivity of the bed (W/m°C)

ρ = density of the bed (kg/m^3)

C = heat capacity of the bed (J/kg°C)

t_c= contact time (s)

H = bed height (m)

The first equation describes the situation where the temperature field extends only a short distance from the wall, since there has not been sufficient time for the bed to experience temperature changes throughout. The second equation is the case when the temperature field has extended through the bed; the temperature distribution is then linear from the wall to the surface. These are essentially analogous to transient and steady-state solutions to the problem. For very short contact times, the assumption that the bed is a continuum no longer holds. This is because the temperature field will span only one particle layer or less, and at this level the discrete effects of the particles and the interstitial gas become important. By analyzing the heat transfer through the interstitial gas, the following relationship was derived;

$$h=\frac{2k_g}{r}\left\{ \left(\frac{\sigma}{r}+1\right)\ln\left(\frac{r}{\sigma}+1\right)-1 \right\} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (3)$$

where;

$\sigma = 2\sigma_0 \frac{2-\gamma}{\gamma}$, σ_0 = mean free path of gas molecules (m)

k_g= thermal conductivity of the interstitial gas (W/m°C)

r = particle radius (m)

γ = accommodation coefficient

An additional term was included to account for radiation heat transfer, but it is not significant at atmospheric pressure and temperature, which are the conditions of most practical applications. This analysis was also based on an assumption of spherical shape for the particles, while most particulate media which would be used in actual processes are not spherical.

Rao and Toor (1984) have examined the heat transfer from a particle imbedded in a particulate medium. Again, it was assumed that the particulate medium acts as a homogeneous medium. In this case, the heat transfer is assumed to act as a solid with an effective thermal conductivity, k_e. The heat transfer equation is therefore simply the solution of the Fourier equation for heat transfer;

$$\frac{\partial T}{\partial t} = \nabla \frac{k_e}{\rho C} \nabla T \quad \text{(4)}$$

The solution of which, for the case of radial heat transfer in a sphere, is:

$$q = \frac{4\pi k_e (T_N - T_0)}{1/r_N - 1/r_0} \quad \text{(5)}$$

where:

T = temperature (°C)

t = time (s)

k_e = effective thermal conductivity of particle bed (W/m°C)

ρ = density of particle bed (kg/m^3)

C = heat capacity (J/kg°C)

q = heat transfer rate (W/m^2)

and the subscripts $_N$ and $_O$ refer to the surface of the heated particle and the outside of the bed, respectively.

Tests were done in which a spherical particle was placed in a spherical bed of granular material, with the outside wall of the bed maintained at constant temperature. The test particle was heated by an electric resistor, so that tests could be performed at steady state. It was found that for beds of powdered materials, that is, where the diameter of the bed particles is very small relative to the test particle, this model was very accurate. For beds with larger particles, however, for example where the test particle and bed particles have the same diameter, the experimental results were found to deviate quite considerably from the model. Another model was then proposed for this case, in which it would no longer be assumed that the bed acts as a solid homogeneous continuum. Since the solid particles in the bed have a much higher thermal conductivity than the interstitial air, the heat transfer is limited by the conduction through the air gaps. An equation for the heat transfer was then derived, but is of little practical use since it assumes spherical particles and requires an evaluation of the particle to particle contacts, which would not be easy to obtain for non-spherical particles. For practical heat transfer problems, it is necessary to obtain relationships for the heat transfer based on easily obtainable properties of the material.

2.3.2 Moving Beds

Harakas and Beatty (1963) experimented with beds of particulate media flowing past a flat plate. It was assumed that the bed acts as a homogeneous material, and again, effective thermal properties were used. This assumption leads to the following equation for the heat transfer coefficient;

$$h = \frac{2}{\sqrt{\pi}} \left(\frac{k_e \rho C U}{L} \right)^{1/2} \quad \ldots\ldots (6)$$

where;

U = flow velocity (m/s)

L = length of heated plate (m)

It was found that the heat transfer to the bed could not be properly described by this model. For beds with smaller particle size and lower bed conductivities, however, the deviation from this model was less. This result for the importance of particle size is in agreement with that observed by Rao and Toor.

Raghavan et al (1974) investigated the heat transfer from a heated sphere to granular material flowing past it. A model was developed which assumed that heat transfer to the sphere was a function of the number of impacts of individual particles against the sphere. It was further assumed that the number of impacts was equal to the number of particles flowing through an area equal to the cross-sectional area of the sphere. Experimental results showed that the heat transfer per impact was related to the inverse of velocity. This can be expected since heat transfer per impact will depend on the time of contact, which depends on the inverse of velocity. It is likely, however, that heat transfer would in fact not depend directly on the inverse of velocity, since for longer contact times the temperature of the particle will increase, leading to a gradually decreasing rate of heat transfer as the contact time increases. Further problems exist with this model, primarily in the assumption that the number of impacts is a function of the cross-sectional area of the sphere. Since the flow of granular materials is not well understood, it is difficult to predict the precise motion of the particles around the sphere, but it is likely that the flow would separate at the top of the sphere, and the particles in contact with the sphere would be limited to those on the circumference of the sphere. This would lead to an assumption that the number of particles which contact the sphere is $\pi D/d$, where D is the sphere diameter and d is the average particle diameter. One could then also consider contact time between the sphere and the particles, which would be a function of flow velocity. As well, since the circumference of the sphere varies as one moves along its length, contact times for some particles would be smaller as they would only contact the sphere near its centre. A model of this type also does not consider the heat transfer from the impacting particles to other particles in the bed further from the sphere, although this may be appropriate if the contact time is sufficiently short that there is not significant temperature changes further than one particle diameter from the heated sphere.

Sullivan and Sabersky (1975) did further work on the heat transfer between a flat plate and a flowing granular material. Three models were developed; one considering the discrete nature of the material, another assuming the material to act as a continuum, and a final model which assumes a contact resistance between the homogeneous particulate material and the wall. This contact resistance may be due to a gas film close to the wall, or due to a change in the bulk properties of the medium close to the wall, as the void ratio of the particulate material effectively increases very close to the wall, within a distance of one particle radius from the wall. The material flowing past the heated plate was assumed to act as a solid material, with plug flow. This assumption is not justified in the paper, and it would seem likely that a small boundary layer similar to that encountered in fluid flow would develop. This boundary layer would be dependent on both the internal friction of the particulate material and the friction of the particles against the wall. The boundary layer would be expected to increase in size with increasing wall friction and decrease in size with increasing internal friction. In the particular experimental set-up used by Sullivan and Sabersky, the friction between the wall and the material is likely to be very small, since the wall is vertical. For flow on plates which are not vertical, however, this would not be the case. The investigations of Sullivan and Sabersky are therefore limited in their applicability to more general situations.

The flow characteristics of the granular material, and the effect of this on heat transfer, have been considered by Patton et. al. (1986). In their study, the heat transfer to rapidly flowing granular materials was examined. The wall in this case was inclined rather than vertical. Although the flow patterns of the material were not considered in great detail, it was assumed that the material did not move with plug flow. A linear velocity distribution was assumed from the wall to the top of the flowing bed, with the velocity of the material at the wall being greater than zero. This differs substantially from the flow pattern for fluids, and indicates the need for greater study of this phenomenon. It can be expected that granular materials flowing at lower velocities would show similar, though less pronounced, behaviour.

In an earlier analysis of heat transfer to a granular material flowing in a vertical pipe (Brinn et al, 1948), the characteristics of granular flow in a vertical pipe were considered. A small amount of coloured granular material was introduced into the flow at the top of the vertical pipe, and the flow pattern was observed after allowing the medium to flow part of the length of the pipe. It was observed that velocity was nearly constant throughout, with the exception that the material velocity near the wall was approximately 15-20% less than the average velocity. This boundary layer was very small, and Brinn et al did not consider its effects in their analysis of the heat transfer. This is also not in agreement with the assumptions of Patton et al, where a velocity gradient was assumed to exist in the entire bed, and the existence of a boundary layer was not considered.

In the study of Sullivan and Sabersky, a distinction is made between the critical (or flowing) state and dense (or stagnant) state of granular materials. Thermal properties are stated for both cases, although it is not clear how these properties were obtained for the critical state. According to the data given by Sullivan and Sabersky, void ratio is higher in the critical state, and bulk density, thermal diffusivity and thermal conductivity are lower for the critical state. This would seem to be in contradiction to the assumption of plug flow used by Sullivan and Sabersky, since void ratio would only increase in a flowing material if there is relative motion between the particles in the material.

For the discrete model, Sullivan and Sabersky (1975) derive the following relation;

$$Nu_L = \frac{K}{d^2 k}\frac{L}{L^*}F(L^*) \quad \text{(7)}$$

where;

$$F(L^*) = \int_0^{L^*} \theta_1(x)dx, \qquad \theta_1(x) = e^{-2x}[I_0(2x) + I_1(2x)]$$

I_n are the modified Bessel functions of the first kind
K = particle to particle conductance (W/°C)
d = particle diameter (m)
L^*, x^* = dimensionless lengths ($L^* = LK/MCU$)
M = mass of a typical particle (kg)

This relation is not compared to the experimental results, however, and instead a continuum model is developed. For any homogeneous solid material, the average Nusselt number for flow past a plate of constant temperature is;

$$\overline{Nu}_L = \frac{2}{\sqrt{\pi}}\sqrt{Pe_L} \quad \text{(8)}$$

where;

Pe_L = Peclet number based on L ($Pe_L = UL/\alpha$)

It should be noted that this equation is identical to those of Wunshmann and Schlünder, and Harakas and Beatty, mentioned earlier, and can be derived from the solution for transient heat flow in a semi-infinite solid, as given by Holman (1991). This is then further expanded by considering the contact resistance at the wall as discussed above. The Nusselt number is then:

$$\overline{Nu}_L = \frac{1}{\frac{d}{L} + \frac{\sqrt{\pi}}{2}\frac{1}{\sqrt{Pe_L}}} \qquad (9)$$

For large L relative to d, that is, where the particle diameter is very small relative to the length of the plate, Nu_L will reduce to the value obtained for the simple continuum model. This trend agrees with that found by Rao and Toor for heat transfer in stagnant beds, where contact resistance was found to be less significant where particle diameter was very small relative to the characteristic dimension of the heat source, that being the diameter of the heated ball for their experiments.

Experimental evaluation of this model demonstrated that the variation of Nusselt number with Peclet number was of the shape indicated by the model. The exact values were not as indicated, and the model was therefore adjusted to reflect the experimental results more closely. The new model is given by;

$$\overline{Nu_d}^* = \frac{1}{\chi + \frac{\sqrt{\pi}}{2}\sqrt{Pe_L^*}} \qquad (10)$$

where;

Pe_L^* = *Modified Peclet Number* $\left(Pe_L^* = \left(\frac{k_e^2}{k_g}\right)\left(\frac{d^2}{L}\right) Pe_L\right)$

k_e = effective thermal conductivity of particulate bed (W/m°C)

k_g = thermal conductivity of interstitial gas (W/m°C)

d = particle diameter (m)

L = plate length (m)

Note that the Nusselt number is now based on particle diameter d rather than plate length L. Thus the main term in the Nusselt number remains the solution for heat flow in a solid, but is expressed in a manner convenient for this analysis. As mentioned above, this situation of plug flow past a heated plate is identical to the problem of transient heat flow in a solid at which the surface temperature is suddenly raised, which is described in Holman (1991). By substituting contact time, t_c for length divided by velocity, L/U, and expressing it as an average heat transfer coefficient rather than a Nusselt number, this formula can be expressed, as is done by Tessier and Raghavan (1984), by;

$$\bar{h} = \left[\frac{\chi d}{k_g} + \frac{\pi t_c}{2\sqrt{k_e \rho C}} \right]^{-1} \qquad (11)$$

where;

t_c = contact time (s)

The value of χ, which is in effect the contact resistance factor, was found by Sullivan and Sabersky to be 0.085, based on the experimental results. Since the contact resistance is likely to be determined by the particular geometry at the wall as well as the ratio of gas to bulk conductivities, χ can be expected to be a function of these factors. The value of 0.085 found by Sullivan and Sabersky was for spherical particles of glass and mustard seeds. Experiments were also done with fine grained sand, and it was found that the given value of χ did not properly describe the heat transfer for the sand. Since differences in the ratio of gas to bulk thermal conductivities for glass and mustard seed did not lead to differences in the contact resistance factor, geometry is likely to be the main factor in determining χ.

In order to find a useful relationship to determine χ, and thus generalize the model of Sullivan and Sabersky, Richard and Raghavan (1980) examined the experimental results of several previous researchers. It was found that χ was small for beds of spherical particles, and increased for more angular particles, becoming very large for flaky particles. An attempt was therefore made to relate χ to the porosity of the material, since porosity is related to the angularity and spacing of particles. The value of χ which was determined using statistical techniques was;

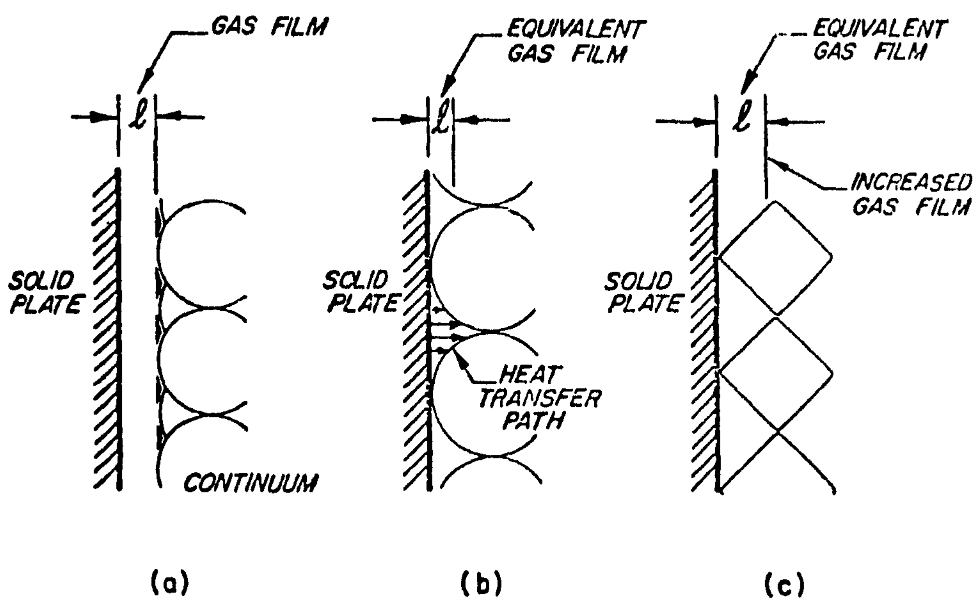
$$\chi = 5.16\, \varepsilon^{5.06} \qquad (12)$$

This model has not been as successful as desired, as Tessier and Raghavan (1984), for example, found that, for the experimental apparatus and particular materials used in their analysis of heat transfer in corn drying, χ could be described by;

$$\chi = 6.93 \cdot 10^{24} \cdot D^{-0.78} \cdot \varepsilon^{-7.58} \cdot \rho^{-9.76} \qquad (13)$$

In this case, however, the experiments were done in a rotating drum rather than with a controlled flow. It is interesting to note, however, that these results show χ decreasing with increased ε while the model of Richard and Raghavan gives χ increasing exponentially with increasing ε.

These models may, therefore, be an oversimplification of the relationship, since what is essentially desired is some relationship for the change in porosity close to the wall. This was discussed earlier, but should be examined in closer detail. Richard and Raghavan use the diagram of Figure 1 to demonstrate the origin of the contact resistance. The contact resistance is assumed to occur as a result of an effective gas film layer at the wall. This gas film is not constant, but can be interpreted as the average distance form the wall to the first layer of particles. Richard and Raghavan indicate with Figure 1c that this equivalent gas film can be expected to be larger for angular particles than spherical particles. The orientation of the angular particles in Figure 1c is perhaps not a very likely one; we are however limited by the lack of understanding of the behaviour of granular materials. One could, for example, propose the orientation shown in figure 2a, which would effectively eliminate the contact resistance for rhomboid particles such as sand. The random orientation shown in figure 2b is more likely to occur, but this is very difficult to describe and analyze. It is unlikely that a useful model can be devised by examining the actual orientation of the particles; it is therefore necessary to attempt to obtain a means for predicting the effective change in porosity of a granular material close to a wall without requiring knowledge of the exact particle orientations.



(from Richard and Raghavan, 1980)

Figure 1: Representation of Contact Resistance

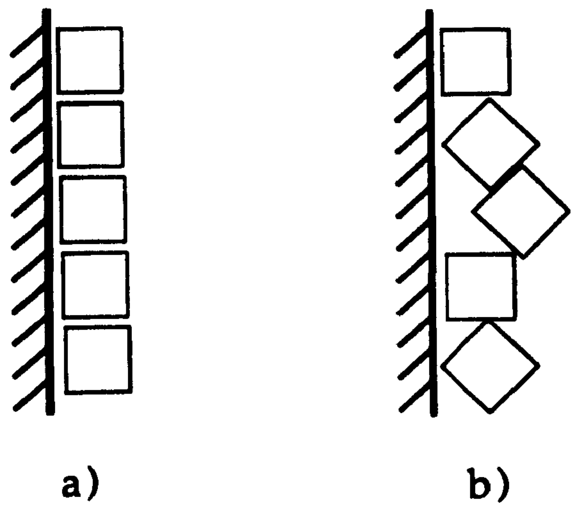


Figure 2: Alternative Particle Orientations

It would be conceivable to devise a method to determine the effective film layer of a particular material, although it may prove difficult because of the very small dimensions. This would become increasingly difficult for smaller particles, but it may be possible to measure the film layer for large particles of a certain shape, and simply scale it down for smaller but similarly shaped particles. The measuring device would work on the principle that, because of the film layer at the wall of a container, the apparent bulk density of a material will become smaller as smaller containers are used for the measurement. This is because the film layer will comprise an increasing portion of the total volume. If two spherical containers, each of different volume, were filled with the granular material, then the volume of each would be occupied by the film layer and the bulk material. Therefore;

$$V = \frac{m}{\rho} + V_f \qquad (14)$$

Since the container is a sphere, the total volume and film layer volume are;

$$V = \frac{4}{3}\pi r^2 \qquad (15)$$

$$V_f = l \cdot 4\pi r^2 \qquad (16)$$

These equations can then be combined to obtain;

$$\frac{1}{\rho}\cdot\frac{m}{r^2} = \frac{4}{3}\pi r - 4\pi l \qquad (17)$$

By using several spherical containers of different radii, it would be possible to determine the film layer by regressing m/r^2 against $\rho(4/3)\pi r$. The y-intercept would then be $-\rho 4\pi l$, from which the apparent film thickness l could be determined. The bulk density ρ could be obtained from the slope of the regression line. The appropriate means of non-dimensionalyzing the value of l for use with materials of different sizes would be by comparison with the particle diameter d, by defining $l' = l/d$, which is identical to the definition of χ given by Sullivan and Sabersky.

The choice of a spherical container is merely arbitrary for the purposes of explanation; in fact, it would be preferable to use a shape with a high surface area to volume ratio, while the sphere is the shape with the lowest surface area to volume ratio. The only restraint is that it should be a container with a small opening such that the volume can be measured very precisely.

One immediate restraint is that these evaluations are to be done on a stagnant bed; as Sullivan and Sabersky indicate, properties will be different for a moving bed. It should be noted, however, that the change in porosity close to the wall is similar in moving beds to stagnant beds.

This methodology would have to be tested to determine its effectiveness; however, it should determine whether or not the model based on an effective film layer is appropriate. This may not be the case, since the thermal resistance of the film layer is not in fact in series with the thermal resistance of the rest of the bed. The air gap is spanned by some of the particles, and therefore heat transfer is occurring through conduction through the solid particles in parallel with the conduction through the apparent film layer. The relationship between the two methods of heat transfer will depend very much on the shape of the particles. Richard and Raghavan (1980), however, suggested that because the shape is very much related to the porosity, using porosity to determine χ would be appropriate. In this case, since what is suggested here is essentially a variation of porosity, the same argument holds. Therefore, the value of l/d determined through this method may not give an actual value of χ, but it may be possible to develop an empirical relationship between χ and l'.

Alternatively, a more direct means of evaluating thermal contact resistance could be devised. This test would be based on standard tests of thermal conductivity on a particulate material, using two flat plates with the granular material between them, and a steady state flow between the plates. In these tests, the thermal conductivity, k, is determined from;

$$q = \frac{kA}{\Delta x}\Delta T \qquad (18)$$

However, if there is a thermal contact resistance, which is modelled as a film layer, the equation to describe heat transfer would more accurately be;

$$q = \frac{A\Delta T}{\frac{\Delta x}{k_e} + 2\frac{l}{k_g}} \quad \ldots \quad (19)$$

Similar to the method discussed above, conductivity measurements could be taken with different plate separations (i.e. varying Δx), and the measurements fitted to the line;

$$\frac{A\Delta T}{q} = \frac{l}{k_g} + \frac{\Delta x}{k_e} \quad \ldots \quad (20)$$

The value of l can then be obtained from the y - intercept. Unfortunately it is not within the scope of this thesis to test either of these methods.

2.3.4 Rotating Drums

The mechanisms of heat transfer from one particulate material to another of different size, as they tumble together in a rotating drum, are quite complex, and would be extremely difficult to analyze precisely. However, with an understanding of the analysis of heat transfer in granular materials under more ideal conditions, some understanding of the dynamics of particle motion in rotating drum, and empirical observations of heat transfer in rotating drums, it is possible to develop some predictive models for heat transfer within a rotating drum.

Richard (1981) used the analysis of Downs et. al. (1977) of the flow of particles in a rotating drum, to analyze the heat transfer. As shown in Figure 3, the material is carried with the drum to some extent, and then rolls down over the bulk of the bed in the sliding layer. Downs et. al. developed an equation to describe the thickness of the sliding layer. Richard used the following equations to describe the heat transfer in the stagnant part of the bed and the sliding layer, respectively:

$$h_b = [\frac{\chi d}{k_g} + \frac{1}{k_b}\sqrt{\frac{\pi}{4}\alpha t_b}\ ]^{-1} \quad \text{(21)}$$

$$h_s = [\frac{\chi d}{k_g} + \frac{1}{k_b}\sqrt{\frac{\pi}{4}\alpha\frac{d}{v}}\ ]^{-1} \quad \text{(22)}$$

where;

χ = film layer coefficient

d = particle diameter (m)

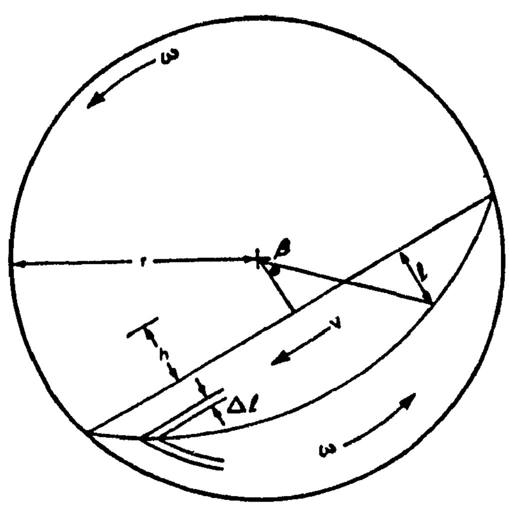
k_g = thermal conductivity of gas (W/m°C)

k_e = effective thermal conductivity of particulate medium (W/m°C)

α = thermal diffusivity of the particulate bed (m^2/s)

t_b = time in stagnant bed (s)

υ = sliding velocity (m/s)



(from Downs et. al., 1977)

Figure 3: Model of Material Flow in a Rotating Drum

The time-weighted average heat transfer coefficient was then computed from the equations of Downs. In the sliding layer, the value of h_s is strongly dependant on χ, since the rigorous mixing reduces the temperature gradients within the particulate medium, and thus the main barrier to heat transfer becomes the film layer (i e. the value of d/v becomes very small as v increases). Since the value of χ cannot be successfully predicted, as mentioned above, and this would be even more true for vigorous mixing around a larger particle, this model was not able to predict the experimental results. However, regressions were performed with the experimental data to determine the apparent values of χ for each case.

2.4 Particulate Medium Heat Processors

Several machines have been developed for the purpose of heat treatment of grain in a particulate medium. The exact treatment for which the machines were originally designed varies, but in general the machines can be used for a variety of purposes. The working of any such machine can be divided into three essential functions: heating of the particulate medium with the heat source; mixing of the particulate medium with the grain; and separation of the grain from the particulate medium, after which the medium is returned to the heat source.

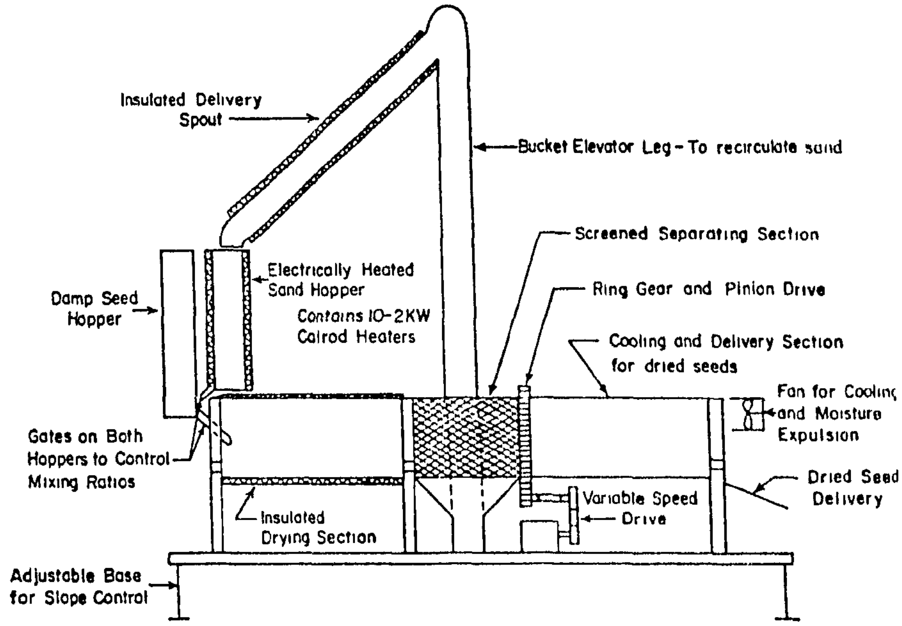
Lapp and Manchur (1974) developed a machine for the drying of oilseeds (specifically rapeseed) in a particulate medium. The apparatus used in their study is shown in Figure 4. In this machine, the particulate medium (sand) is heated by electric heaters placed in the wall of a hopper. The grain is mixed with the sand in a rotating, inclined cylinder, and the two are mixed as they move through the cylinder. The central section of the cylinder is made of mesh, which allows the sand to flow out, and it is collected and returned to the heaters with a bucket elevator. The grain then progresses through the remaining length of cylinder, where a fan cools it and carries away moisture.

Raghavan (1973) developed a machine for particulate medium heat treatment which was used both for grain drying and soybean roasting. The system is shown in Figure 5. In this case, a bed of salt is maintained in an inclined, rotating drum, which is heated from below by gas burners. The grain is introduced at the base of the drum, and mixes with the medium. As the drum rotates, a mesh helix within the drum moves the grain up and out of the drum while allowing the salt to remain behind.

A machine was developed by Khan (1973) for the drying and parboiling of rice in heated sand. In this machine, the sand is heated as it is swept along a pan with burners located below the pan. This sweeping is performed by brushes on the exterior of a rotating cylinder, inside of which the sand and rice are being mixed. When the sand reaches the end of the pan, scoops attached to the rotating drum pick up the sand and deposit in the drum. A diagram of the machine is shown in Figure 6.

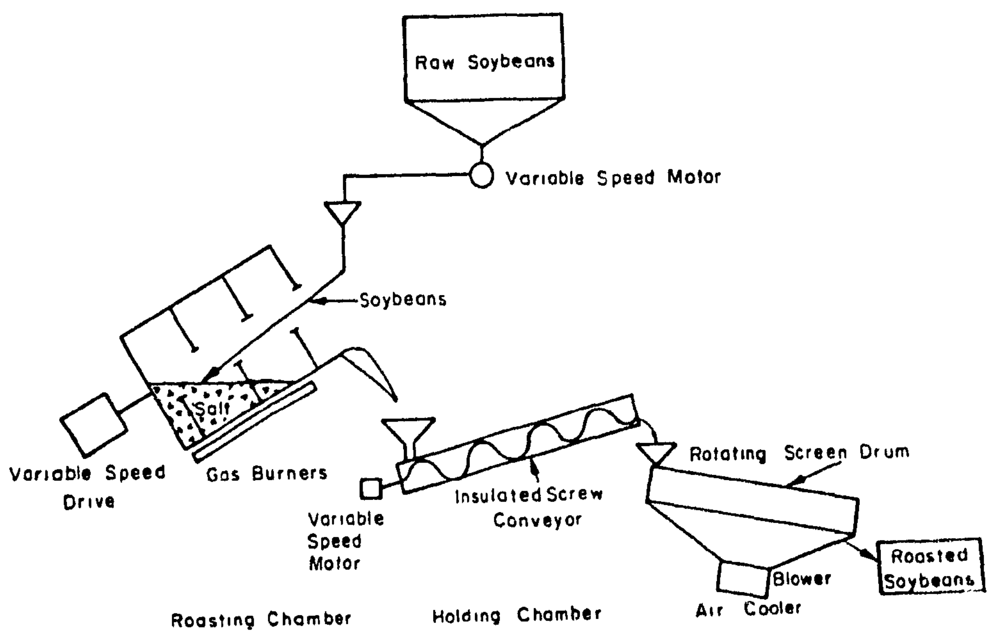
Tessier (1982) performed experiments with a machine developed by Raghavan and Langlois (1984), shown in cross-section in Figure 7. In this case, the heat is obtained from flame exhaust gasses, which pass through the central shaft of the machine, and are directed to an annular space around the surface of the drum, from which heat is transferred to both the particulate medium in the outermost section, and the mixture of particulate medium and grain in the central section. The drum is placed on an incline, and the internal helix moves the mixture up the slope, and the medium, after being separated from the grain, moves down the slope in the outer annulus.

Raghavan and Pannu (1986) designed the machine shown in Figure 8. This machine was used in the current study and will be discussed later in greater detail.



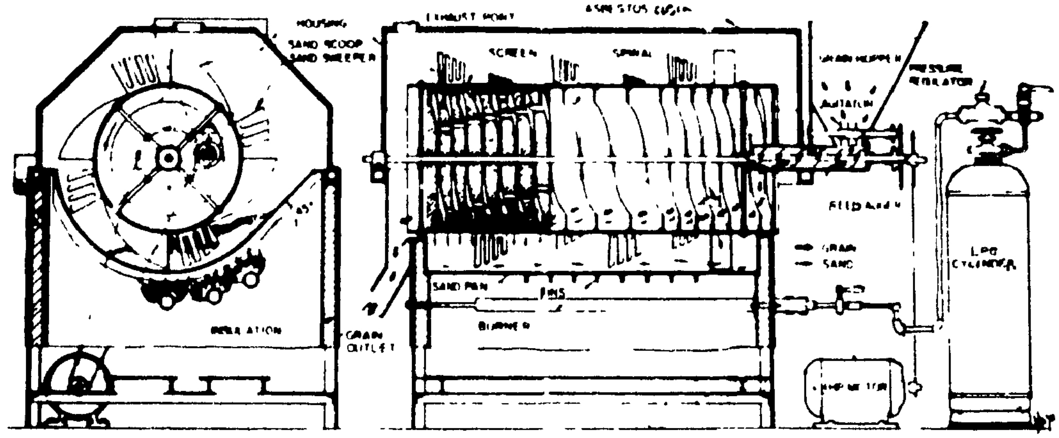
(from Lapp and Manchur, 1974)

Figure 4: Heat Processor Described by Lapp and Manchur (1974)



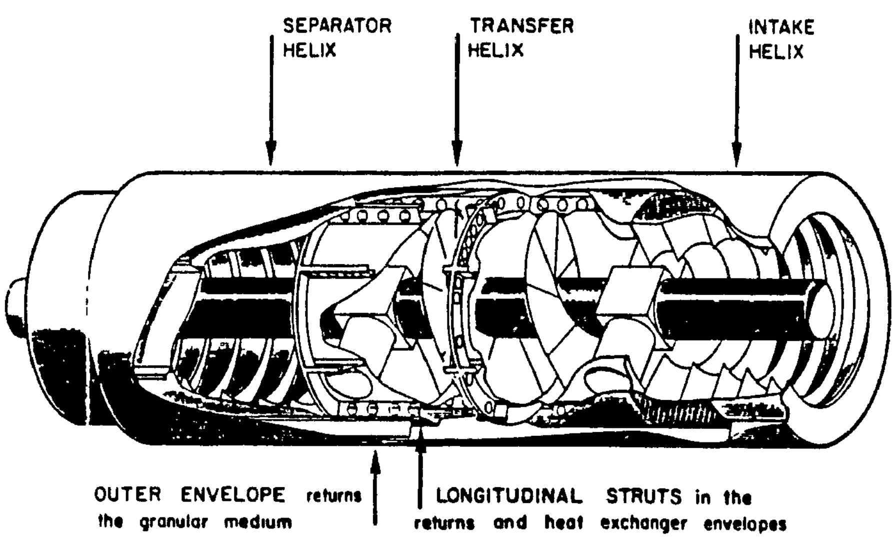
(from Raghavan, 1973)

Figure 5: Heat Processor of Raghavan (1973)



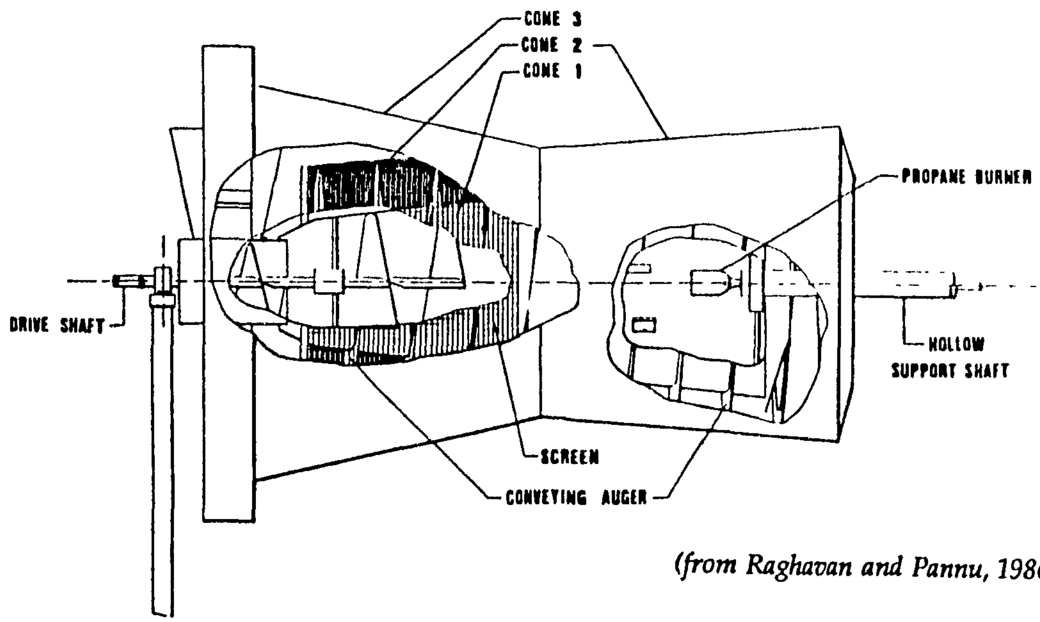
(from Khan et. al., 1973)

Figure 6: Heat processor of Khan et. al. (1973)



(from Raghavan and Langlois, 1984)

Figure 7: Heat Processor of Raghavan and Langlois (1984)



(from Raghavan and Pannu, 1986)

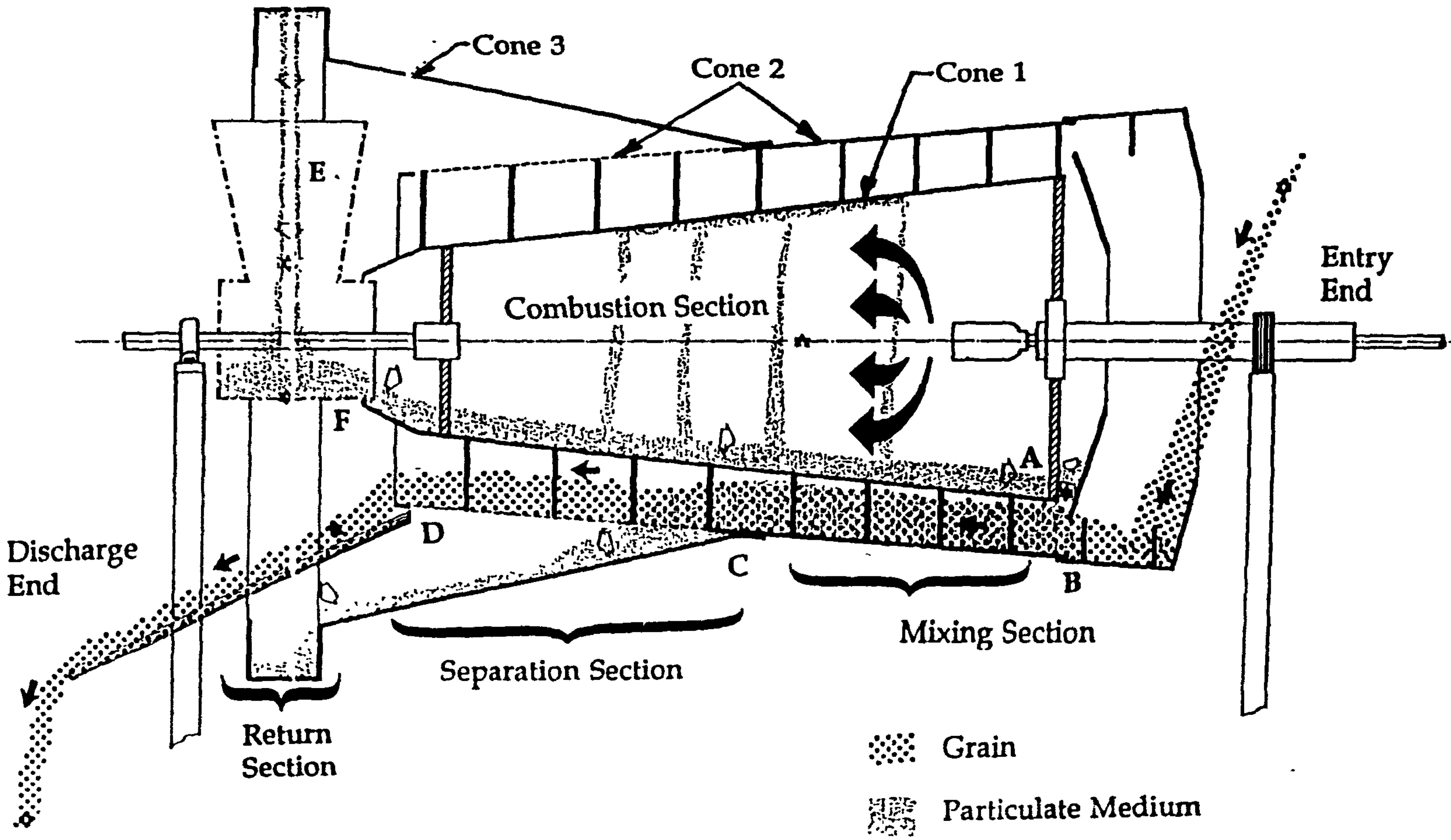
Figure 8: Processor of Raghavan and Pannu (1986)

III. Materials and Methods

3.1 Apparatus

The experiments in this study were performed with the previously described processor invented by Raghavan and Pannu (1986), with modifications as described by McBratney (1989). A cross-sectional diagram of this processor is shown in Figure 9. In this processor, the medium is heated in the central section of the processor, to be referred to as the combustion section, or cone 1. Buckets placed in cone 1 carry the medium up and shower it through the flame as the drum rotates. The slope of the cone causes the medium to move toward point A, where it falls from the combustion section to cone 2, the mixing section. The medium then mixes with the grain, which is fed into the entry end, and the heat transfer occurs as the medium and grain are moved together towards the discharge end of the machine by a helix. The wall of cone 2 is made of mesh between points C and D, and thus, as the mixture reaches point C, the medium passes through the mesh, while the grain is carried through to the exit chute. The salt is carried in the outer cone (cone 3) to the return section, where buckets carry it up to be dropped in the funnel (E) and returned to the combustion section. The drum is powered by a D.C. motor with variable speed control to allow it to be operated at a range of rotational speeds. Further details of the operation of this machine can be found in Pannu (1987).

Due to some problems observed in initial trial runs, a few modifications were made prior to the experiments. The funnel which collects salt in the return section was expanded and redesigned to capture a larger portion of the cascading salt, and reduce the amount of cascading salt leaving the machine. The angle of the funnel was decreased in order to increase the amount of showering salt collected per revolution. When the salt



(adapted from Pannu, 1984)

Figure 9: Detailed Cross-section of the Prototype Processor

is cascading from the buckets in the return section, some of the salt falls out of the end. The guides on either side of the funnel were designed to catch this salt which was headed out of the machine and redirect it to the bottom of the return section. While this reduced the problem to some extent, there was still salt lost on to the floor during the experiments. A photo of the modified funnel is shown in Figure 10.

Problems also existed with the salt leaking at point F, where salt from the funnel is moved by an auger into the combustion section. Due to a gap between the stationary auger housing and the rotating drum, salt was able to fall through the opening and fall onto the grain as it fell down the discharge chute. This resulted in salt being collected in the collection bin with the grain, thus negating to some extent the separation of salt from grain. This was alleviated by placing a guide funnel underneath the leak to deliver the leaking salt to the return section without having it fall on the grain. This funnel can also be seen in Figure 10. It should be noted that this modification is intended only to be a temporary one for the purposes of these experiments, and that this problem of leaking particulate medium must be resolved in further design refinements of the processor.

The machine was insulated with 3 mm asbestos cloth under 5 cm fibreglass insulation and a reflective aluminum foil to reduce convective and radiative heat losses to the environment. A supply hopper for the soybean was constructed, with an auger and chute attached to deliver the grain to the machine. The auger was powered by a D.C. motor with speed control, such that the auger could be used to control the soybean feedrate to the machine.

An air compressor was used to supply air to the flame, as earlier users of the processor had found that the torch could not draw sufficient air for proper combustion when enclosed in the machine.

An insulated collection bin was constructed to collect the soybean after roasting, and to hold it with minimum heat loss. This bin was constructed from a garbage bin of diameter 36 cm. Fibreglass insulation of thickness approximately 8 cm was placed around the interior of the bin, and coveıed with reflective aluminum foil vapour barrier. The dimensions of the interior of the bin were 20 cm diameter and 17 cm in height. A lid of the same insulation was also made to cover the bin. In the centre of this bin was suspended a thermocouple from an aluminum support. As well, several mesh-bottomed trays of dimensions 15 cm x 15 cm were made in which the soybean could be placed and allowed to cool in ambient air with natural convection. An overall view of the apparatus can be seen in Figure 11, and details of the collection bin and cooling trays are shown in Figures 12 and 13.

3.2 Experimental Design

Since previous work had been done on salt-bed soybean roasting by Raghavan et al (1974), these results were used to determine the most likely parameter levels to achieve optimal soybean quality. The soybean in their study was roasted in the salt-bed for a certain residence time, then held in an insulated screw conveyor for some time before being air cooled above a fan. Temperature levels used in the roaster were 204, 238 and 272 °C, with residence times of 13, 20, and 27 s. Holding times in the conveyor were 0, 60 and 120 s. The soybean was fed to broiler chicks, and optimum weight gains were achieved with soybean treated at 272°C for 20 s and held for 120 s. For these experiments, longer holding times generally resulted in higher weight gains, and thus it is unlikely that any advantage is to be gained by cooling the soybean soon after roasting. Also, a statistical analysis demonstrated that temperature was a significant factor in determining weight gain, but examination of the means indicates that the difference of

Figure 10: View of Modified Return Section

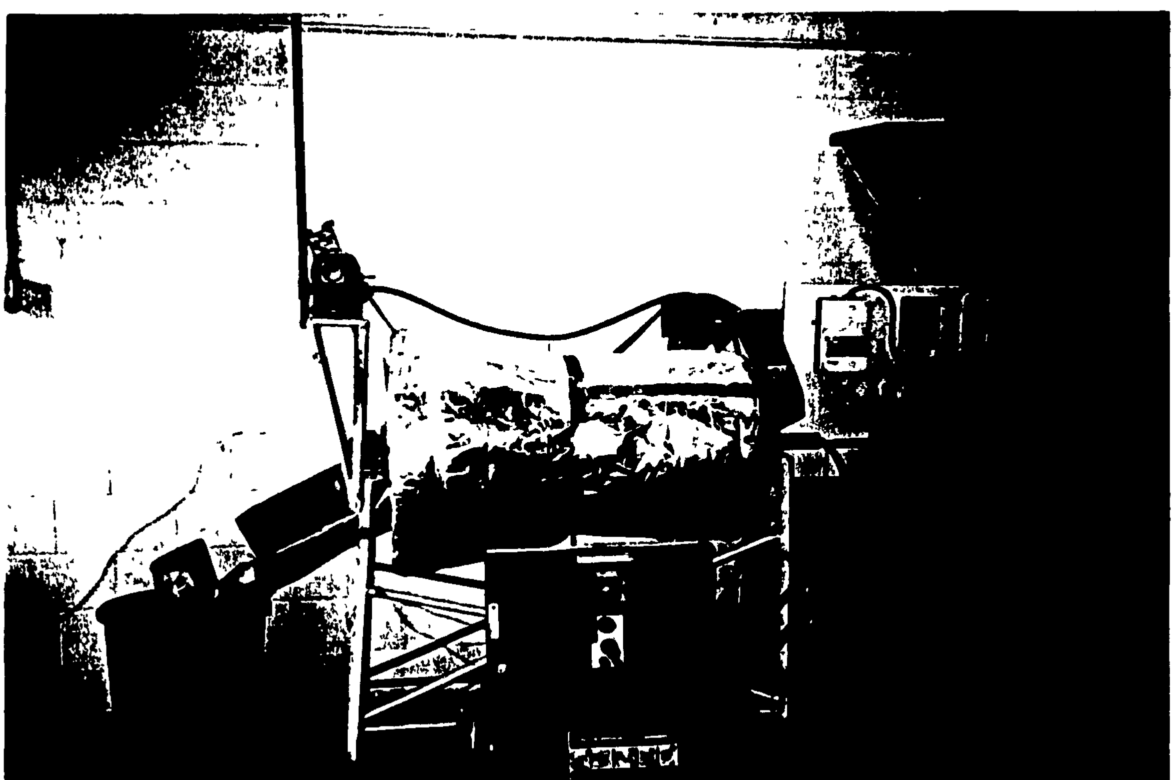


Figure 11: Overall View of Apparatus

Figure 12: Insulated Collecting Bin

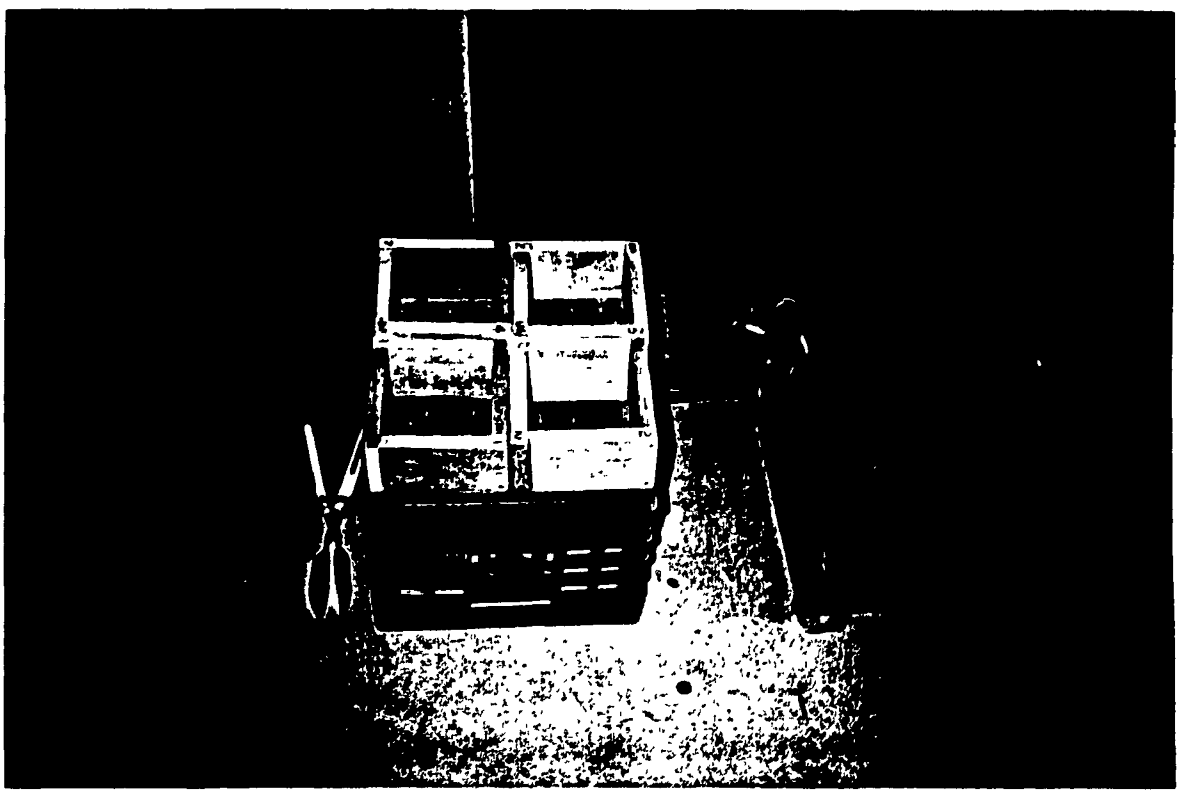


Figure 13: Soybean Cooling Trays

temperature effects is primarily due to the difference between the lowest temperature level and the two higher temperature levels (582 g weight gain for treatment at 204 °C *vs.* 606 and 610 g at 238 and 272 °C respectively). Unfortunately it is not stated whether or not the difference between the two higher temperature effects is statistically significant. Since Raghavan et. al. (1974) observed charring of soybean at temperatures above 272 °C, it would not likely be advantageous to use temperatures much above this level. As well, with the apparatus being used in this study it is difficult to maintain constant temperature very accurately; fluctuations in the salt bed temperature are often 5°C and can be as great as 10°C. Temperature levels should therefore be sufficiently different such that this error will not be of great significance. Temperature levels of 225, 250, and 275 °C were therefore used.

In order to test a wide, but reasonable range of residence times, and obtain information from which trends could be observed, residence times of 15, 30, and 60 s were used (corresponding to 20, 10 and 5 rpm for the experimental machine).

In order to set the salt-to-grain mass ratio (SGMR), the maximum power available from the machine is an important factor limiting the mass flow rate of soybean through the machine, and thus the SGMR. A test was performed to determine the maximum flow rate for which the machine can maintain steady state (i.e. the flame provides sufficient heat to replace the heat removed by the soybean) for the highest levels of temperature and machine rotational speed (275°C, 20 rpm). This was found to be approximately 2 kg/min. The flow rate of salt was approximately 1 kg/rev, and thus the SGMR was approximately 10. To maintain the SGMR, the soybean flowrate was reduced to 1 kg/min and .5 kg/min for speeds of 10 rpm and 5 rpm respectively. Since this value of SGMR is essentially the minimum SGMR for this machine under these conditions, it was not possible to test the effect of SGMR with lower values. Using higher values of SGMR would not have been useful, since the effect of SGMR above this level has not been found to be great in the past, particularly for short residence times.

An additional factor which has been shown, in some of the studies discussed earlier, to affect soybean quality, is the moisture content of the soybean. Although the effects of moisture content on the effectiveness of roasting of whole soybean has not bean documented, this effect has been studied for heat treatment of soybean meal. McNaughton and Reece (1980) found that heat treatment of soybean meal was more effective (i.e. greater destruction of urease and trypsin inhibitors) when the moisture content of the meal was higher. The moisture values used in the experiments were in the range 0 - 16%, and the benefit of added moisture declined as the moisture content increased. For whole soybean, moisture levels would generally be at least 10%, ranging up to 25% if the soybean is roasted immediately after harvest. It is therefore not clear if these results for soybean meal with its low moisture contents are relevant to whole soybean with higher moisture contents. It would, however, be beneficial to determine whether or not moisture content before roasting does affect the final nutritive value, and therefore it would be worthwhile to use two moisture levels in the experiments. By roasting at both 13%, a typical moisture content for long term storage, and 22% moisture, a typical level at harvest, the effect of moisture can be determined both for theoretical interest, as well as to determine if roasting at harvest may be preferable to roasting just prior to use.

In the study of Raghavan et. al.(1974), the soybean was moved slowly through an insulated screw conveyor after roasting, after which the soybean was cooled. Holding times used in this conveyor were 0, 60, and 120 s. However, the optimum quality soybean from the study was achieved with a holding time of 120 s, and in general, quality was seen to increase with longer holding time for all variations of salt temperature and residence time. Therefore it is possible that an even longer holder time could have resulted in higher quality. In the studies discussed in the previous section on soybean heat treatment methods, the soybean was in many cases maintained at elevated temperatures in the range of 20 - 30 min. For this study, since rapid roasting is the goal, and since the study of Raghavan did show good results with a holding time of only 2 min, whereas other researchers have used much longer times, a wide range is desirable. The roasted soybean was therefore held at elevated temperature for 0, 5, 10, or 15 min prior to cooling.

A summary of the treatment levels used is given in Table 1.

Table 1: Experiment Treatment Levels

Factor	Levels			
Moisture content (% w.b.)	13	23		
Residence time (s)	15	30	60	
Temperature (°C)	225	250	275	
Holding times (min)	0	5	10	15

Due to the nature of the experimental set-up, it is very difficult to perform the experiments in a completely randomized design. Changing the soybean supply to the machine from one test to the next is extremely tedious and time consuming. As well, for the different levels of holding time, holding samples from one run in the roaster for each of the four holding times greatly reduces the number of individual tests required. Therefore the experiments were performed as a split-split plot, with the 2 soybean moisture contents randomized to the first level and the temperature-residence time combinations randomized within each moisture content for each replicate. Samples of treated soybean were then taken at each of the four holding times. Five replicates were performed, providing a total of 360 samples of soybean for analysis, and 90 sets of temperature data for heat transfer analysis.

3.3 Materials

The particulate medium used in this study was conventional table salt purchased from a Montréal grocery store. The bulk density was found to be 1370 kg/m^2, and the specific gravity of NaCl is 2.165 (CRC, 1990). This indicates that the salt has a void ratio of 37%. Particle size was determined by sieves; 34.8% passed through 850 µm mesh but was retained on 500 µm mesh, 63.2% passed 500 µm mesh but was retained on 250 µm mesh, and the remaining 2.0% passed through the 250 µm sieve. From these values, using the methodology of the ASAE (1991), the average particle size was estimated to be approximately 430 µm.

The soybean used in the tests was of the Maple Glen variety, produced near Montréal. The soybean was received with a moisture content of 15.5% w.b. and stored in a refrigerator at 1-2°C until used. The moisture content of the soybean was adjusted by drying or rewetting to bring it close to the desired moisture content of either 13 or 23%. Drying of the soybean to 13% was performed in an experimental spouted-bed dryer available in the laboratory where the roasting experiments were performed. The drying was performed with no heating other than that produced by the fans, in order to avoid the possibility of elevated temperatures which might have had some roasting effect prior to the roasting experiments. In order to raise the moisture content of soybean for the 23% moisture tests, the contents of a 40 kg sac of soybean were emptied into a large container, to which was added 3.3 kg of water. The soybean were then periodically mixed until no free water was visible on the surface of the grains. The soybean was then left in the covered container at ambient temperature for at least 24 hrs prior to being roasted in order for the moisture to diffuse throughout the grains. The soybean was not allowed to stand for more than 60 hrs before being used, as mould could form quickly at 23% moisture and room temperature.

The specific gravity and average volume per bean of soybean were determined with a method similar to that described by Mohsenin (1986). For soybean at each moisture content, 100 randomly chosen beans were weighed and then placed in a 100 ml volumetric flask, which was then filled to the gradation mark with toluene. The mass of the contents of the flask was determined, as was the mass of the contents containing only toluene. The volume of the flask was calibrated with water at room temperature. From these measurements, the specific gravity, and volume per bean, were determined. Approximating the beans as spherical, an apparent radius was then calculated as well. These values are given in Table 2.

Table 2: Soybean specific Gravity and Grain Size

Moisture Content	Specific Gravity	Volume/bean	Apparent Radius
13.5%	1.2145	0.1856 cm^3	3.538 mm
23.0%	1.1915	0.2178 cm^3	3.732 mm

3.4 Procedure

The experiments were performed in sets, corresponding to one replicate at one moisture level, and in most cases each set was performed in a single day. After rewetting or drying the soybean, and allowing sufficient time for tempering, the soybean was loaded into the hopper. The processor was then turned on and the salt was brought to the temperature required for the first test. This temperature of the salt was monitored at the point where the salt leaves the combustion section and enters the mixing section (at point A in Fig. 9), and the propane supply was adjusted manually as required to maintain the salt temperature as close as possible to the desired level for the duration of the test. Once the processor was at the correct temperature and rotational speed, and the soybean supply auger set for the correct feed rate correlating to the processor speed, the flow of soybean was started. The flow would continue for sufficient time to process enough soybean to approximately fill the holding bin, and ensure that the thermocouple in the centre of the holding bin was well covered with soybean. At the point where the bin was approximately half full, which corresponds to the time when the soybean is at approximately the level of the thermocouple, a timer was started to measure holding times. As well, two samples of the soybean were taken from the discharge chute immediately as the soybean left the machine. One of these samples was quickly placed in a closed container for moisture content analysis, while the other sample was placed on a cooling tray as a sample of a holding time of zero.

As soon as the last bit of soybean was roasted and had exited the machine, the holding bin was covered with an insulated cover. At timer readings of 5, 10 and 15 min, the lid was removed and a sample of soybean was removed from the centre of the bin. Each of these samples was immediately placed in a cooling tray. The cooling trays were in all cases filled only to a thickness of approximately one bean diameter in order to allow for a high rate of free convection. After the final sample was removed at the longest holding time (15 min), an additional sample was placed in a cooling tray in order to determine the moisture content that could be removed through ambient temperature free convection (i.e. no additional energy input) after roasting. The bin was then emptied and prepared for the next test. Throughout the entire time in which there was soybean in the collection bin, the temperature read by the thermocouple in the centre of the bin was recorded every 15 s.

This process was then repeated for the 9 temperature - residence time combinations of the experimental set. Throughout the process, the temperature of the soybean in the hopper was monitored as an indicator of the temperature prior to roasting.

3.5 Soybean Quality Analysis

3.5.1 Sample Preparation

Samples of roasted soybean were collected from each test as described above, and placed in a freezer for storage until the analysis could be performed. Each sample was first ground, with the grindings passed through a 100 mesh screen, and only that portion that passed through was used in the analysis. Care was taken during the grinding to ensure that the temperature of the soybean would not be raised to levels sufficient for trypsin denaturing.

Extraction of oil was then performed in erlenmyer flasks with hexane. Approximately 10 g of sample was placed in an erlenmyer flask, to which was added 100 ml of hexane. The flask was then stirred on a magnetic stirrer at low setting for 1 hr. The solution was then allowed to settle, after which the solvent was removed. The moisture content of each sample was determined approximately using a moisture balance at 145°C for 10 minutes, in order that results could be reported on a dry matter basis.

3.5.2 Trypsin Analysis

The trypsin content of the soybeans was determined using the methodology of the AACC (1983, method 71-10). One gram of the finely ground sample was extracted with 50 ml of 0.01 N NaOH (pH 8.4-10) for 3 hours. Quantities (0, 0.6, 1.0, 1.4, and 1.8

ml) of diluted suspension were placed in duplicate sets of test tubes and adjusted to 2 ml with distilled water. A trypsin solution was prepared by dissolving 4 mg of trypsin powder (2X crystalyzed, salt free) in 200 ml of 0.001 M HCl. To each test tube was added 2 ml of this trypsin solution, and the tubes were placed in a water bath at 37°C. A solution of BAPA (benzoyl-DL-arginine-*p*-nitroanalide) was prepared by dissolving 40 mg of BAPA in 1 ml of dimethyl sulfoxide and diluting to 100 ml with *tris*-buffer. The *tris*-buffer contained 0.05 M *tris* (hydroxymethylamino methane) and 0.02 M $CaCl_2$. Five ml of BAPA solution (prewarmwd to 37°C) was added to each test tube, and exactly 10 min later, the reaction was stopped by the addition of 1 ml of 30% acetic acid. The solution was mixed and the absorbance at 410 nm was measured with a spectrophotometer. One trypsin unit is defined as an increase of 0.01 absorbance units at 410 nm per 10 ml of the reaction mixture, and trypsin inhibitor activity is expressed in terms of the trypsin units inhibited per gram of sample (TIU/g).

3.5.3 Protein Solubility Analysis

Araba and Dale (1990) have proposed the use of a protein solubility test as a test of overprocessing of soybean, and damage to proteins. This test is suggested as an alternative to the previously used urease activity test. The urease activity test is unfortunately limited in that well processed soybean may have a urease activity of zero, and therefore overprocessing cannot be measured. The data of Araba and Dale indicate that protein solubility is a good indicator of overprocessing, and this test has been adopted by other researchers (e.g. Herkelman et. al.,1991).

Samples of 1.5 g were placed in 125 ml flask, to which was added 75 ml of 0.2% KOH (0.036 N, pH 12.5). The mixture was then stirred for 20 min on a magnetic stirrer, after which, a 15 ml aliquot of the mixture was removed with a pipette. This sample was then centrifuged for 15 min at 2700 rpm, after which triplicate 15 ml aliquots of the supernatant were removed and filtered. The total nitrogen content of the supernatant was determined using the Kjeldahl method, and the protein content was calculated using the factor protein mass equals 6.25 times nitrogen mass. Although Araba and Dale express protein solubility as a percentage of total protein, in this case the soluble protein is expressed merely in terms of a percentage of the total dry mass of the sample. This eliminates the need to determine total protein for each sample, but still allows for a valid comparison of protein solubility between samples.

IV. Results and Discussion

4.1 Heat Transfer

The recorded values of final grain temperatures and moisture contents as measured in the collecting bin are given in Appendix 1 with the corresponding initial temperatures and moisture contents. The temperature of the salt after processing, although it could not be measured directly, was calculated from the measured data. Knowing both the temperature and moisture changes in the soybean, it was possible to calculate total heat transferred to the soybean. This was calculated from;

$$Q = \Delta M \cdot \Delta h_v + \Delta T_g \cdot C_g \qquad (23)$$

Where:

Q = total heat transfer per unit mass of grain (kJ/kg)

Δh_v = heat of vaporization of water (kJ/kg)

ΔT_g = change in temperature of the grain (°C)

C_g = heat capacity of the grain (kJ/kg°C)

and ΔM is the ratio of the mass of water lost to the original total mass of grain, and is obtained from;

$$\Delta M = [M_i - M_f(\frac{1-M_i}{1-M_f})] \qquad (24)$$

where:

M_i = initial grain moisture content (% wet basis)

M_f = final grain moisture content (% wet basis)

The value of the heat of vaporization of water from the soybean was taken as 2500 kJ/kg. This value was used since there is no published data on the change in heat of evaporation with moisture content and temperature, and thus it was necessary to make this approximation. Watts and Bilanski (1970) provide values for the specific heat of soybean at different moisture contents as shown in Table 3. Due to the small variation in the value of C_g, and the difficulty of attempting to account for the changing C_g as the moisture content changes, the value of specific heat of soybean was approximated at 2.0 kJ/kg°C. From the value of heat transferred to the soybean, and assuming no heat losses, the temperature change in the salt medium was calculated from;

$$\Delta T_m = Q / C_m \qquad (25)$$

where;

Q = total heat transfer per unit mass of grain (kJ/kg)

C_m = heat capacity of the particulate medium (kJ/kg°C)

The value of C_m for NaCl was obtained from CRC (1991) as 865 kJ/kg°C.

Table 3: Soybean Specific Heat Values from Watts and Bilanski (1970)

Moisture Content (% w.b.)	Specific Heat (kJ/kg°C)
7.4	1.88
17.72	1.97
21.72	2.05

The above calculations assume that energy gain by the soybean is equivalent to the heat loss by the salt. The two main problems with this assumption arise from heat loss from the machine, so that heat from the salt is lost to the environment as well as to the soybean, and from heat loss by the soybean between the time it is heated and the time the temperature is measured in the collecting bin.

For the first source of error, the maximum possible heat loss from the mixing section of the machine was estimated. Using the insulating values for asbestos and fibreglass given by Holman (1990), and neglecting the convection factor (i.e. assuming the exterior of the insulation to be at room temperature), the heat loss per pitch of the machine with the interior at 275 °C was calculated to be approximately 20 W. With the contents of each pitch being approximately 1 kg salt and 0.1 kg soybean, with a combined heat capacity of 1065 J/°C, and maximum residence time of 60 s, the maximum reduction in temperature as a result of these losses would be 1 °C. As this is a very liberal estimate of the losses, it is reasonable to neglect theses losses.

For the heat losses form the soybean as it travels to the collecting bin, the information available from Holman (1991) is used. Assuming the bean travels approximately 1 m through ambient temperature air in 2 s, the calculated temperature drop was 2.5 °C, for a soybean initially at 120°C. This calculation is very approximate, as it is based on the assumption that there is no significant temperature gradient in the bean, which is quite invalid. However, the fact that a temperature gradient does exists means that the heat loss would be less than that obtained from this calculation.

A further source of doubt arises from the time the soybean resides in the sieve section of the machine. At this time, heat transfer can also occur between the soybean and the air. As the temperature of the air in this section could not be measured, it is not at all possible to estimate the heat transfer, However, it is quite likely that the temperature in this section is above 120 °C and is thus heating the soybean. Therefore, to account for the losses on the exit chute and not account for possible heat gains in the sieve section, could introduce greater error than that introduced by neglecting both.

Therefore, both were neglected in these calculations.

Although a constant SGMR of 10 was intended, an unintentional variation in the SGMR occurred. The actual mass of salt carried per pitch of the machine, which was measured approximately to be 1.0 kg, was found by more careful measurement to vary quite consistently with machine speed. At each of the three speeds used in the experiment, three measurement of the mass of salt in one pitch were performed. For these measurements, the machine was operated for at least 5 min with the maximum amount of salt that could be handled by the return section. The machine was then stopped and backed up so that the contents of one pitch could be removed and measured. The three measurements taken at each speed did not vary by more than the precision of the balance used (5 g), and were 1.10 kg, 0.96 kg, and 0.85 kg for machine speeds of 20, 10 and 5 rpm, respectively. Therefore, this variation could be accounted for in the calculations of heat transfer; however, because the changes in SGMR are confounded with residence time, this variation in SGMR will lead to some error when comparing the effect of the different residence times.

A summary of this data, giving the average over the five replicates of values both directly measured and computed, is contained in Table 4.

The data thus obtained both directly and indirectly were analyzed for statistical validity using the RSREG procedure of SAS software. The entire data set was analyzed in order to test the linear, quadratic, and interaction effects of the three factors (moisture content, salt-bed temperature and residence time) on the results. The results to which the factors were compared were the final temperature of the soybean, the temperature change in the soybean, moisture loss, and total heat transfer. The SAS program and output are given in Appendix 2.

Table 4: Experimental Temperature, Moisture Content and Heat Transfer Data; Average of five Replicates

Moisture Content	Salt Temp. (°C)	Residence time (s)	T_f (soy) (°C)	T_f (salt) (°C)	M_f (soy) (% w.b.)	Q (kJ/kg)
13 %	225	15	115.4	200.2	11.4	235.6
		30	121.2	193.2	10.8	264.0
		60	121.8	178.5	7.9	341.7
	250	15	117.6	224.5	11.3	242.3
		30	117.4	210.6	8.1	327.4
		60	123.8	195.4	5.7	401.2
	275	15	118.8	246.2	10.2	274.1
		30	123.4	229.4	6.5	378.3
		60	128.6	213.6	4.0	451.1
23 %	225	15	110.2	197.3	21.0	263.8
		30	110.8	183.7	18.3	342.6
		60	110.4	162.8	14.0	457.6
	250	15	110.4	220.5	20.4	280.8
		30	110.4	201.8	16.2	400.4
		60	109.6	176.3	10.7	542.0
	275	15	111.8	240.8	19.0	325.7
		30	109.6	215.1	12.4	497.7
		60	109.8	195.5	8.8	584.4

In all cases the three factors of salt temperature, residence time, and initial moisture content were found to have significant effects on the dependant variables. Regression equations were generated and these results are presented graphically in Figures 14-25. For each dependant variable considered, two response surfaces with salt temperature and residence time as independant variables are presented. The two response surfaces are for values of 13% and 23% initial soybean moisture content. In order to indicate the effect of moisture content over the range of levels, Figures 16,19,22 and 25 are also provided indicating the effect of initial moisture content at the two extreme levels of each of the other two independant variables.

Results for final temperature indicated that the linear effects were not significant at the .05 level, and only the cross-product effects of moisture content with salt temperature, and moisture content with residence time, were significant. The two response surfaces generated show very different behaviour; the surface at the lower moisture content shows a clear trend, as would be expected, of increasing final soybean temperature as residence time and salt temperature increase. However, at the higher moisture content, the soy temperature shows quadratic behaviour with salt temperature, having a minimum near 250°C. This effect is very small, however, and is not statistically significant. In general, as is shown by the graph of final temperature *vs* moisture content, the final temperature tends to converge towards a level of 110°C as the moisture content approaches 22-23% (wet basis). This can be attributed to the fact that the higher moisture bean is likely to experience greater moisture loss. This vaporization of water removes heat from the bean, lowering its temperature. Since the rate of vaporization becomes very high above 100°C, it is reasonable that the heat absorbed by the bean and the heat lost to water vaporization would reach steady state at some value of temperature slightly above 100°C. Thus it may prove very difficult to achieve higher bean temperatures than

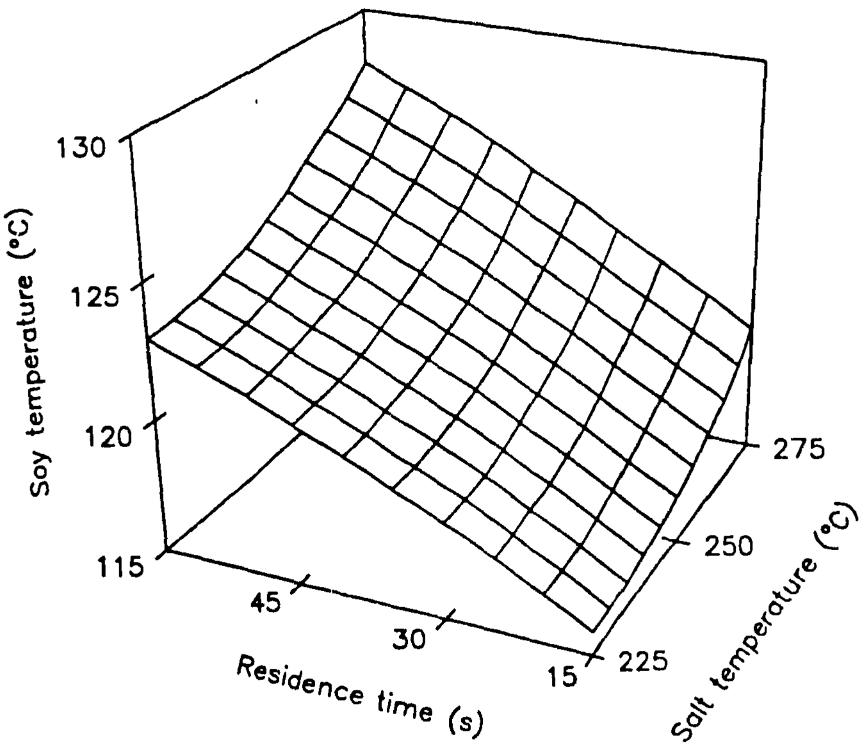


Figure 14: Variation of Final Temperature; M_i=13%

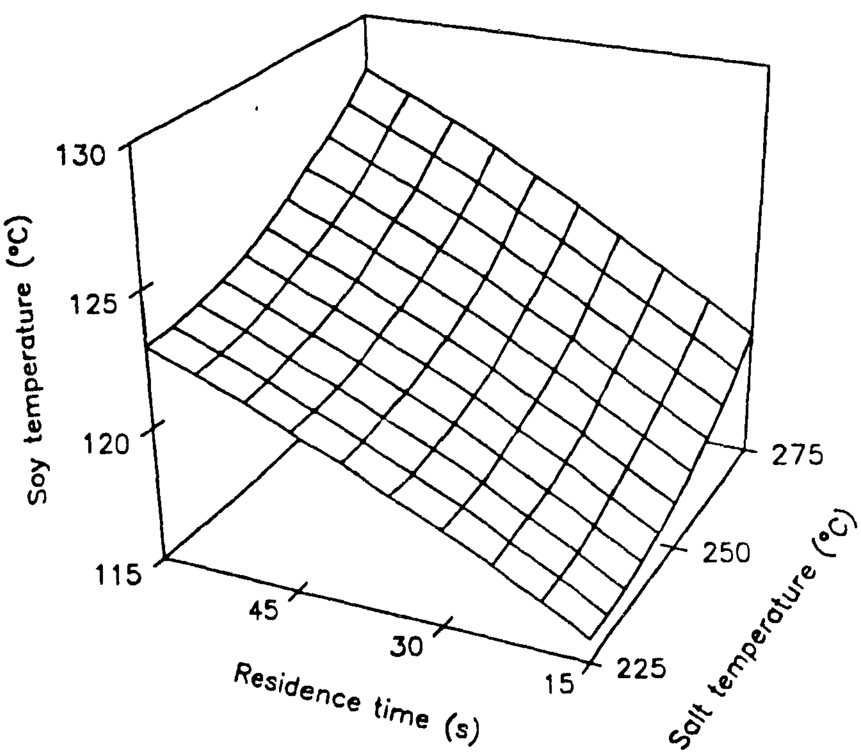


Figure 15: Variation of Final Temperature; M_i=23%

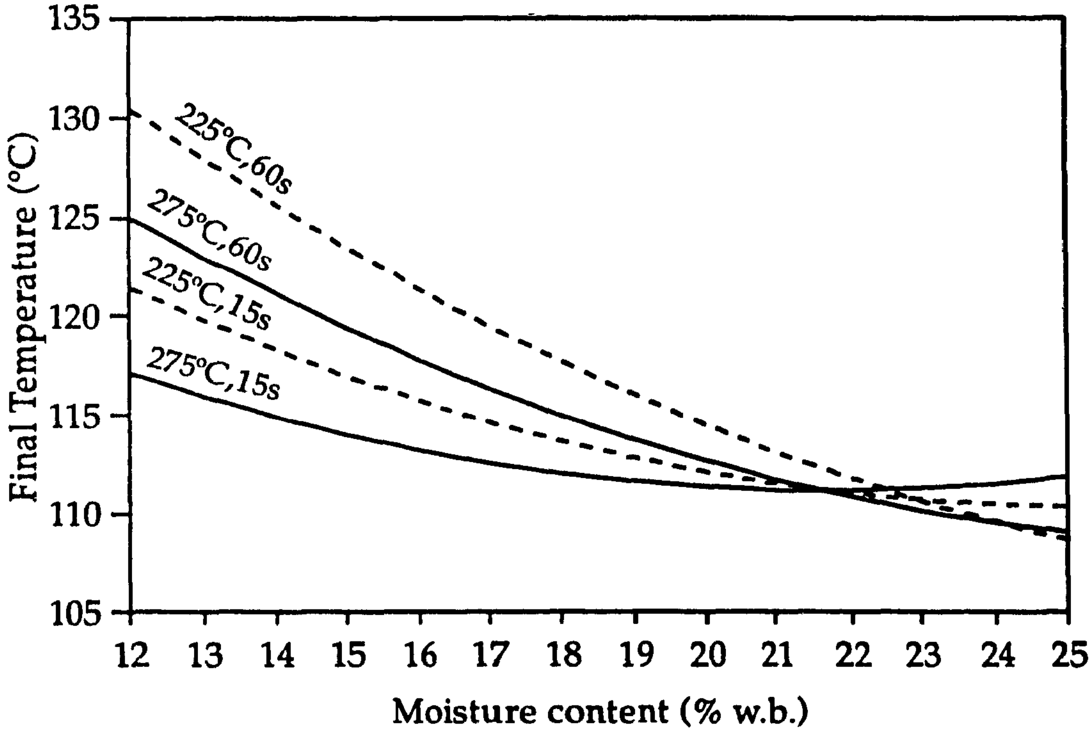


Figure 16: Variation of Final Temperature with Initial Moisture Content

110°C with high moisture soybean, unless the rate of heat transfer is increased considerably.

Temperature change was found to be significantly affected both linearly and quadratically by moisture content at the .01 level, and the cross-product effects of moisture content with both salt temperature and residence time were significant at the .05 and .01 levels, respectively. The graphs show similar behaviour as those for final temperature, with more pronounced quadratic effects of salt temperature and moisture content. Because a level heat transfer leads to a change in temperature rather than the attainment of a particular temperature, it was hoped that temperature change would show more consistent results than simply the final temperature, but this has not been the case.

The analysis of moisture change indicated a significant linear effect of initial moisture content, significant quadratic effects of moisture content and residence time (all at the .01 level), and significant cross-product effects of residence time with moisture content at the .01 level, and with salt temperature at the .05 level. The response surfaces show greater moisture loss with increasing salt temperature and residence time at both 13% and 23% initial moisture content. The graph of the effect of initial moisture content shows maximum moisture loss at levels of initial moisture content ranging from 19 to 22%. It is not clear why moisture loss would not continue to increase as initial moisture content increases. This effect cannot be discarded, as it is statistically significant, but it is difficult to explain.

The factors which were found to significantly affect total heat transfer were the same as those which affected moisture loss. This is due to the fact that of the heat transferred to the soybean, a very large part provided energy for the vaporization of moisture. This was particularly true at higher levels of all of the the independant

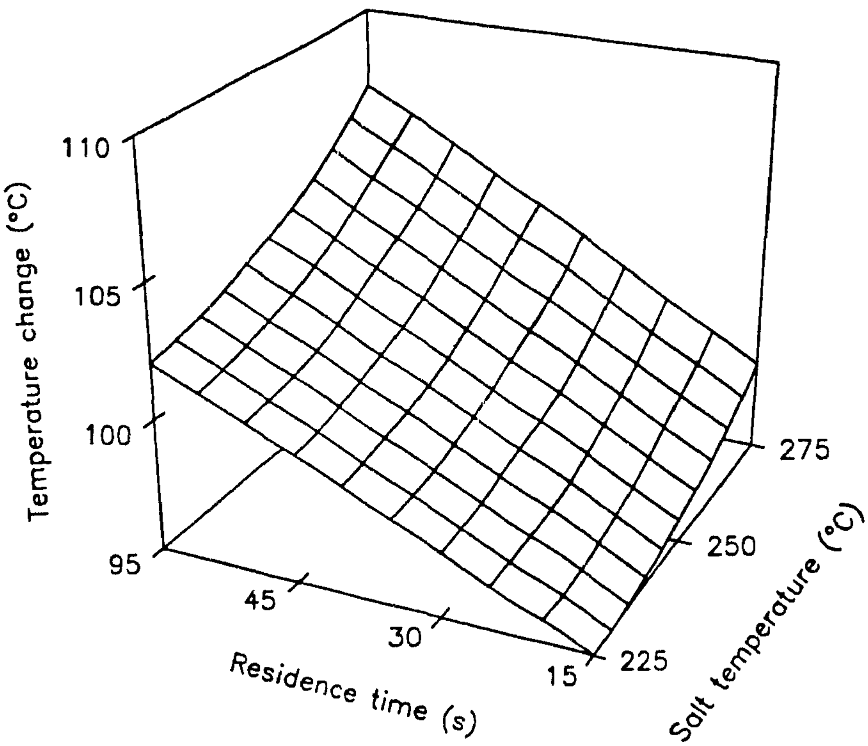


Figure 17: Variation of Temperature Change; M_i=13%

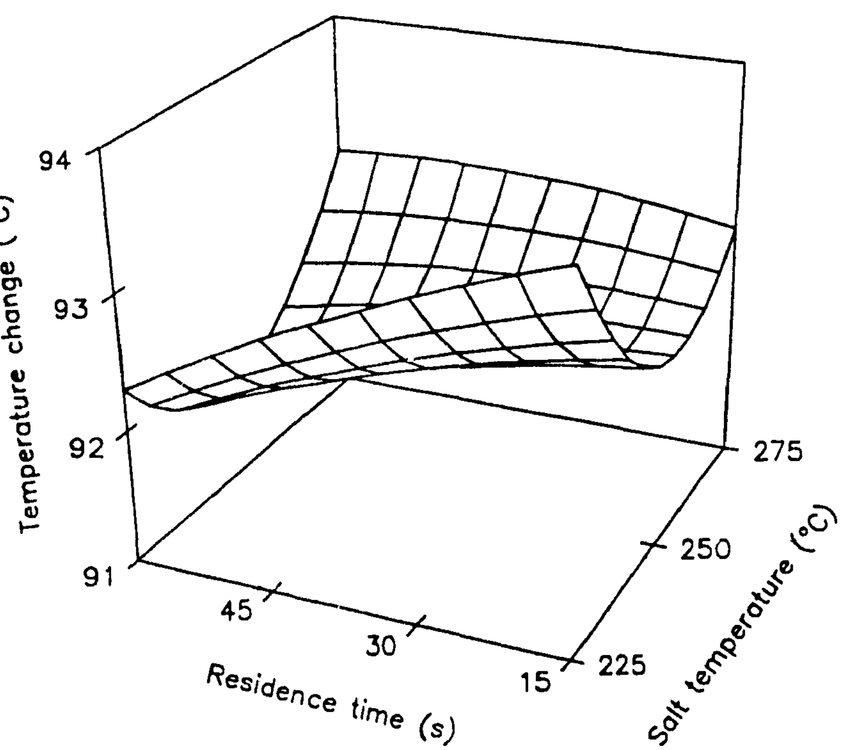


Figure 18: Variation of Temperature Change; M_i=23%

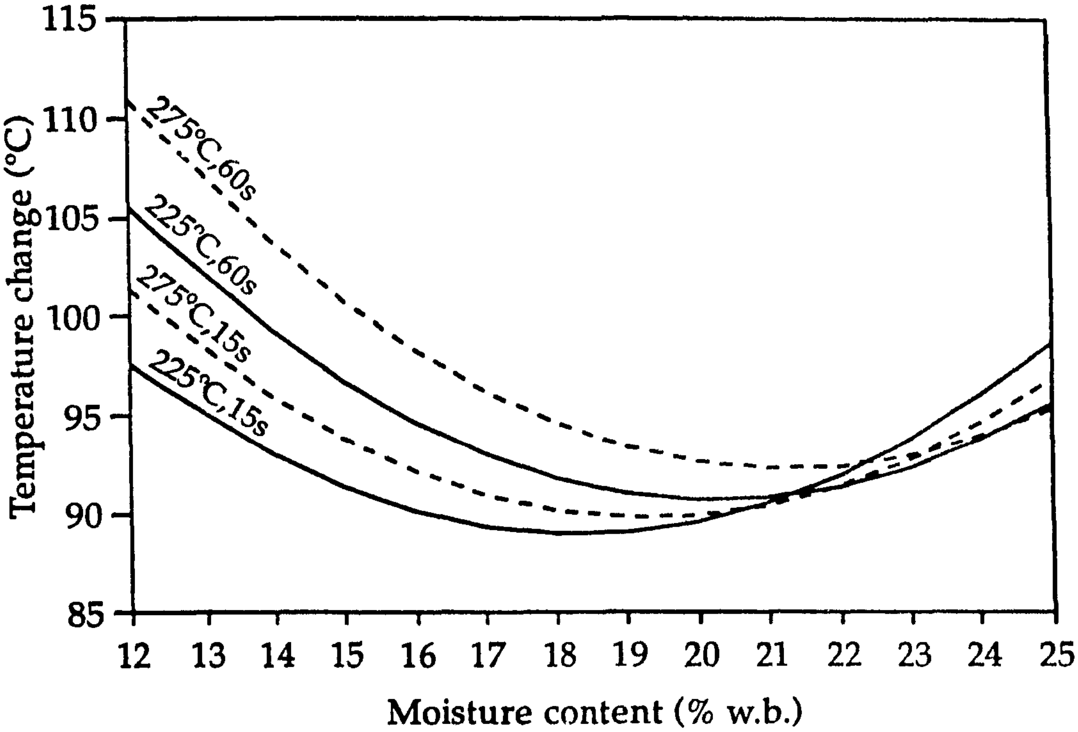


Figure 19: Variation of Temperature Change with Initial Moisture Content

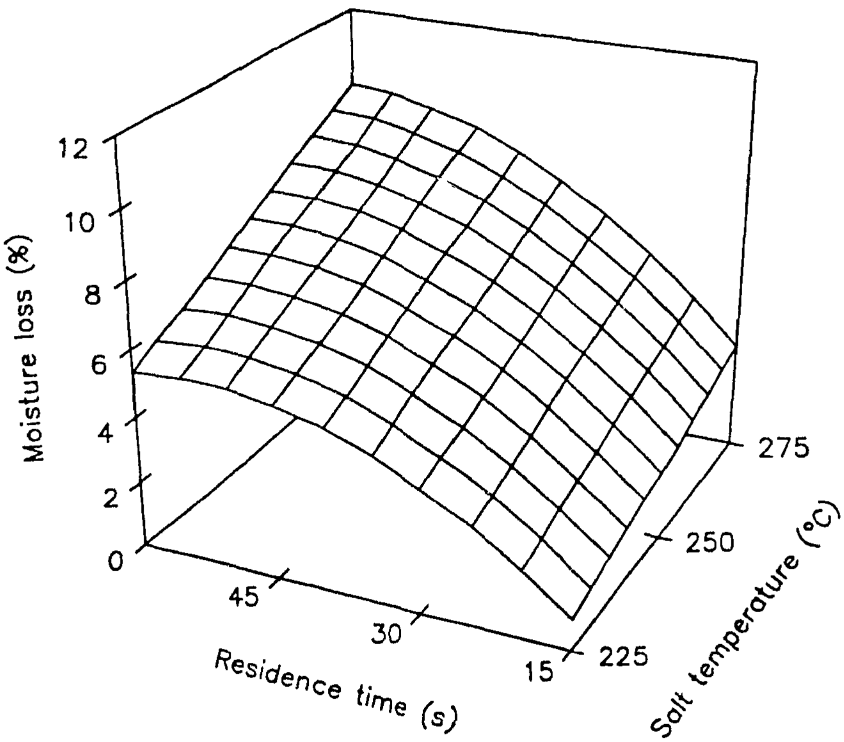


Figure 20: Variation of Moisture Change; M_i=13%

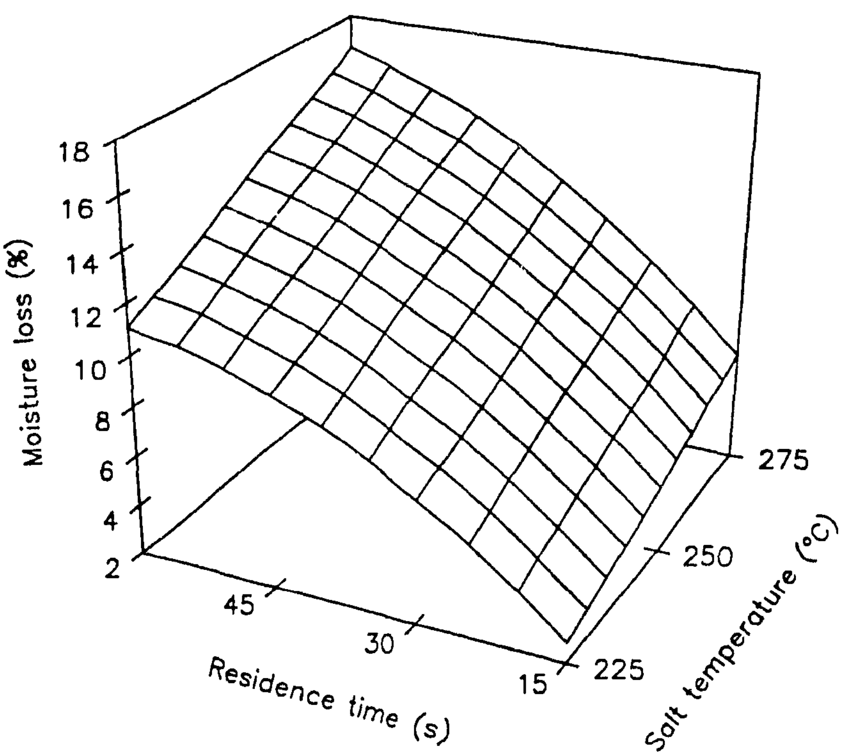


Figure 21: Variation of Moisture Change; M_i=23%

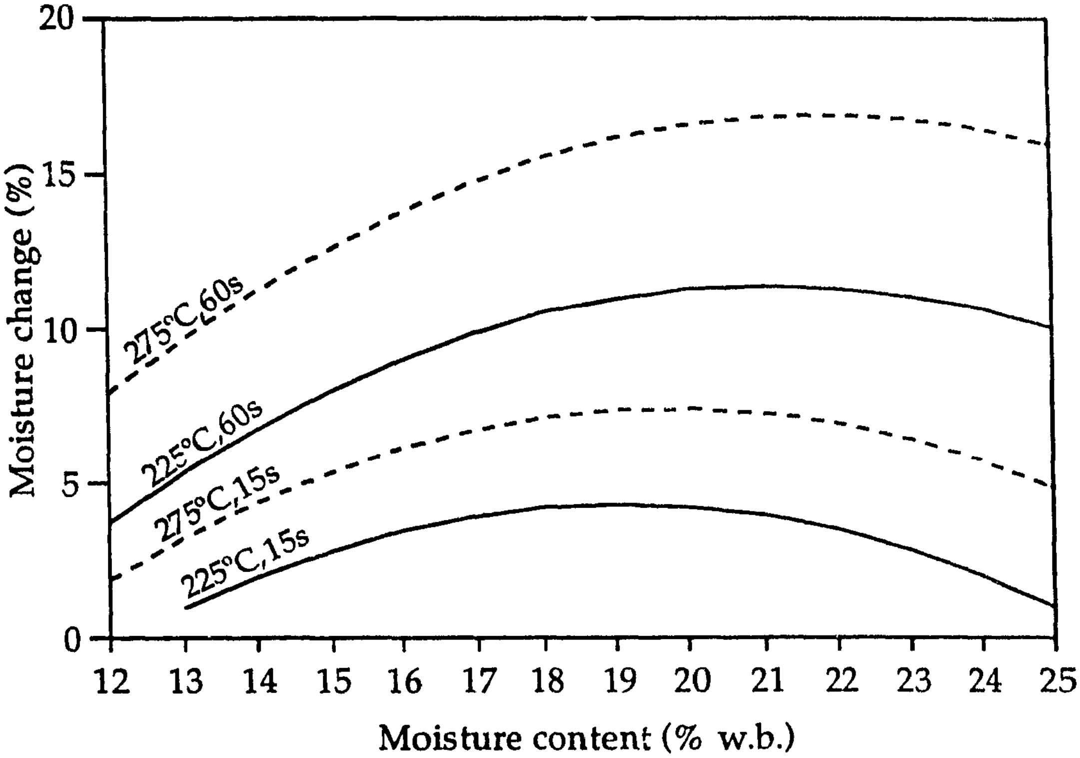


Figure 22: Variation of Moisture Change with Initial Moisture Content

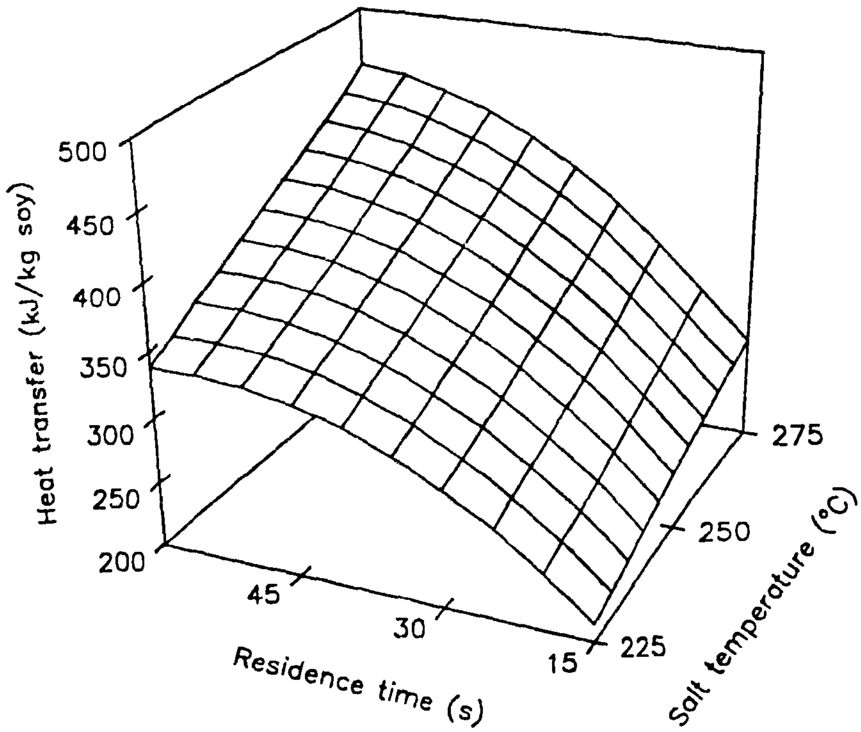


Figure 23: Variation of Heat Transfer; M_i=13%

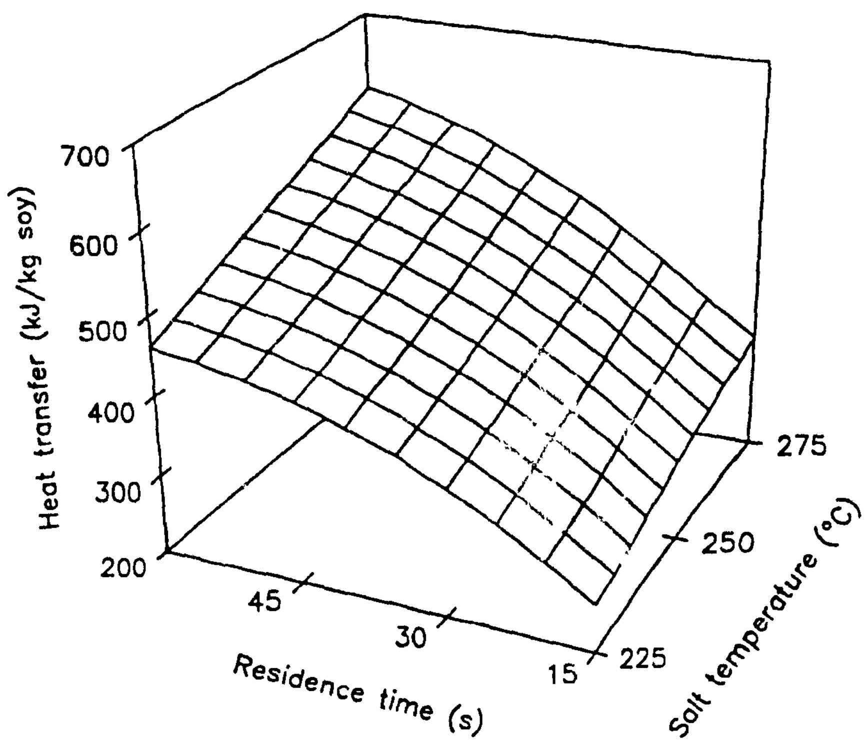


Figure 24: Variation of Heat Transfer; M_i=23%

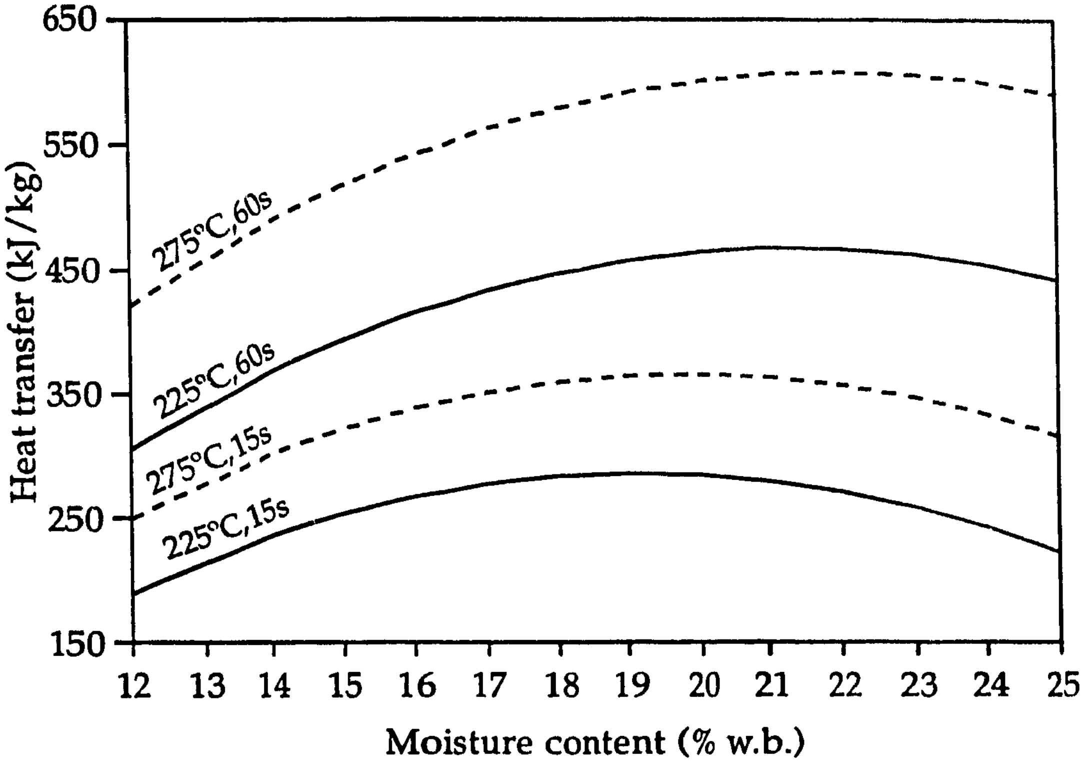


Figure 25: Variation of Heat Transfer with Initial Moisture Content

variables The graphs showing these results therefore demonstrate increased heat transfer with increased residence time and increased salt temperature. It can also be seen that heat transfer increases linearly with salt temperature, while the effect of residence time shows decreasing slope. This is because as the residence time increases, the temperature differential between the soybean and the salt decreases, and therefore the rate of heat transfer decreases The quadratic effect that was observed with moisture loss is also present for total heat transfer, and once again there is no clear explanaton for this.

In general, although some behaviours remain difficult to explain, the total heat transfer increases essentially as expected. It is more difficult to predict how this heat transfer will be divided between temperature gain in the soybean and moisture loss. This is further aggravated by the experimental procedure, which allowed some variation in the time allowed for moisture loss and subsequent decreases in temperature.

The temperatures achieved by the soybean in these experiments can be compared to the results of Alikhani et. al (1991). In this study, soybean was roasted in a small scale adiabatic rotating drum in batches. From the temperature results obtained from these experiments, the following equation was obtained from regression analysis;

$$\Delta T_g = 18(T_{s,i})^{.34}(Fo)^{11}(\alpha_s/\alpha_g)^{-.02}(SGMR)^{02}(M_i)^{-08} \qquad (26)$$

The form of this equation is taken from a similar equation developed by Sibley (1986) to describe temperature change in corn heated in a sand bed. This equation was applied to the data of the current study. The value of thermal diffusivity for soybean used was $1.26 \cdot 10^{-7}$ m^2/s, which was obtained from Watts and Bilanski (1973). The values of actual measured temperatures were plotted against the expected temperatures given by this equation. The graph of this comparison is shown in Figure 26. Although this graph demonstrates that the equation of Alikhani et. al. cannot be extended to this larger

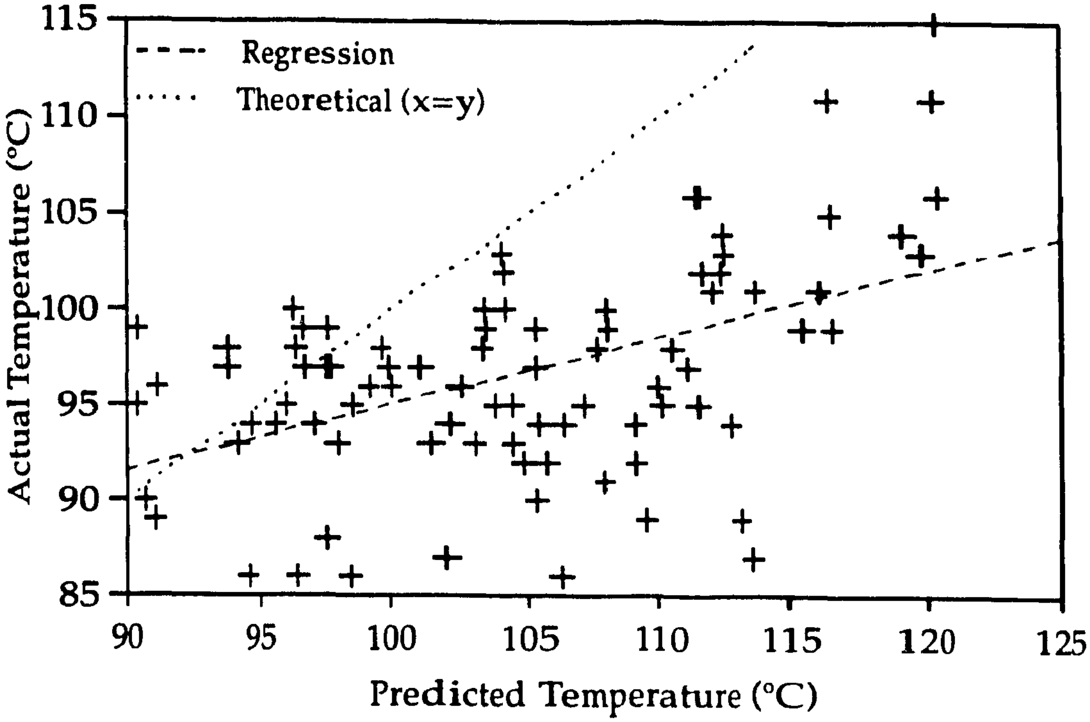


Figure 26: Actual *vs* Predicted Final Soy Temperature

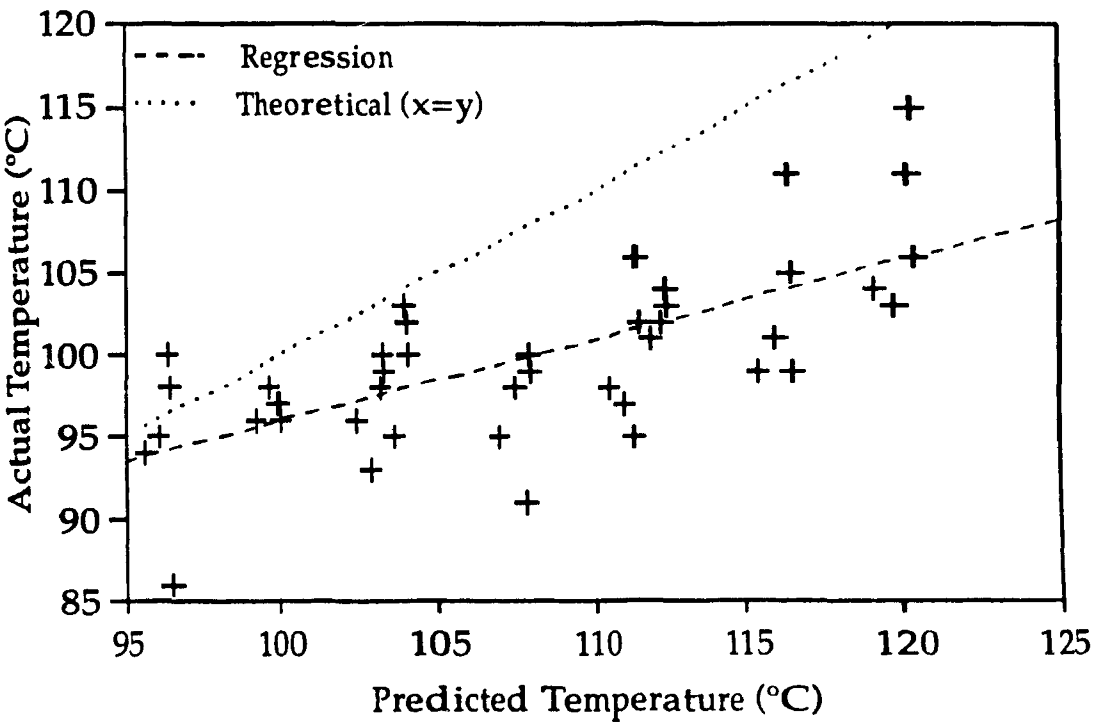


Figure 27: Actual *vs* Predicted Final Soy Temperature: Low Moisture Soybean

continuous machine, the data are not completely scattered, and show a somewhat consistently lower temperature than expected. However, as the value of r^2 for the regression performed was 0.24, this trend cannot be considered significant.

Because the temperature results for high moisture soybean showed very little variation as discussed earlier, another plot was created comparing the expectations of the equation with the actual results, but with these data removed. This graph is shown in Figure 27. In this case a more consistent trend can be observed with a somewhat higher r^2 of 0.48.

It is not surprising that the results for the continuous roaster show lower temperatures than those achieved in the adiabatic batch roaster. In the continuous roaster, the soybean is moved through the separation section and discharge chute for a period of time close to the residence time prior to being collected in the holding bin. It can be expected that moisture loss in this period results in a reduction in temperature.

As well, in the adiabatic tester, the drum speed, which will affect the amount of mixing, was held constant at an optimal level regardless of the residence time. In the continuous roaster, the machine speed is used to control the residence time. Therefore, for the longer residence times of 30 and 60 s, the level of mixing is reduced, and thus lower rates of heat transfer can be expected to occur.

It is therefore very difficult to predict temperatures achieved in this roaster using data from more controlled experiments.

4.2 Moisture Removal

The recorded values for moisture loss, while providing information about heat transfer, are also interesting in themselves as indicators of the potential of this machine as a drier as well as a roaster. McKenzie and Gottbrath (1971) have suggested that it may be advantageous to combine roasting of soybean with drying, and thus achieve a higher combined efficiency than can be achieved by performing the two operations separately. As can be seen in the data in Table 4, substantial moisture losses occur in the roasting process. For the soybean roasted at high moisture content, the moisture content after roasting was in many cases sufficiently low for long-term storage. The more complete data set in Appendix 1 shows the even greater moisture losses that were achieved with no additional energy input when the soybean was allowed to cool in ambient conditions. These results are highly variable, however, due to the variations in ambient temperature and relative humidity.

The moisture losses recorded without further air drying can be compared favourably to the results of previous studies in particulate medium drying of grains. In general, grain drying experiments have been performed with lower temperatures than those used in these roasting experiments, due to concern about the possible nutritional effects of high temperatures. However, since the objective in soybean processing is to modify nutritive qualities, higher temperatures can be used, which may lead to higher drying rates. The most relevant comparison is that of the results of Pannu and Raghavan (1984), who used the same processor as in this study. In that case, using sand rather than salt as the particulate medium, and processing corn rather than soybean, the maximum moisture loss without aeration was 5.32 percentage points with a residence time of 24.6 s and sand temperature of 235 °C. In the current experiments, the maximum moisture loss was acheived with a salt temperature of 275°C and residence time of 60 s. The greatest moisture loss in a single replicate at these levels was 16.6 percentage points, while the average of all five replicates was 14.2 percentage points.

Previous studies of particulate medium drying have generally acheived lower rates of moisture loss, and this may be attributable to the lower temperatures generally used, as well as the lower levels of SGMR. Table 5 gives a summary of these results.

Table 5: Moisture Losses achieved in Particulate Medium Drying Experiments

Study	Temp. (°C)	Res. time (s)	SGMR	ΔM
Lapp & Manchur (1974)	232	120	8:1	6.7
Tessier (1982)	*	41	*	4.5
Sibley (1984)	232	120	6:1	4.6
Pannu (1984)	235	24.6	*	5.3
Current	275	60	10:1	14.2

* data not provided

Considering the very high levels of drying achieved in these tests, and given that considerable energy is used by this drying whether or not it is desirable, it does appear that the optimal use of a roasting machine of the type used in this study would be for both roasting and drying.

4.3 Soybean Quality

While a large number of samples were collected at the different treatment levels, and with 5 replicates (a total of 360 samples), it was not possible, due to time limitations, to analyze all of these, and this has been left for a later study. However, in order to verify that this processor is capable of proper soybean roasting, and to determine an initial indication of the importance of the four different factors used in these experiments, a small number of samples was analyzed for trypsin inhibitor content and protein solubility. The samples analyzed were selected in order to give an indication of the maximum and minimum levels of treatment achieved, to indicate at least one level of treatment that produces soybean of the desired quality, and to examine the effects of varying a single factor while maintaining the other factors constant. The levels chosen were as shown with the results in Table 6, with a sample at both high and low moisture analyzed in each case.

Table 6: Results of Soybean Quality Analysis

Salt Temp. (°C)	Residence Time (s)	Holding Time (min)	Low Moisture		High Moisture	
			TIU/g	S.P.(%)	TIU/g	S.P.(%)
225	15	0	75.1	44.7	83.9	49.7
275	60	15	26.5	39.0	42.0	43.7
250	15	5	61.3	45 3	66.0	49.7
	30	5	49.3	43.4	63.3	48.1
	60	5	38.9	40.0	43.4	45.0
275	30	0	51.8	44.1	61.7	46.8
		5	49.5	42.4	53.8	47.1
		10	42.8	42.1	51.9	45.2
		15	36.5	41.8	45.2	45.0
225	30	5	63.5	43.9	68.3	49.7

The first two levels represent the highest and lowest treatment levels used, respectively. The treatments at 250°C were analyzed to give an indication of mid-range treatment, as well as to indicate the effect of residence time. The four treatments at 275°C and 30 residence time were analyzed to show the effect of holding time The levels of 275°C and 30 s were chosen because the optimum results in the study of Raghavan et. al. (1974) were achieved with 272°C temperature and 27 s residence time. The final sample was analyzed in order that the variation due to temperature with the other levels constant (30 s residence time, 5 min holding time) could be evaluated.

In each case, a single sample from a single replicate was analyzed. In order that the sample analyzed be as representative as possible of the data set, temperatures recorded in the holding bin were examined. Graphs of temperature vs. time over the 15 min holding time were produced, showing the temperature for all five replicates as well as the average temperature. Sample graphs for 275°C and 30 s residence time for both low and high moisture soybean are shown in Figures 28 and 29, and graphs for all treatment levels are given in Appendix 3. From these graphs, the replicate which behaved most similarly to the average was selected as the representative of that treatment level. This method was used rather than a comparison of the peak temperature achieved since there is some random error in the temperature data, and this examination of a longer term trend can be expected to be more reliable than data from single temperature readings. The graphs of temperature change in the holding bin show occasional erratic readings, which may be a result of instrument problems. Agitation of the bin when samples were removed at the 5 min and 10 min marks may also be responsible for erratic values in some of the data. Alternatively, it may have been desirable to select samples from a single replicate, in order to eliminate possible effects of variations between replicates, but this was not done since the variation in quality between replicates was not expected to be systematic, and would in any event likely be due to different average temperatures achieved.

In examining the results, it is first of all necessary to determine if the levels of trypsin inhibitor destruction are sufficient to ensure proper nutritive quality. This can be done by comparison of the results of previous studies which included feeding trials. Due to the variety of units used in the measurement of trypsin inhibitor content, comparisons will be made on the basis of a percentage of the trypsin inhibitor in untreated soybean for each study. Borchers and Manage (1972) acheived optimum growth in rats with dielectric heated soybean when the trypsin inhibitor level was 30% of its original level (61 *vs* 193 TIU/g). Herkelman et. al. (1991) found optimum growth

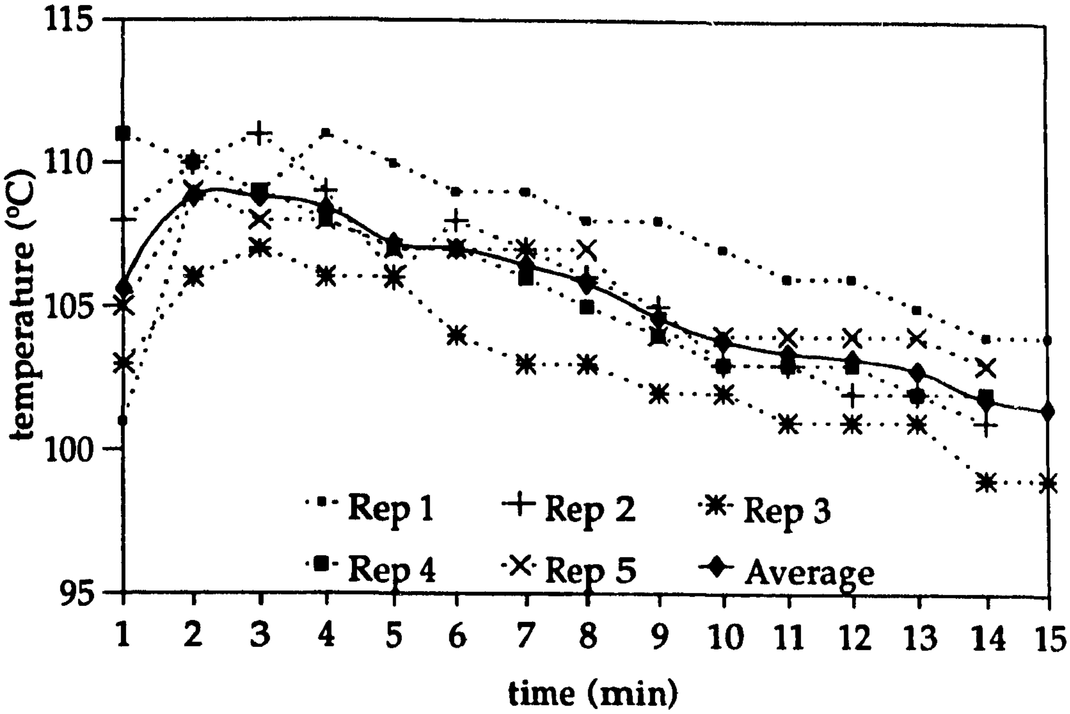


Figure 28: Temperature Variation in Collecting Bin for 275°C, 30 s Treatment, Low Moisture Content

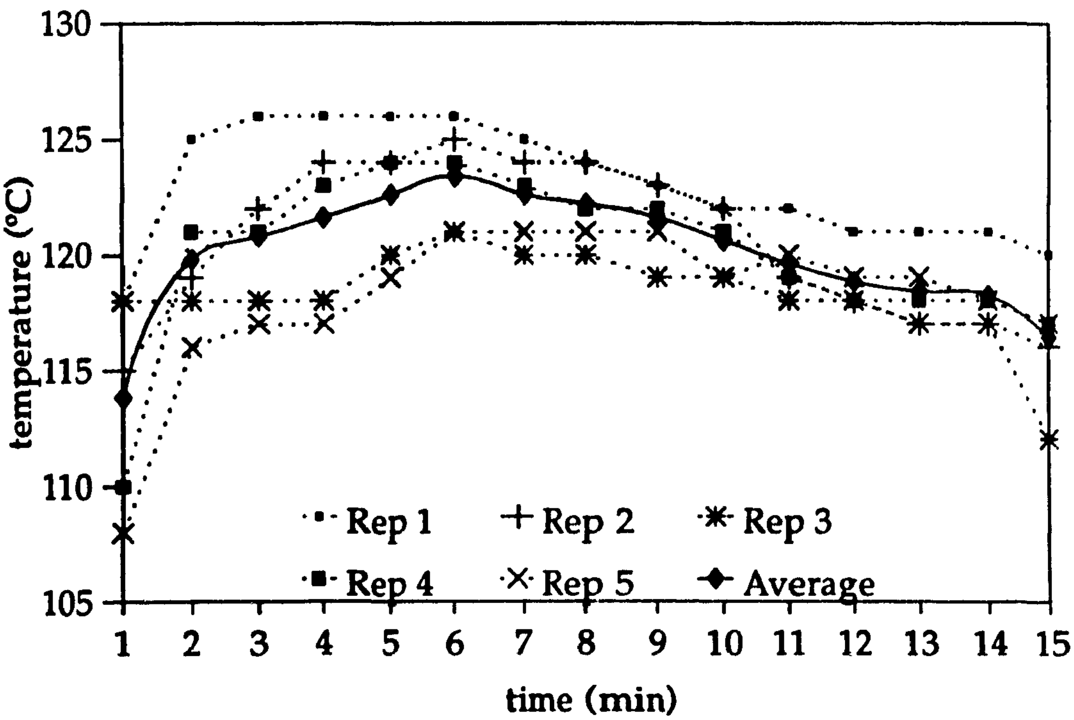


Figure 29: Temperature Variation in Collecting Bin for 275°C, 30 s Treatment, High Moisture Content

of chicks fed autoclaved whole soybean when the trypsin inhibitor level was 8% of the level in unheated soybean (2 *vs* 24 mg/g). In a study of soybeal meal treatment, McNaughton et. al. (1981) found best growth when the trypsin inhibitor level was 15% of the unteated level (1.77 *vs* 12.12 μg trypsin inhibited per mg protein). In the current study, trypsin inhibitor levels raged from 20% (26.5 TIU/g) to 63% (83.9 TIU/g) of the levels in the untreated control (134.0 TIU/g). Thus it cannot be guaranteed that the trypsin levels are sufficiently low, although they are within the range of levels found by the previous studies. Certainly the higher trypsin inhibitor levels are too high for animal feeding. Further studies will be required, with feeding trials, to determine whethter or not the treatments acheived are adequate, and such studies should focus on the highest levels of treatment of this experiment, along with even higher levels. It should be noted, however, that despite the high levels of trypsin inhibitor from these treatments, very similar treatment levels used in the experiments of Raghavan et. al. (1974) were used in diets which resulted in good chick growth.

As with the trypsin inhibitor, soluble protein results can be compared to the levels in untreated soybean. In the study of Araba and Dale (1990), it is suggested that soluble protein levels should not fall below 75%. In this study, soluble protein ranged from 84% to 107% of the soluble protein value of the untreated sample. As Araba and Dale have not reported any cases of an increase in soluble protein with treatment, and all protein solubility levels greter than that of the control are from high moisture soybean, it is not clear whether treatment has actually increased soluble protein or a systematic error is present. In either case, it can be stated that for all treatment levels of this experiment, the protein solubility has not been sufficiently reduced to conclude that overprocessing has occurred.

Although the effects of each factor (salt temperature, residence time, and holding time) on the trypsin inhibitor levels and protein solubility cannot be tested for statistcal significance, the analysis does allow some comparison to determine if trends are evident. Graphs showing the effect of each of these factors are shown in Figures 30, 31 and 32. In each case it can be seen that both protein solubility and trypsin inhibitor activity decline with an increase in the temperature or time.

In order to test the hypothesis that the extent of heat treatment can be expected to be a result of the temperature achieved in the soybean, graphs were plotted of the variation of soluble protein and trypsin inhibitor with final soybean temperature. Due to the different temperature levels involved, as well as the possible confounding effect of moisture content, different graphs were plotted for low and high moisture contents. In all cases, data were limited to those treatments for which the holding time was 5 minutes. These graphs are shown in Figures 33 and 34. For the graph of low moisture soybean, trypsin inhibitor content and soluble protein are seen to decrease with increased temperature, which is as expected. However, the variation in the data is greater than that in the graphs of salt temperature and residence time, indicating that these are likely to be better indicators of the effectiveness of treatment than final temperature. The graph of the effect of final temperature for high moisture soybean shows an opposite trend; increasing soluble protein and trypsin inhibitor with increasing temperature. This result shows a high correlation of r^2=.96, but is contrary to what would be expected. This cannot be explained, but may be the result of experimental error.

A comparison of trypsin inhibitor activity to soluble protein was performed in order to determine whether or not a strong correlation exists. This comparison is shown in Figure 35. The value of r^2 for the regression is .65, indicating that soluble protein is not a sufficiently strong indicator of trypsin inhibitor content, although it is a statistically significant factor ($p<.01$). However, if protein solubility is not strongly correlated to trypsin inhibitor content, it may be possible that certain types of treatment may have less effect on protein solubility than others while having the same effect on trypsin inhibitor activity. An example of this is that longer treatment at lower temperature may be preferable to rapid treatment at high temperature (or vice versa), although trends of this type cannot be discerned from the present data.

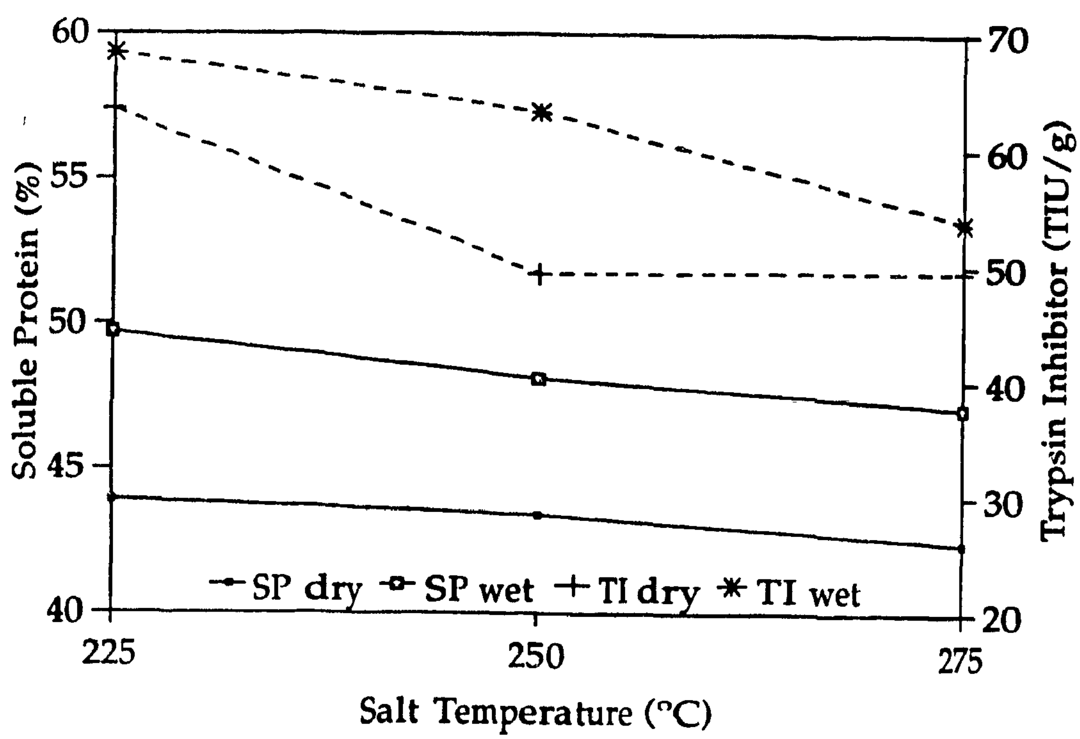


Figure 30: Variation of Soluble Protein and Trypsin Inhibitor Activity with Salt Temperature

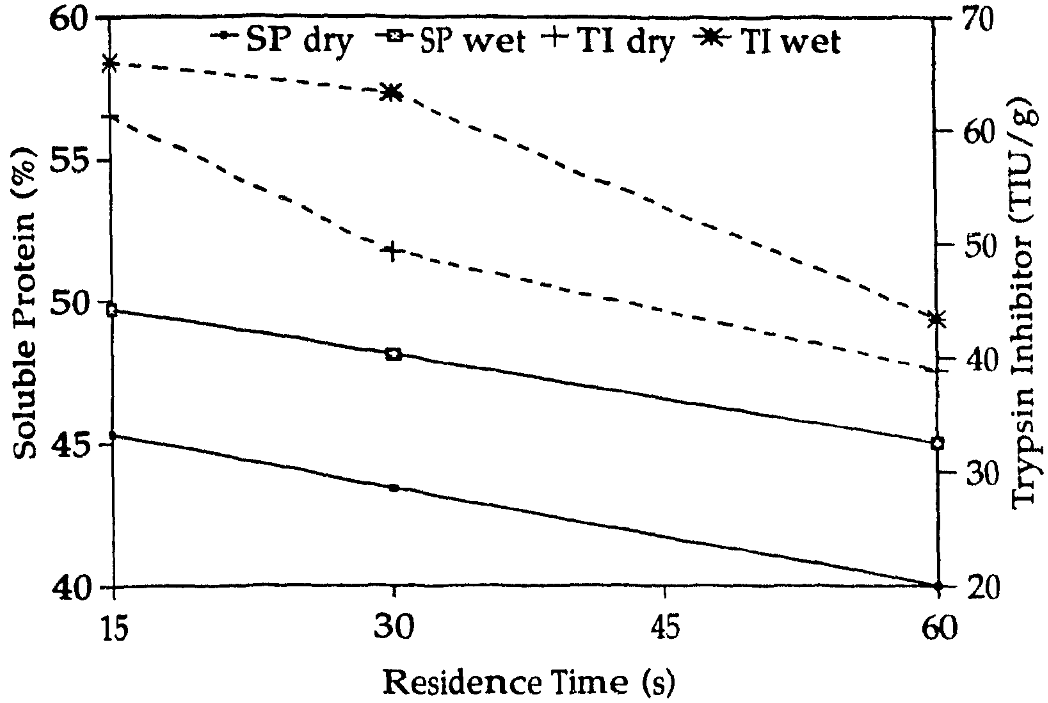


Figure 31: Variation of Soluble Protein and Trypsin Inhibitor Content with Residence Time

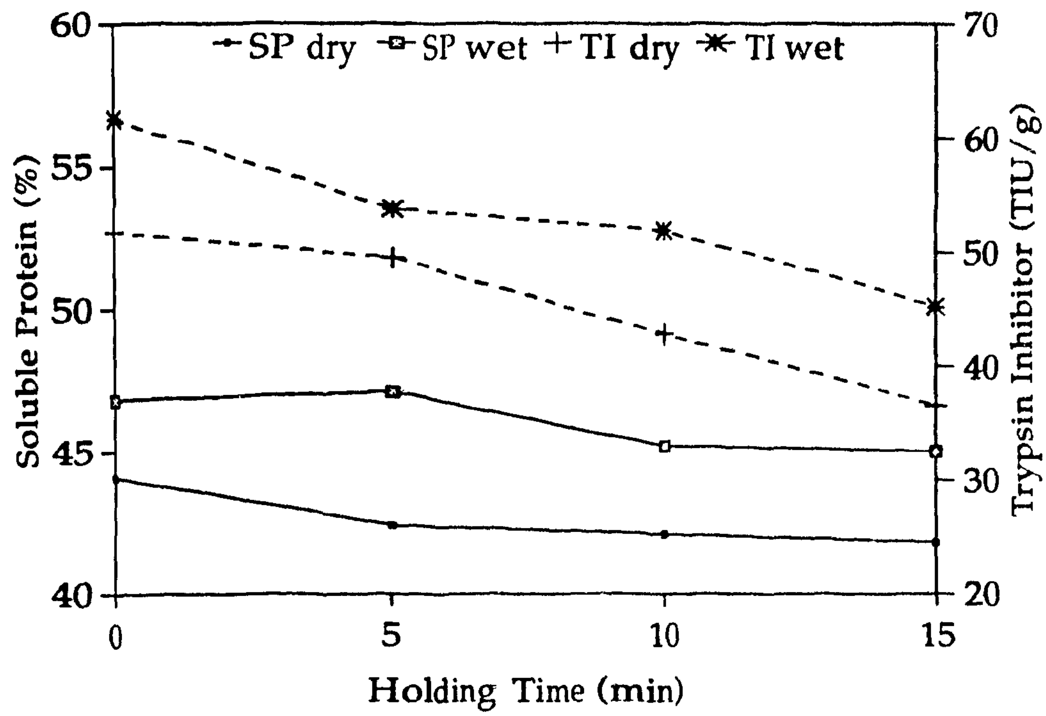


Figure 32: Variation of Soluble Protein and Trypsin Inhibitor Content with Holding Time

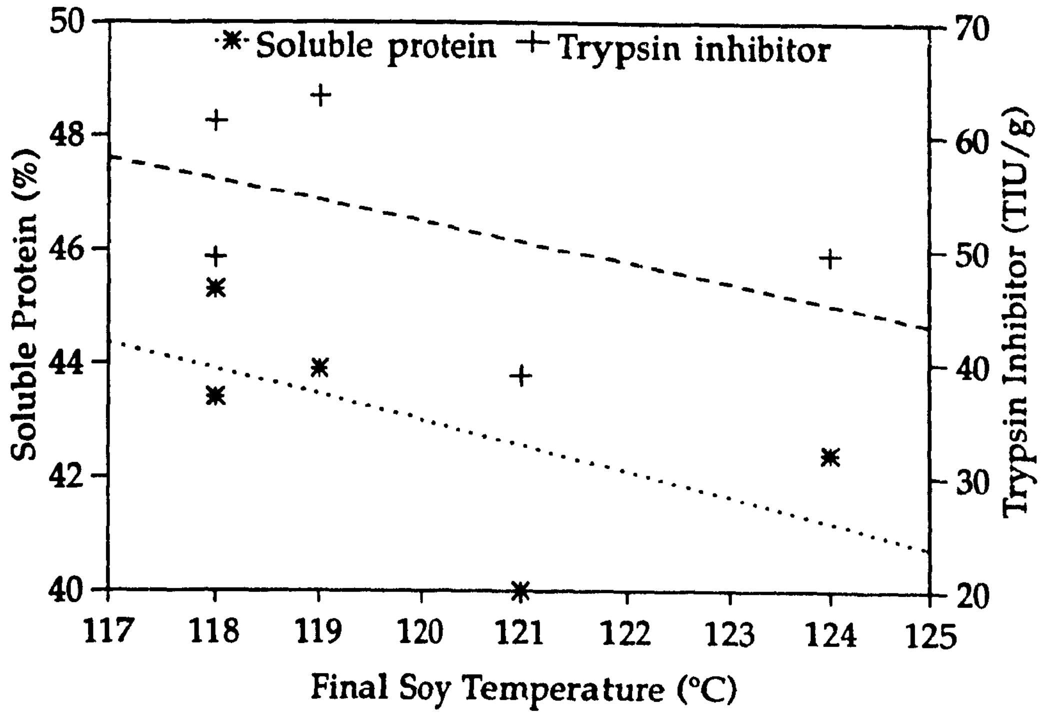


Figure 33: Variation of Soluble Protein and Trypsin Inhibitor Activity with Final Soybean Temperature; Low Moisture Content

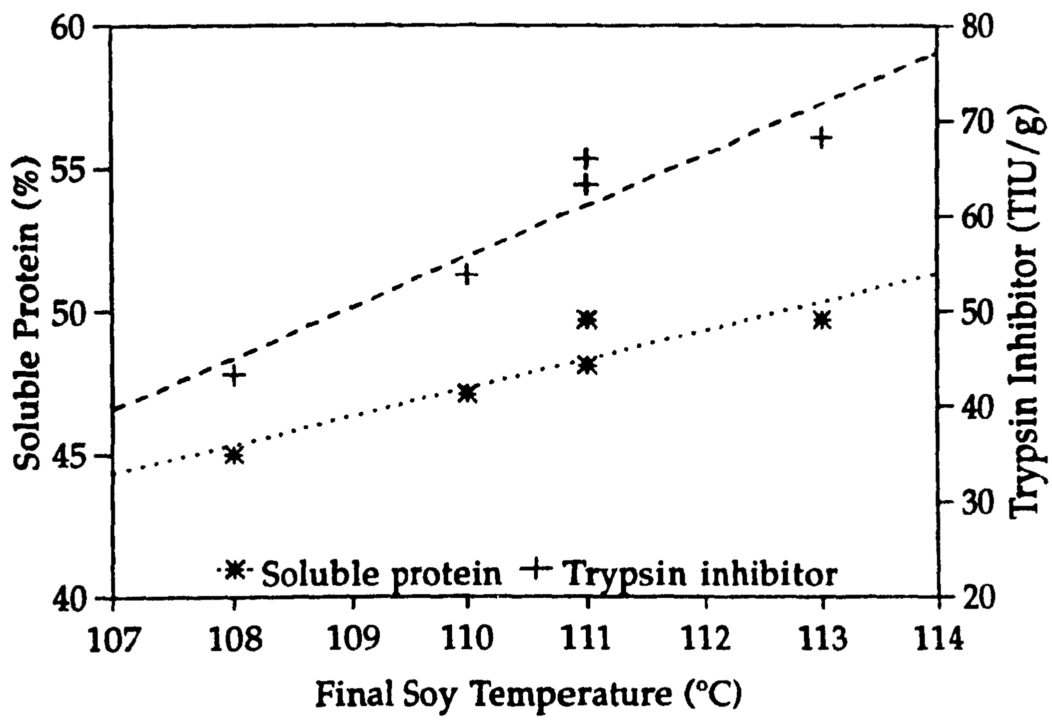


Figure 34: Variation of Soluble Protein and Trypsin Inhibitor Activity with Final Soybean Temperature; High Moisture Content

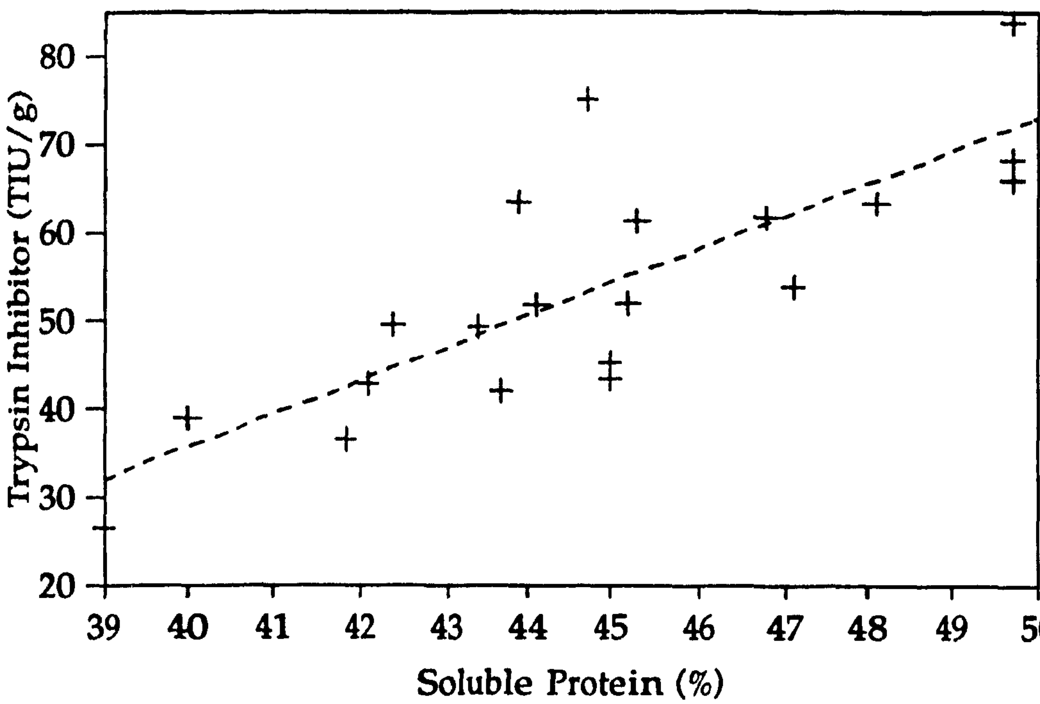


Figure 35: Variation of Trypsin Inhibitor Activity with Soluble Protein

4.4 Machine Performance

4.4.1 Energy efficiency

In order to evaluate the energy efficiency of the machine, a set of experiments was performed specifically for that purpose separate from the main set of experiments. This was done because of limitations in the amount of data that could be recorded during the main experiments, particularly when the operator was required to manually control fuel flow to the machine in order to maintain as constant a temperature as possible. This constant modification of the fuel flow rate made it impossible to accurately record the amount of fuel being supplied. However, by performing a separate set of experiments, it was possible to focus on recording energy input and maintain more constant energy input while allowing the temperature of the salt to fluctuate somewhat.

A total of 5 experiments were performed with the same batch of rewetted soybean at 26% moisture content. For all experiments, the temperatures of the salt entering the mixing section (point A in Figure 9), the salt entering the combustion section (point F) and the temperature in the holding bin, were recorded every 15 s. As well, triplicate samples of soybean were taken from the discharge chute for moisture content determination. Sample of soybean were also taken from the discharge chute, and from the holding bin after 5 min holding time, and placed in cooling trays for air drying.

The first two experiments were performed with the objective of determining efficiency at the conditions of 30 s residence time and 275°C salt. These levels were chosen both because of indications from an earlier study (Raghavan et. al. 1974) that this was an appropriate level for proper roasting, as well as the fact that the fuel flow required to maintain steady state at higher speed (15 s or 20 rpm) was beyond the range of the flowmeter used to measure fuel flow. Higher flow rates were not only outside the range of the flowmeter, but also produced a flame which was larger than could be contained within the combustion section of the machine. As a result of this, the flame would extend out of the entry end of the machine. Therefore, part of the combustion was occurring outside of the machine and efficiency would clearly be very low. Since this problem would have to be solved in any further developements of a machine of this type, efficiency tests would have to be done at levels where this does not occur in order to accurately reflect the potential of this machine.

These first tests showed, however, that even the reduced speed required fuel flow slightly beyond the range of the flowmeter. In both cases, the temperature of the salt declined to about 265°C with the fuel rate at its highest measurable value. However, steady state was achieved at this temperature, and thus these data are useful for analysis. For the third and fourth tests, the target salt temperature was 250 °C, which could be maintained with some consistency and minimal manipulation of the fuel flow. The final test was performed with no manipulation of the fuel flow; rather, the fuel was set at the maximum measurable level and the machine was allowed to come to a steady state temperature.

For each experiment, the energy output, in heat gain and moisture loss by the soybean were calculated. The energy input was determined using calibration data for the flowmeter supplied by the manufacturer, and multiplying the mass rate of propane supplied by the heat value of propane (46 000 kJ/kg). An overall efficiency could then be determined by simple comparison of the useful energy output to the energy input as given by;

$$\eta = \frac{\dot{m}_g C_p \Delta T + \dot{m}_w \Delta h_v}{\dot{m}_p \Delta h_p} \qquad (27)$$

Where;

m_g = mass flow rate of grain (kg/s)

C_g = heat capacity of the grain (kJ/kg°C)

ΔT = temperature change of the grain (°C)

m_w = rate of water vaporation from the grain (obtained from $m_g \cdot \Delta M$, where ΔM is calcuated from equation #24)

Δh_v= heat of vaporation of water (kJ/kg)

m_p = mass flow rate of propane to burner (kg/s)

Δh_p= heat of combustion of propane (kJ/kg)

The values of efficiency for the five runs, with efficiency divided into heating and drying efficiencies, are given in Table 7. It can be seen that the heating efficiencies are very low, but when combined with the drying efficiency, better overall efficiency is achieved. This again confirms the considerable advantage to be gained by combining drying with roasting of soybean.

Table 7: Results of Efficiency Tests

Run #	$m_g C_g \Delta T$	$m_w \Delta h_v$	$m_p \Delta h_c$	Efficiency (%)		
				heating	drying	overall
1	2.77	5.26	15.96	17.3	33.0	50.3
2	2.77	5.04	18.55	14.9	27.2	42.1
3	2.83	3.83	15.96	17.7	24.0	41.7
4	2.87	3.73	17.09	16.8	21.8	38.6
5	2.87	4.33	18.55	15.5	23.3	38.8

Although energy data is not available on all of the methods of soybean roasting described earlier, McKenzie and Gottbrath (1971) do provide sufficient data for the Roast -a-Tron and Brady Crop Cooker from which to make an evaluation of efficiency. For the

Roast-a-Tron, the processing rate is 340 kg/hr, and the energy use is 265 MJ/hr. The Brady Crop Cooker processes 900 kg/hr with power of 150 hp supplied from a tractor PTO. As the Brady Crop Cooker requires the use of a tractor, the efficiency of the tractor engine must be taken into acount, and can be estimated at 30% With this data, the efficiencies of these two machines are then 23% and 12% respectively. Thus the performance of the processor used in this study is within the range of other soybean processors.

In order to more closely determine the source of inefficiencies in the machine, the temperature of the salt as it enters the combustion section was compared with the theoretically computed salt temperature. This temperature was calculated by assuming that heat loss by the salt is exactly equal to heat gain by the soybean The calculated and measured values of salt temperature are shown in Table 8. With the exception of the first run, the actual salt temperature change was greater than the calculated value. As the calculated temperature change is proportional to the heat aquired by the soybean, and measured temperature is proportional to heat lost by the salt, a comparison of the two gives a value for the efficiency of heat transfer from salt to soybean. These efficiency values are also given in Table 8. With the exception of the first run, with an efficiency of 108%, which is clearly impossible and must be discarded, the efficiencies are approximately 90%. Therefore, heat losses in the mixing, separation, and return sections is relatively small, and the greatest cause for the inefficiency of the machine would be the combustion section. Pannu (1984) reported that Mayfield (1974) found that fuel efficiency of heat transfer from a flame to a particulate medium in a flighted rotating drum of this type was about 65%. If an efficiency of 65% were achieved in the combustion section, and an efficiency of 90% achieved in the remaining sections of the machine, the overall efficiency of this machine would be about 58%. As the efficiencies found in this study are approximately 40%, it should be possible that improvements in the design of the combustion section can be made to improve the efficiency.

Table [illegible] Calculated and Measured Temperature Change for the Salt

Run #	ΔT_m Calculated	ΔT_m Measured	η (%)
1	58.0	53.7	108
2	56.4	61.7	91
3	48.2	53.2	91
4	[illegible]	55.1	87
5	[illegible]	56.6	92

While the design of [illegible] to be an important factor in efficiency, the supply of air to the flame may also [illegible] had an important impact on the efficiency in these experiments. If too much air is being supplied, this will reduce the efficiency of the machine, as an excess amount of gas will be heated, and the average temperature of the flame will be reduced, causing lower rates of heat transfer. If an insufficient amount of air is supplied, incomplete combustion will occur.

4.4.2 Problems Encountered

Several problems were encountered in the operation of this machine, some of which were outlined in the discussions of the apparatus and the machine efficiency.

As discussed above, some loss of the particulate medium occurs at the exit end, as the cascading material falls out of the end. Although small losses of this type are not serious, it would be preferable to minimize these losses.

When operating the machine at the highest speed in these experiments, the flame required to supply the heat could not be contained by the combustion cone. The flame would start to extend out of the entry end of the machine. This is due not only to the inadequate size of the combustion cone, but also to the fact that there is no path by which the exhaust can leave through the exit side of the machine, and the exhaust gases are therfore forced to return to the entry end.

Within the combustion section, a build-up of salt developed on certain surfaces. Although it is not certain which surfaces were affected since most of the interior of the machine is not visible, deposits could be seen on the helix inside the combustion section. A photograph of the interior of the combustion section is shown in Figure 36, which shows that the helix at the back is covered in salt. Deposits of this type can not be seen on other surfaces. Occasionally, these deposits would break loose, usually due to temperature changes at start-up or shut-down. Several of these clumps were collected and a sample is shown in Figure 37 with a 30 cm ruler for size comparison. It is not clear how these clumps formed, although one likely explanation is that since the flame touches the helix, the surface may become sufficiently hot for the salt to melt slightly and bond. This is not necessarily a problem if sand or zeolite are to be used in the machine; however, if salt is to be used, surfaces should not be in direct contact with thew flame. It is also possible that moisture has caused these salt deposits, since the salt comes into contact with considerable moisture, and salt will bond to surfaces if sufficiently wet. The pattern of the deposits could be explained by the fact that the salt would dry as is enters the combustion section and thus become bonded to the surfaces which it is in contact with when it dries.

The bearings which support the machine on the entry end are subjected to high temperature because they are located inside the combustion section. This has led to failure of the bearings. Moreover, the fact that the machine rotates around a central axis, but is suspended from two different axles (one at each end of the machine), has resulted in the two axles becoming somewhat out of alignment, causing the machine to flex as it turns. This not only stresses the entire machine, but also leads to stress on the bearings, which may have also contributed to the failure of the bearings.

Figure 36: View of Interior of Combustion Section

Figure 37: Salt Clumps Formed in Processor

4.5 Machine design

Due to the above-mentioned problems with the existing processor, several modifications of the existing design can be suggested. A modified design has been developed in order to illustrate these points, and is shown in Figures 38 and 39. The following list outlines the new design, and explains its advantages relative to the existing machine. The basic design of the machine remains the same; the following are merely modifications which arise from the experience of using the machine.

The conical shape of the machine was not found to provide any great advantage, and considerably complicates the construction of the machine. Thus it is recommended that a future design use cylinders in place of cones 1 and 2 (referring back to Figure 9). The slope of cone 1, which is important in order to move the particulate medium towards the front of the combustion section, can be replaced by placing the entire machine on an incline. In the current machine, the volume per pitch in the mixing section increases as the grain progresses through the machine. This may provide space for expanding gases and vaporizing H_2O; however, by providing sufficient volume in the mixing section throughout, it would be possible to ensure that expanding gases can escape by passing between the salt bed and cone 1.

Problems with efficiency in the combustion section could be resolved by lengthening the combustion section, which would allow the fuel to burn completely within the machine, as well as providing a greater space for heat transfer between the salt and the flame to occur. This can be done both by lengthening the machine, and by placing the burner slightly outside of the entry end of the machine, with the flame covered such that the flame is guided into the machine. As well a path for escape of the exhaust gases is needed at the discharge end.

In order to reduce the problems resulting from the fact that the machine is suspended on a central axis, it is suggested that it would be preferable to have the machine rotate on rollers which support it on the exterior. This would also eliminate the need for rigid stuctural members connecting the machine to the central axis, which inhibit access to the inside of the current machine.

It has been mentioned above that the particulate medium was seen to spill from the machine at the exit end, and that some heat losses occur in this area The modified design reduces these problems by closing off the return section from the environment, eliminating salt losses and drastically reducing heat losses. This has required a redesign of the return section, using a design more like that of Khan et. al. (1973). This design involves the use of scoops to draw the salt into the central section. Greater detail on these scoops is shown in the perspective drawing of a quarter of the return section in Figure 39. As the machine rotates (counter-clockwise), and a scoop passes through the 4 o'clock position, the scoop picks up salt and the salt is drawn towards cone 2 A passage connecting cone 1 and cone 2 (one passage for each scoop) allows the salt to pass through from the return section to the combustion section In the figure, the inner section between cones 1 and 2 (through which the soybean passes) is shown separated from the outer section between cones 2 and 3 (in which the separated salt collects, and the scoops return it to the combustion section). This is done for clarity, the two sections of the drawing fit together as indicated by the broken lines

The design shown, with the given dimensions, was designed for a processing rate of 300 kg/hr of 23% moisture soybean. This machine could also be modified for use in other heat treatment applications such as grain drying. The residence time can be modified as needed by changing the pitch in the helix.

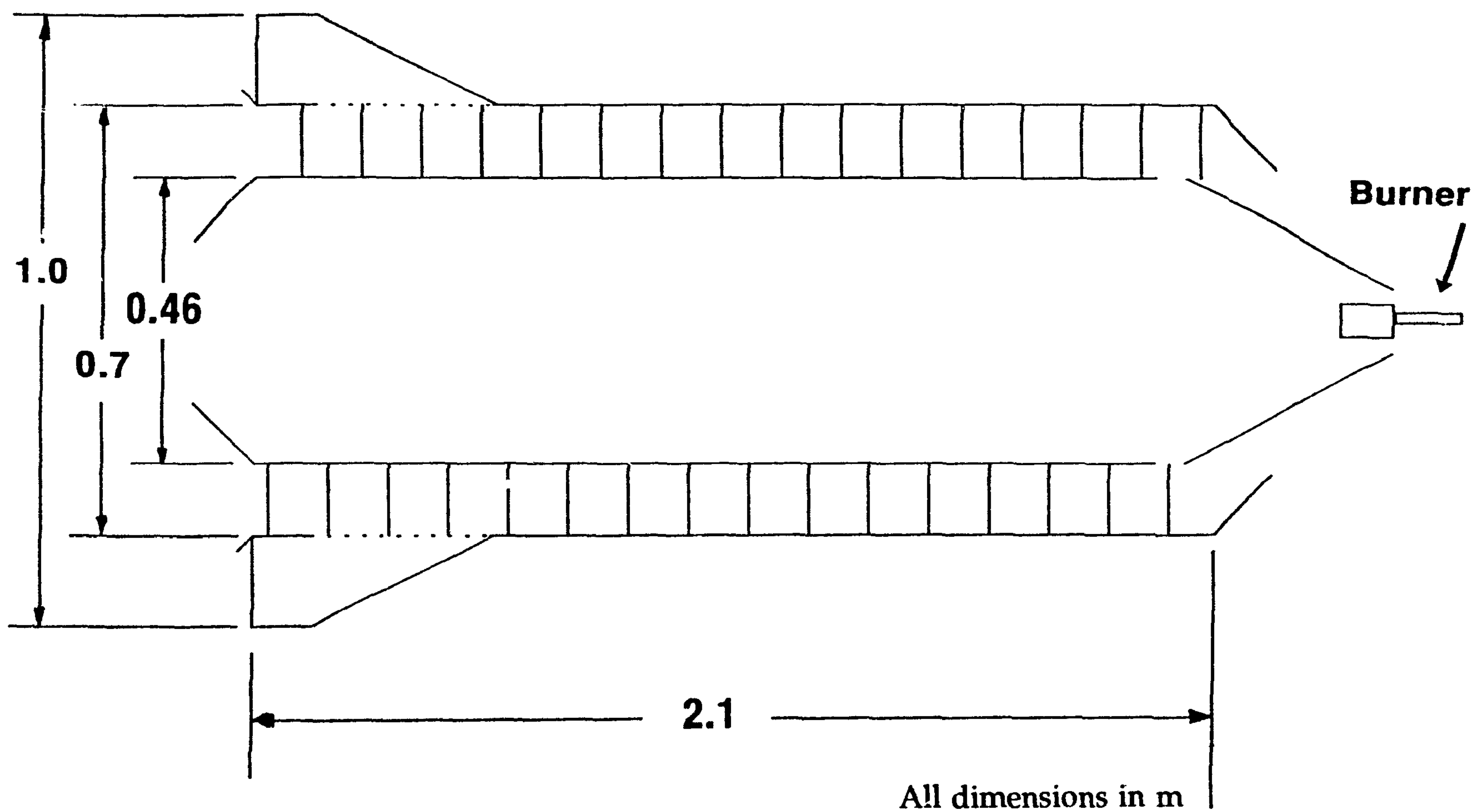


Figure 38: Cross-Section of Processor With Proposed Modifications

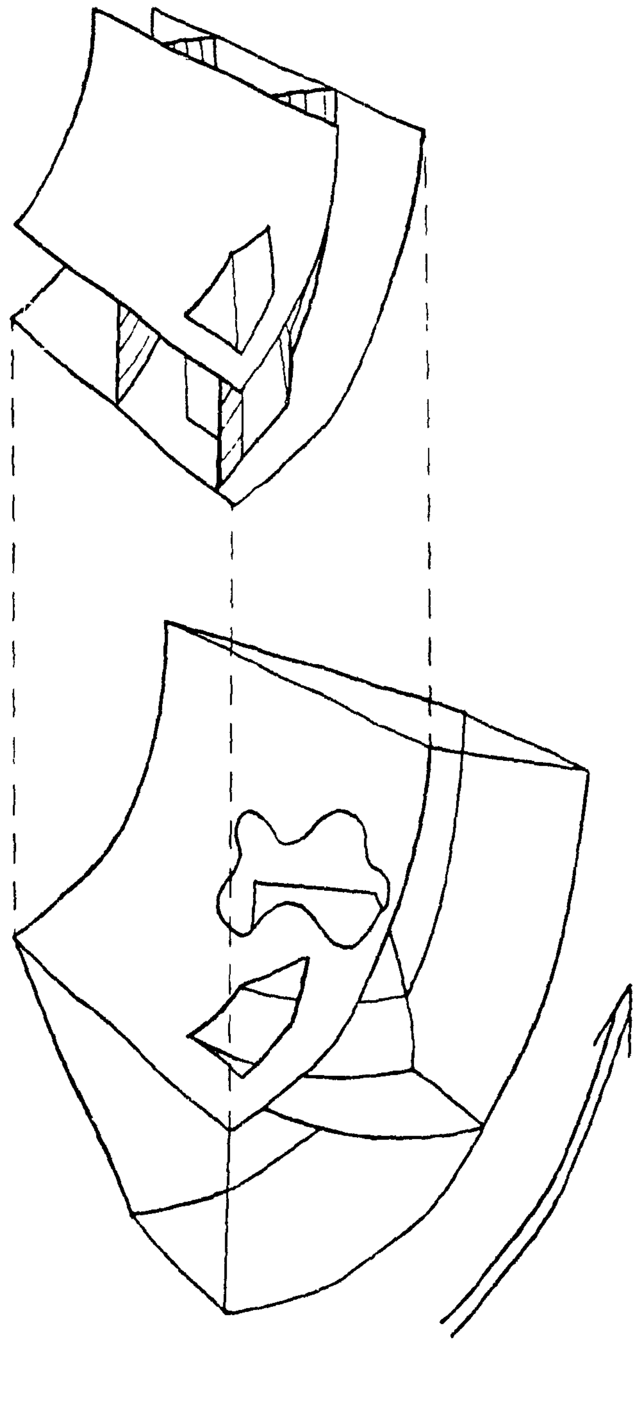


Figure 39: Perspective View of Suggested Modified Return Section

V. Summary and Conclusions

An existing particulate medium heat processor which had been developed for drying of corn, was used for soybean roasting experiments. A set of experiments were performed in which soybean was roasted in the processor with salt as the particulate medium at a salt to grain mass ratio of 10:1. Soybean with moisture contents of 13 and 23% was roasted at three different salt temperatures for three different residence times, after which, the soybean was kept in an insulated container for four different holding times.

As a result of the roasting process, the soybean reached final temperatures ranging from 107 to 134°C, and experienced reductions in moisture content of from 1.5% to as much as 17.5%. The temperatures achieved by the soybean, the change in soybean temperature, the change in moisture content, and the total heat transfer per kg of soybean were determined. These were analyzed with respect to the independant variables of salt temperature, residence time, and initial soybean moisture content. In all cases, the three independant variables were found to have some significant effect on the dependant varables, though in some cases the shape of the regression surface was difficult to explain.

It was also found that at higher levels of moisture content, the final temperature was generally about 110°C, which could be explained by the fact that higher moisture content leads to higher moisture loss, which reduces the soybean temperature. This result indicates that it may be difficult using salt-bed roasting to acheive temperatures above this level in high moisture soybean.

A selection of soybean samples were analyzed for trypsin inhibitor content and protein solubility, with the bulk of the sample kept for analysis in a future study. Samples treated at the higher levels of temperature and longer residence and holding times were found to have trypsin inhibitor contents which are likely to be sufficiently low for livestock feeding without having serious protein destruction. However, as only a subset of the samples was analyzed, analysis of the full set must be performed to find the optimum treatment within the treatment levels of this study. Within the set that was analyzed, salt temperature, residence time, and holding time all appeared to affect trypsin destruction, although insufficient samples were analyzed for testing of statistical significance. An attempt was made to correlate trypsin inhibitor and soluble protein contents to final soybean temperature, but this did not result in a strong correlation.

Additional tests were performed to determine the efficiency of the processor. Heating efficiency was found to be about 15%, but when the drying was included in the calculation, total efficiency was about 40%, indicating that considerable advantage can be gained by combining roasting with drying. A further analysis showed that heat losses were primarily due to problems in the combustion section, where efficiency was approximately 45%, as compared to 65% expected based on experiments by a previous researcher.

As a result of problems with efficiency and other problems encountered in the course of the experiment, several design modification have been suggested for the prototype processor used in the study.

VI. Recommendations

The full set of soybean samples from these experiments should be analyzed to confirm statistically the trends found in this study. A livestock feeding trial should then be required to confirm the value of the processed product.

As the machine has been shown to work well from a technical standpoint, it should also be tested for social and economic feasability. Therefore it is recommended that on-farm tests be performed with an improved prototype, enlisting the cooperation of a soybean producer and/or swine or poultry producer.

The processor design, while essentially complete, lacks one important component which will be required if it is to be used on a large scale. A control system is needed to control fuel flow to the flame in order to control the temperature of the salt. Due to the time lag between the effect of the flame and the measurement of the salt temperature as it leaves the combustion section, a simple control system increasing or decreasing fuel flow based on the temperature of the salt as it leaves the combustion section may be somewhat unstable. It would be preferable to develop a control system which could make use of the temperature of the salt as it enters the combustion section as well as as it exits in order to best control the salt temperature.

It was not clear from the literature whether protein destruction is necessarily directly correlated to trypsin inhibitor destruction. In this study it was found that although there is a statistically significant relationship between them, they may not necessarily be directly correlated. It would be useful to determine if any heating methods might decrease the amount of protein destruction for the same amount of trypsin inhibitor destruction as compared to other methods. This might be possible if, for example, the onset of denaturation of trypsin inhibitor occurred at a different temperature than the denaturation of most other proteins. This would make it possible to produce higher quality soybean with less of the generally accepted trade-off of protein loss in return for trypsin inhibitor destruction.

With respect to particulate medium heat transfer, it is recommended that the relationship between the physical effective film layer and the thermal effective film layer be examined, using the methodology proposed herein, to determine if the two can be correlated.

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Appendices

Appendix 1: Experimental Temperature and Moisture Data

M_i/ T_i (%/°C)	Salt temp. (°C)	Res time (s)	Final soy T (°C)	Final soy M (%w.b)	Heat transfer[1] (kJ/kg)	final salt temp.[1] (°C)	Soy M air dry[2] (%w.b.)
12.78	225	15	120	10.8	255.4932	198.1483	8.63
20	225	30	123	10.29	275.3902	191.8364	7.0
	225	60	122	9.32	299.3903	184.2804	5.76
	250	15	117	11.33	234.8819	225.3145	8.43
	250	30	111	7.62	321.6406	211.2667	5.26
	250	60	131	6.01	402.0723	195.3148	2.31
	275	15	118	10.2	267.8262	246.8522	7.23
	275	30	126	5.88	395.2766	227.3992	3.93
	275	60	131	5.31	419.2225	217.9823	2.29
22.26	225	15	108	20.22	241.9257	199.5742	16.55
21	225	30	107	17.47	317.0987	186.8137	13.97
	225	60	107	10.24	506.7816	156.0735	10.87
	250	15	107	19.56	255.9134	223.1042	16.07
	250	30	108	14.74	394.5019	202.4925	12.9
	250	60	115	9.27	549.9301	175.2050	6.03
	275	15	109	16.86	338.3767	239.4375	14.23
	275	30	111	10.45	509.7040	213.6194	7.31
	275	60	108	7.73	567.6815	197.7906	6.76
12.64	225	15	117	11.03	241.2399	199.6463	8.71
19	225	30	121	10.07	275.4444	191.8299	7.33
	225	60	123	5.82	389.0363	172.0878	5.08
	250	15	116	10.87	243.6465	224.3934	8.1
	250	30	119	7.92	328.1494	210.4829	5.59
	250	60	124	4.58	421.1716	192.7172	5.16
	275	15	119	9.5	286.7403	244.8643	6.73
	275	30	125	6.72	370.6620	230.3634	4.27
	275	60	134	2.44	491.3776	208.1686	2.15
21.94	225	15	113	19.47	268.6794	196.7625	17.13
17	225	30	112	14.24	414.4636	175.0886	12.72
	225	60	111	9.33	535.6894	152.1418	10.93
	250	15	111	17.79	314.2011	216.9783	15.05
	250	30	111	11.84	474.4110	192.8695	12.81
	250	60	112	7.7	575.6988	171.7002	10.6
	275	15	114	15.98	371.3387	235.9733	14.45
	275	30	111	7.1	587.3541	204.2685	9.32
	275	60	118	5.29	641.4995	187.7508	7.14
13.27	225	15	115	11.75	233.0594	200.5060	10.38
20	225	30	119	11.28	246.0752	195.3666	9.09
	225	60	121	7.57	356.1707	176.5578	7.33
	250	15	118	11.38	249.3175	223.7974	9.78
	250	30	118	8.96	314.3545	212.1441	7.3
	250	60	121	6.06	393.8777	196.4294	5.02
	275	15	117	10.77	256.0437	248.0905	8.45
	275	30	121	7.59	347.6630	233.1330	6.95
	275	60	123	4.36	438.9046	215.3053	5.04

M_i/ T_i	Salt temp.	Res time	Final soy T	Final soy M	Heat transfer[1]	final salt temp.[1]	Soy M air dry[2]
(%/°C)	(°C)	(s)	(°C)	(%w.b)	(kJ/kg)	(°C)	(%w.b.)
24.64	225	15	109	22.35	263.7282	197.2828	20.09
14	225	30	111	19.66	348.9663	182.9761	18.08
	225	60	111	18.4	385.1764	172.6128	17.02
	250	15	111	22.2	272.4061	221.3708	19.25
	250	30	111	18.32	387.4378	203.3432	16.69
	250	60	108	12.79	527.6972	178.2288	15.08
	275	15	113	21.1	310.1673	242.4022	17.78
	275	30	107	15.43	458.2596	219.8145	14.87
	275	60	108	10.55	581.7954	195.8710	12.66
12.56	225	15	108	11.23	209.4563	202.9867	10.1
22	225	30	122	10.55	256.1766	194.1502	8.74
	225	60	125	9.17	299.3061	184.2919	8.78
	250	15	118	10.82	240.7777	224.6949	8.83
	250	30	121	8.56	307.3613	212.9863	6.76
	250	60	121	5.7	379.8663	198.3350	7.23
	275	15	121	10.22	263.1592	247.3426	8.06
	275	30	124	6.86	356.9954	232.0092	5.51
	275	60	128	4.37	426.1064	217.0460	4.56
23.53	225	15	108	21.07	257.9171	197.8936	18.61
18	225	30	111	19.38	314.6901	187.1037	16.98
	225	60	110	17.92	354.8698	176.7348	16.25
	250	15	111	21.28	257.4557	222.9421	18.03
	250	30	111	17.88	358.0043	206.8877	15.31
	250	60	107	12.03	504.8159	181.3409	13.85
	275	15	112	19.39	316.3959	241.7476	16.54
	275	30	110	13.83	465.4204	218.9522	12.73
	275	60	107	11.94	507.0370	206.0388	12.02
14.1	225	15	117	12.32	238.7527	199.9077	9.57
23	225	30	121	11.6	266.7013	192.8827	8.87
	225	60	118	7.65	364.6074	175.4104	8.13
	250	15	119	12.32	242.7527	224.4873	10.55
	250	30	118	7.61	365.6142	205.9713	7.3
	250	60	122	6.18	409.0424	194.3668	5.28
	275	15	119	10.35	296.5733	243.8309	9.27
	275	30	121	5.6	421.1059	224.2887	5.77
	275	60	127	3.62	479.8406	209.7377	4.36
24.59	225	15	113	21.81	286.8860	194.8490	19.24
14	225	30	113	20.79	317.9343	186.7131	17.44
	225	60	113	14.01	505.5939	156.2351	16.26
	250	15	112	21.18	304.1578	218.0338	18.62
	250	30	111	18.25	387.8837	203.2895	15.54
	250	60	106	11.58	551.8466	174.9443	11.16
	275	15	111	21.5	292.4076	244.2687	17.51
	275	30	109	15.16	467.8760	218.6565	13.98
	275	60	108	8.65	624.2342	190.0990	11.47

Notes:

[1] calculated values
[2] moisture content after roasting followed by cooling in ambient conditions

Appendix 2: Statistical Analyses of Temperature and Moisture Change

Coding Coefficients for the Independent Variables

Factor	Subtracted off	Divided by
MO	18.600000	6.040000
T	250.000000	25.000000
I	37.500000	22.500000

(Final Temperature)

Response Surface for Variable TF

Response Mean	115.611111
Root MSE	2.834127
R-Square	0.8307
Coef. of Variation	2.4514

Regression	Degrees of Freedom	Type I Sum of Squares	R-Square	F-Ratio	Prob > F
Linear	3	2724.129784	0.7177	113.0	0.0000
Quadratic	3	56.640560	0.0149	2.351	0.0786
Crossproduct	3	372.036518	0.0980	15.439	0.0000
Total Regress	9	3152.806863	0.8307	43.613	0.0000

Residual	Degrees of Freedom	Sum of Squares	Mean Square
Total Error	80	642.582026	8.032275

Parameter	Degrees of Freedom	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEPT	1	203.153423	65.569483	3.098	0.0027
MO	1	-0.490085	1.413058	-0.347	0.7296
T	1	-0.707268	0.510481	-1.385	0.1698
I	1	0.342483	0.232018	1.476	0.1438
MO*MO	1	0.063840	0.033279	1.918	0.0586
T*MO	1	-0.008890	0.002794	-3.182	0.0021
T*T	1	0.001787	0.001014	1.762	0.0819
I*MO	1	-0.018246	0.003048	-5.985	0.0000
I*T	1	0.000476	0.000782	0.609	0.5444
I*I	1	-0.000741	0.001434	-0.517	0.6069

Parameter	Parameter Estimate from Coded Data
INTERCEPT	113.176424
MO	-6.171912
T	0.964423
I	1.498513
MO*MO	2.328990
T*MO	-1.342320
T*T	1.116667
I*MO	-2.479621
I*T	0.267857
I*I	-0.375000

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Prob > F
MO	4	2898.586228	724.646557	90.217	0.0000
T	4	171.244579	42.811145	5.330	0.0007
I	4	455.012574	113.753143	14.162	0.0000

Canonical Analysis of Response Surface
(based on coded data)

Factor	Critical Value Coded	Critical Value Uncoded
MO	0.903673	24.058186
T	0.220561	255.514037
I	-0.910900	17.004761

Predicted value at stationary point 109.811588

Eigenvalues	Eigenvectors MO	Eigenvectors T	Eigenvectors I
3.047179	0.883263	-0.330171	-0.332916
0.888447	0.284458	0.941771	-0.179306
-0.864969	0.372732	0.063674	0.925752

Stationary point is a saddle point.

(Temperature Change)

Response Surface for Variable DT

Response Mean	96.722222
Root MSE	3.562652
R-Square	0.6353
Coef. of Variation	3.6834

Regression	Degrees of Freedom	Type I Sum of Squares	R-Square	F-Ratio	Prob > F
Linear	3	1022.050036	0.3671	26.841	0.0000
Quadratic	3	355.570737	0.1277	9.338	0.0000
Crossproduct	3	391.035625	0.1405	10.269	0.0000
Total Regress	9	1768.656398	0.6353	15.483	0.0000

Residual	Degrees of Freedom	Sum of Squares	Mean Square
Total Error	80	1015.399158	12.692489

Parameter	Degrees of Freedom	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEPT	1	204.705675	82.424415	2.484	0.0151
MO	1	-5.704545	1.776291	-3.211	0.0019
T	1	-0.537822	0.641703	-0.838	0.4045
I	1	0.259269	0.291659	0.889	0.3767
MO*MO	1	0.216456	0.041833	5.174	0.0000
T*MO	1	-0.008603	0.003512	-2.450	0.0165
T*T	1	0.001413	0.001275	1.109	0.2708
I*MO	1	-0.018888	0.003832	-4.929	0.0000
I*T	1	0.000705	0.000983	0.717	0.4757
I*I	1	-0.000198	0.001803	-0.110	0.9130

Parameter	Parameter Estimate from Coded Data
INTERCEPT	90.236882
MO	-3.089293
T	0.881350
I	1.559848
MO*MO	7.896669
T*MO	-1.299081
T*T	0.883333
I*MO	-2.566889
I*T	0.396429
I*I	-0.100000

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Prob > F
MO	4	1514.626239	378.656560	29.833	0.0000
T	4	148.699872	37.174968	2.929	0.0258
I	4	496.365912	124.091478	9.777	0.0000

Canonical Analysis of Response Surface
(based on coded data)

Factor	Critical Value Coded	Uncoded
MO	0.401974	21.027924
T	-0.550756	236.231095
I	1.548449	72.340112

Predicted value at stationary point 90.580942

Eigenvalues	Eigenvectors MO	T	I
8.159750	0.983611	-0.092027	-0.155047
0.829179	0.103636	0.992252	0.068520
-0.308927	0.147540	-0.083465	0.985528

Stationary point is a saddle point.

(Moisture Loss)

Response Surface for Variable DM

Response Mean	6.953171
Root MSE	1.381935
R-Square	0.9087
Coef. of Variation	19.8749

Regression	Degrees of Freedom	Type I Sum of Squares	R-Square	F-Ratio	Prob > F
Linear	3	1340.904143	0.8014	234.0	0.0000
Quadratic	3	97.521035	0.0583	17.022	0.0000
Crossproduct	3	82.058844	0.0490	14.323	0.0000
Total Regress	9	1520.484022	0.9087	88.463	0.0000

Residual	Degrees of Freedom	Sum of Squares	Mean Square
Total Error	80	152.779627	1.909745

Parameter	Degrees of Freedom	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEPT	1	-28.773802	31.972029	-0.900	0.3708
MO	1	2.805691	0.689014	4.072	0.0001
T	1	-0.021876	0.248913	-0.0879	0.9302
I	1	0.004021	0.113133	0.0355	0.9717
MO*MO	1	-0.092888	0.016227	-5.724	0.0000
T*MO	1	0.002662	0.001362	1.954	0.0542
T*T	1	0.000038367	0.000494	0.0776	0.9383
I*MO	1	0.008590	0.001486	5.779	0.0000
I*T	1	0.000915	0.000381	2.399	0.0188
I*I	1	-0.002991	0.000699	-4.277	0.0001

Parameter	Parameter Estimate from Coded Data
INTERCEPT	11.101539
MO	2.041182
T	2.028656
I	3.786423
MO*MO	-3.388694
T*MO	0.402001
T*T	0.023979
I*MO	1.167333
I*T	0.514810
I*I	-1.514077

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Prob > F
MO	4	453.702060	113.425515	59.393	0.0000
T	4	245.722452	61.430613	32.167	0.0000
I	4	903.118355	225.779589	118.2	0.0000

Canonical Analysis of Response Surface
(based on coded data)

Factor	Critical Value Coded	Critical Value Uncoded
MO	-0.928204	12.993649
T	-15.611319	-140.282970
I	-1.761457	-2.132787

Predicted value at stationary point -9.015589

Eigenvalues	Eigenvectors MO	T	I
0.091786	0.088146	0.978050	0.188810
-1.410776	0.257719	-0.205486	0.944117
-3.559802	0.962191	-0.034560	-0.270175

Stationary point is a saddle point.

(Heat Transfer)

Response Surface for Variable DH

Response Mean	367.273708
Root MSE	36.418382
R-Square	0.8972
Coef. of Variation	9.9159

Regression	Degrees of Freedom	Type I Sum of Squares	R-Square	F-Ratio	Prob > F
Linear	3	840499	0.8144	211.2	0.0000
Quadratic	3	48064	0.0466	12.080	0.0000
Crossproduct	3	37318	0.0362	9.379	0.0000
Total Regress	9	925881	0.8972	77.566	0.0000

Residual	Degrees of Freedom	Sum of Squares	Mean Square
Total Error	80	106104	1326.298553

Parameter	Degrees of Freedom	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEPT	1	-309.933067	842.564415	-0.368	0.7140
MO	1	58.733212	18.157718	3.235	0.0018
T	1	-1.622552	6.559659	-0.247	0.8053
I	1	0.619070	2.981418	0.208	0.8360
MO*MO	1	-1.889282	0.427633	-4.418	0.0000
T*MO	1	0.049350	0.035902	1.375	0.1731
T*T	1	0.003786	0.013029	0.291	0.7721
I*MO	1	0.176965	0.039172	4.518	0.0000
I*T	1	0.024290	0.010052	2.416	0.0180
I*I	1	-0.075164	0.018429	-4.079	0.0001

Parameter	Parameter Estimate from Coded Data
INTERCEPT	458.012238
MO	44.850983
T	52.479124
I	97.780302
MO*MO	-68.924035
T*MO	7.451878
T*T	2.366162
I*MO	24.049573
I*T	13.663107
I*I	-38.051934

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	Prob > F
MO	4	208367	52092	39.276	0.0000
T	4	163412	40853	30.802	0.0000
I	4	591420	147855	111.5	0.0000

Canonical Analysis of Response Surface
(based on coded data)

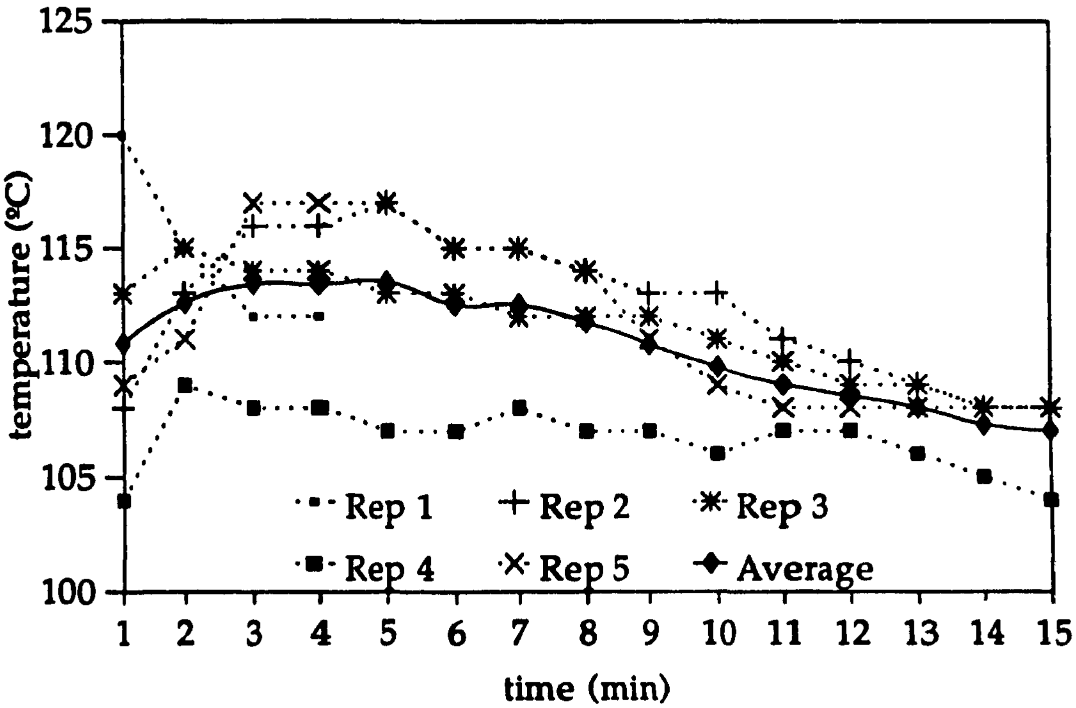
Factor	Critical Value Coded	Critical Value Uncoded
MO	-0.260591	17.026029
T	-9.319983	17.000430
I	-0.470761	26.907878

Predicted value at stationary point 184.600514

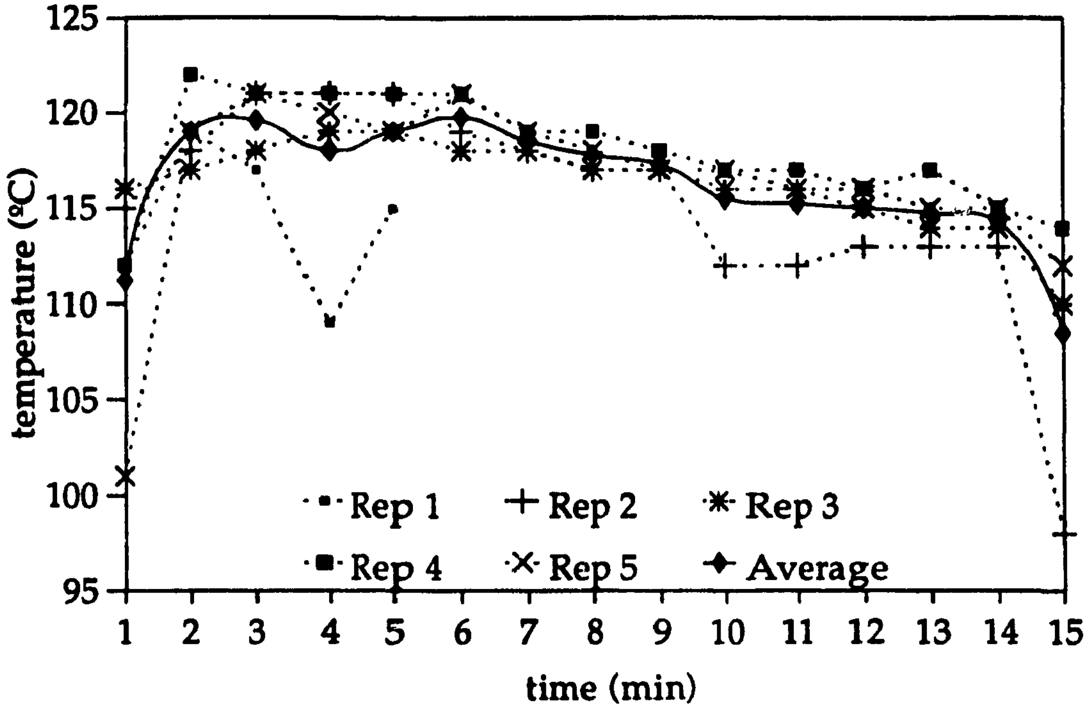
Eigenvalues	Eigenvectors MO	T	I
3.942564	0.080206	0.979951	0.182382
-35.474390	0.311914	-0.198457	0.929152
-73.077981	0.946719	-0.017636	-0.321578

Stationary point is a saddle point.

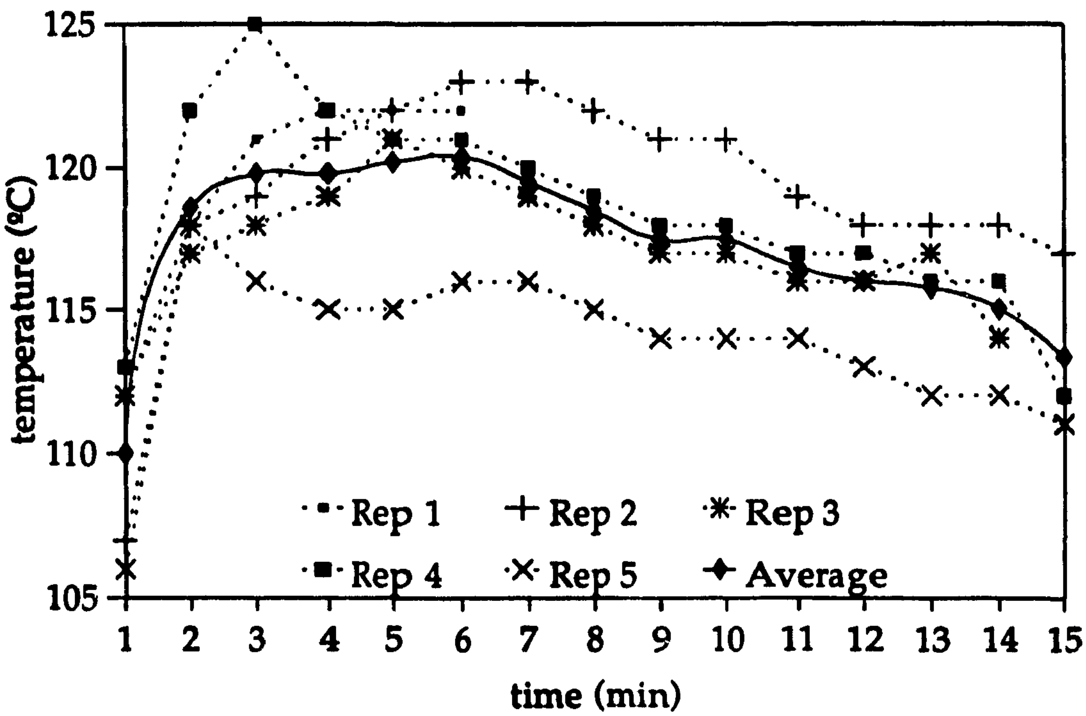
Appendix 3:
Graphs of Temperature Variation
in the Holding Bin



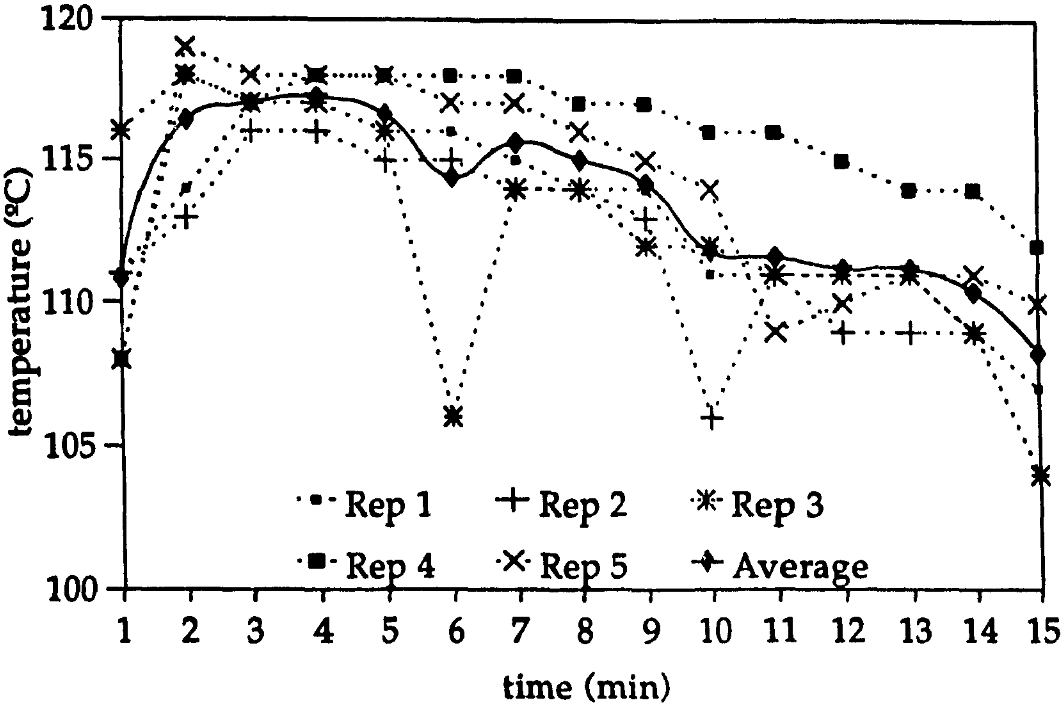
Moisture Content: 13%
Salt Temperature: 225°C Residence time: 15 s



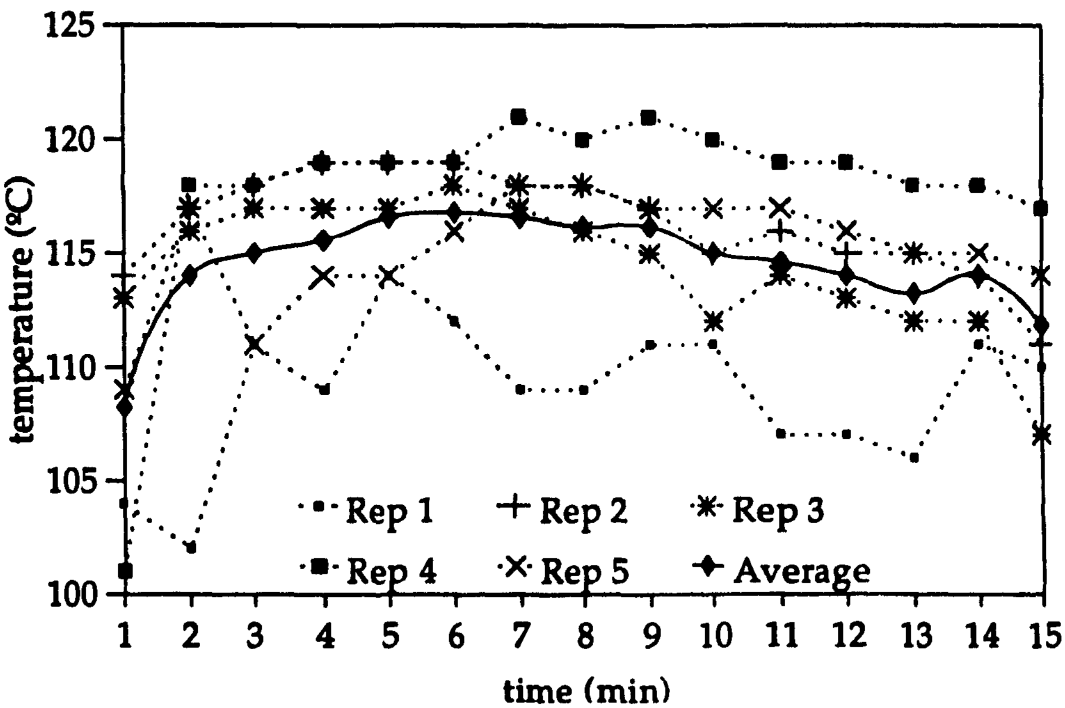
Moisture Content: 13%
Salt Temperature: 225°C   Residence time: 30 s



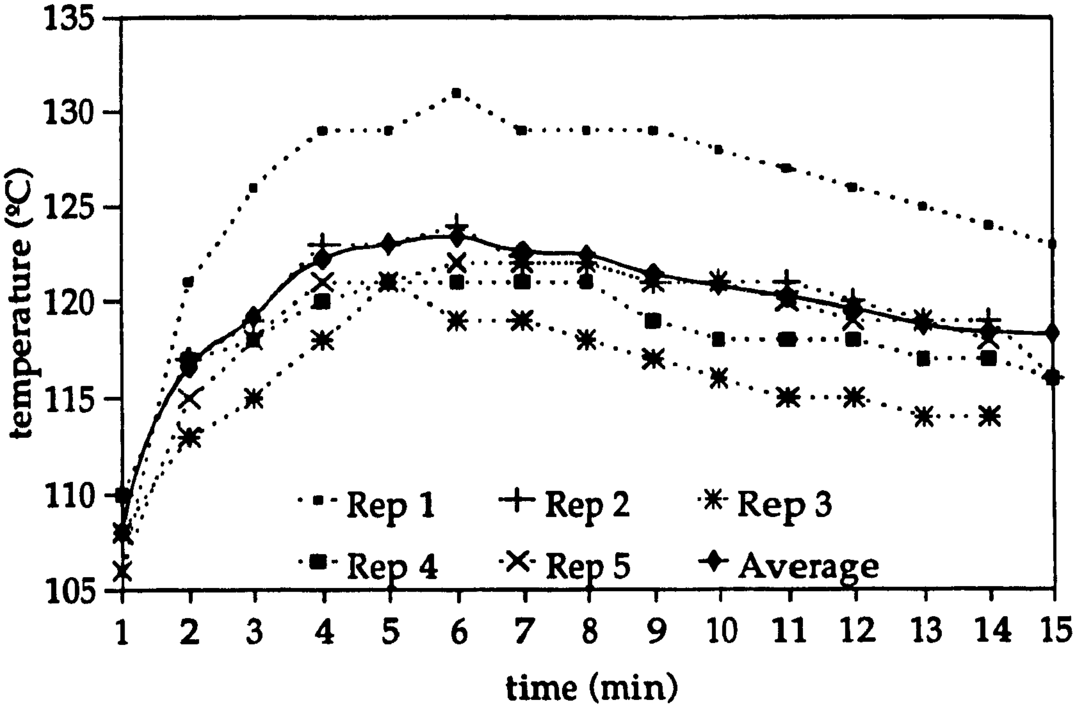
Moisture Content: 13%
Salt Temperature: 225°C   Residence time: 60 s



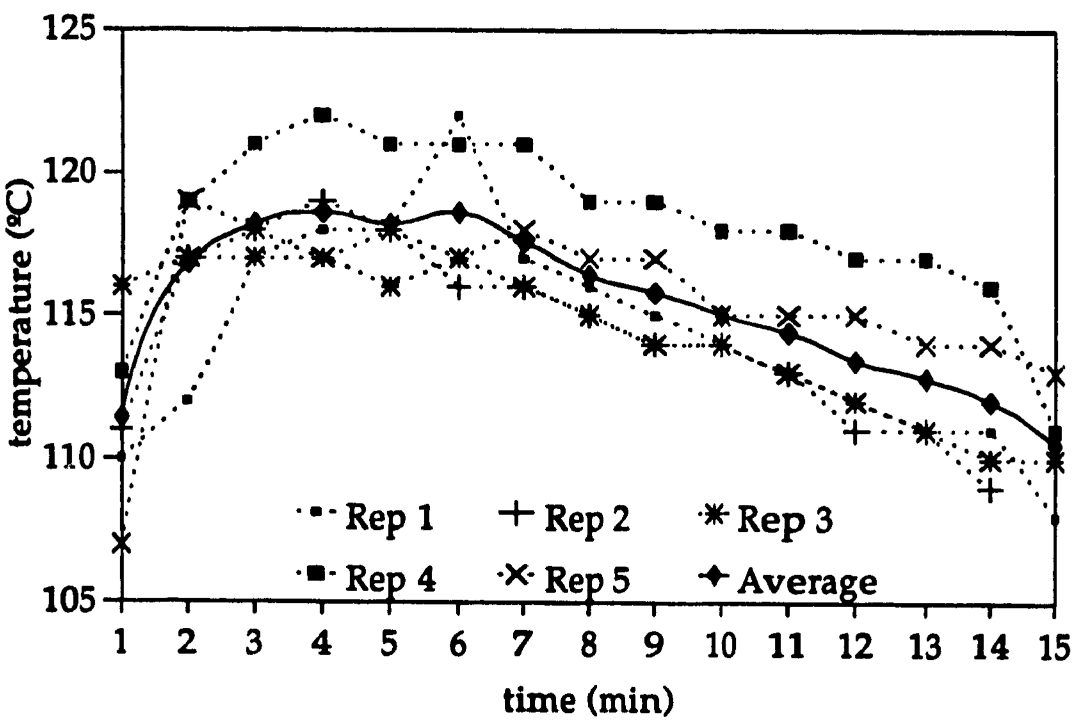
Moisture Content: 13%
Salt Temperature: 250°C Residence time: 15 s



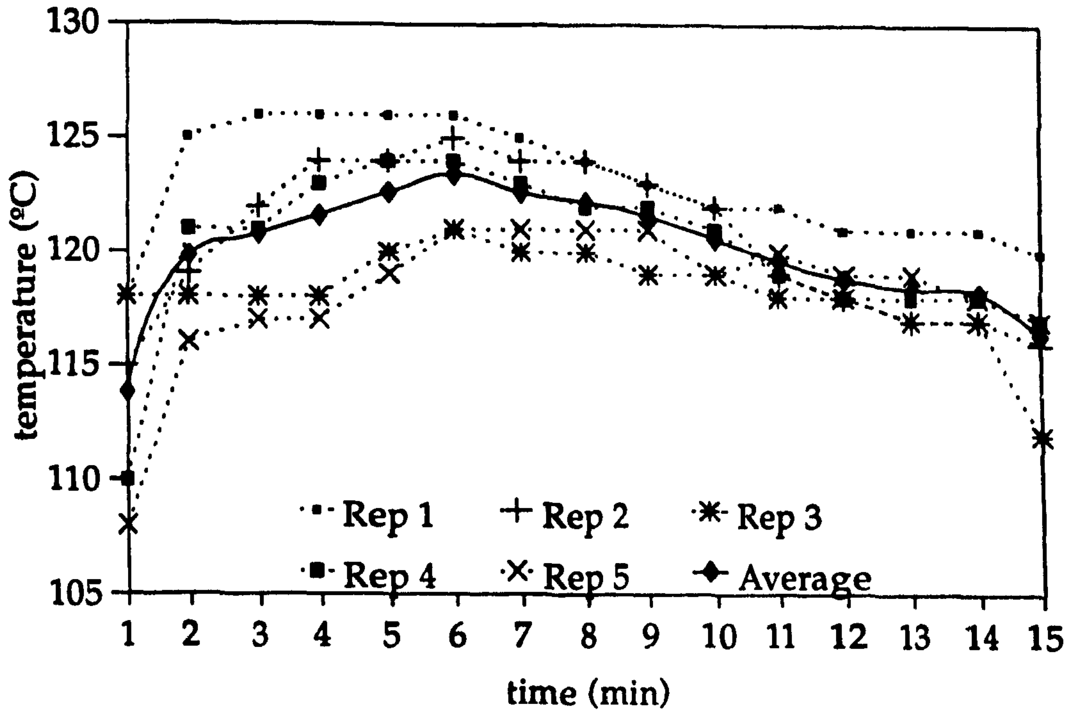
Moisture Content: 13%
Salt Temperature: 250°C Residence time: 30 s



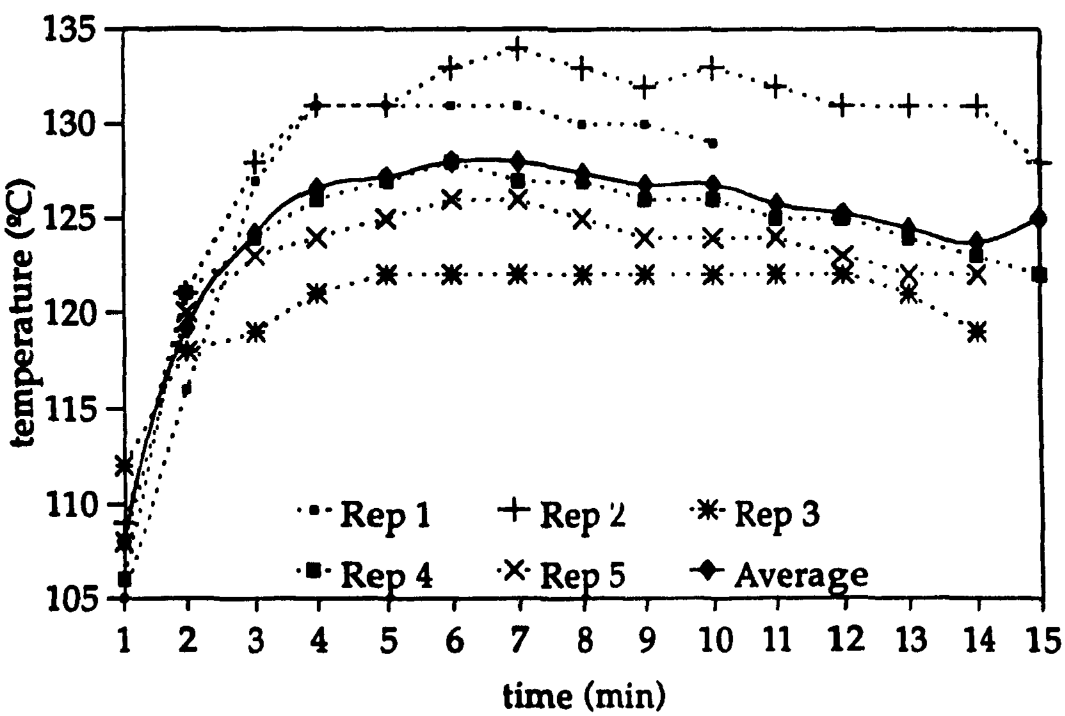
Moisture Content: 13%
Salt Temperature: 250°C   Residence time: 60 s



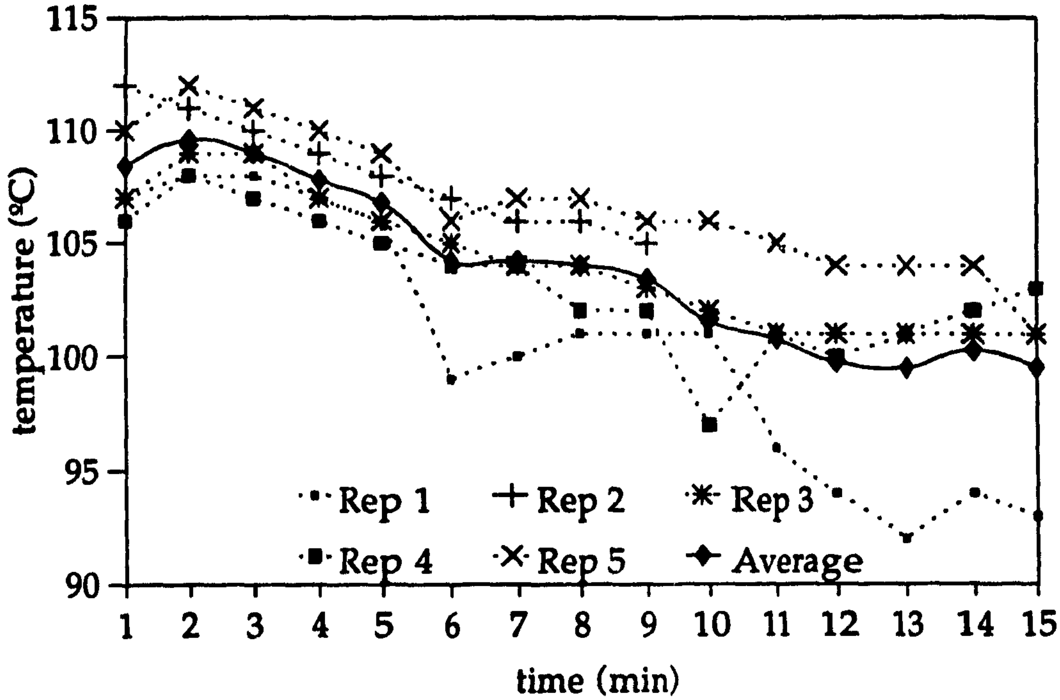
Moisture Content: 13%
Salt Temperature: 275°C   Residence time: 15 s



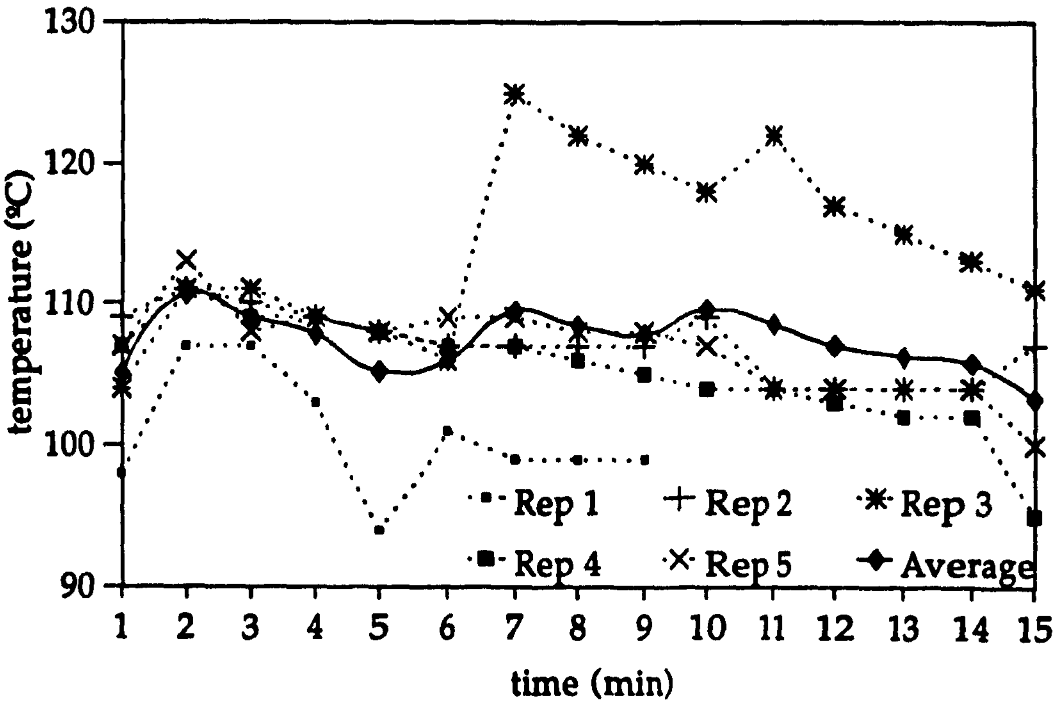
Moisture Content: 13%
Salt Temperature: 275°C Residence time: 30 s



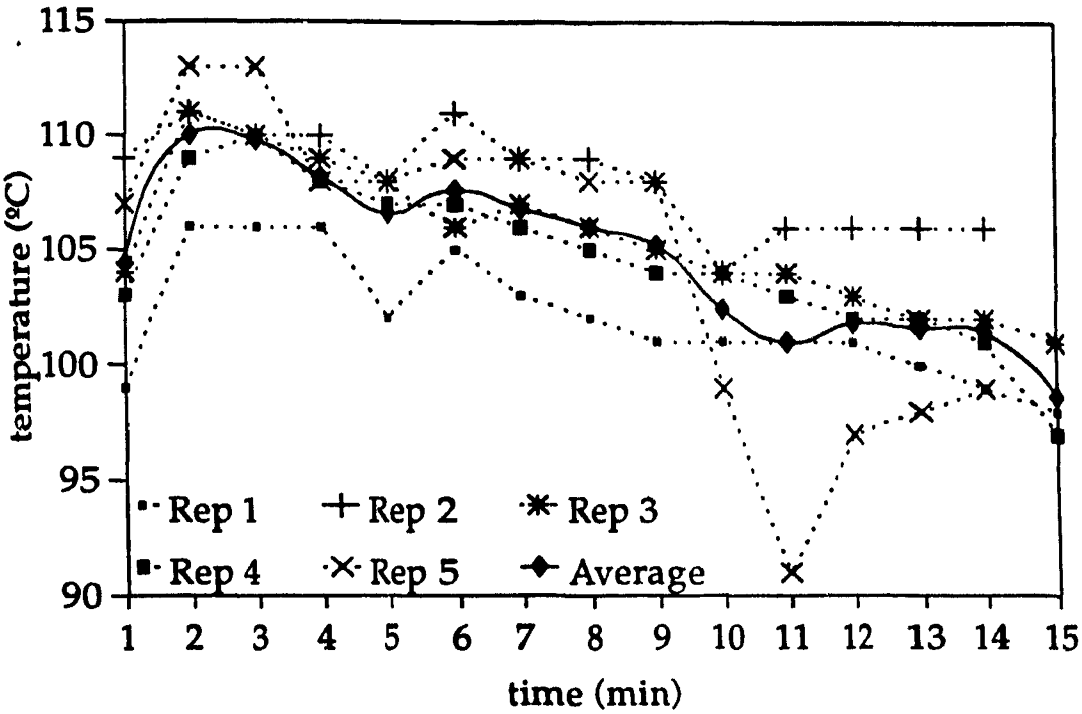
Moisture Contenc 13%
Salt Temperature: 275°C Residence time: 60 s



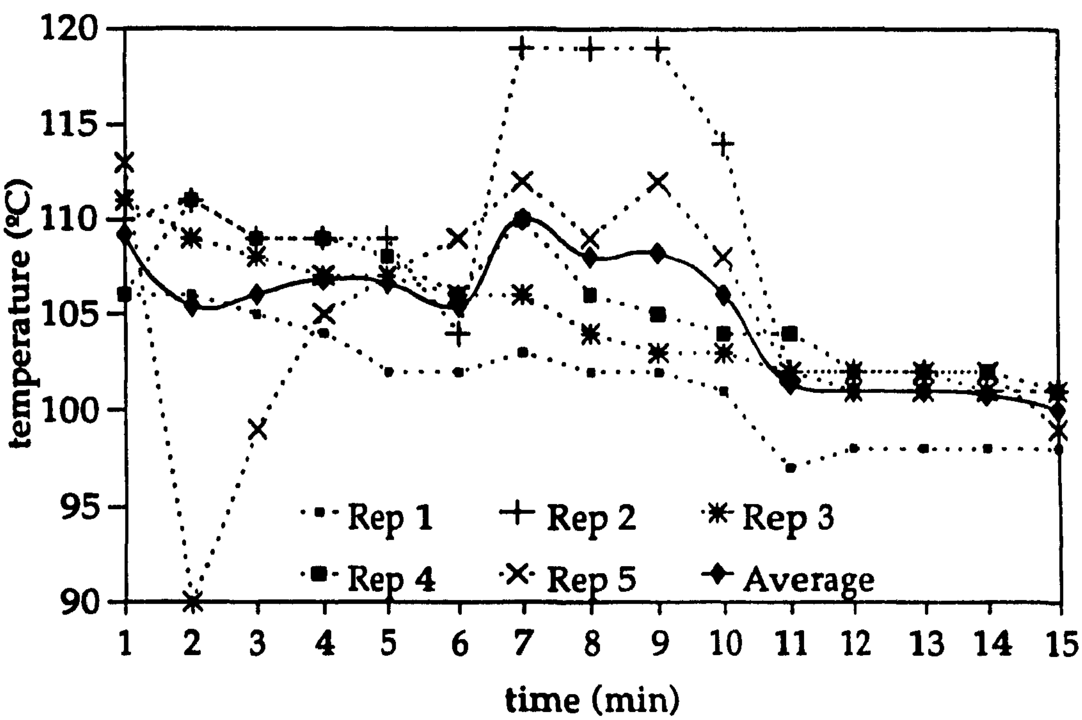
Moisture Content: 23%
Salt Temperature: 225°C   Residence time: 15 s



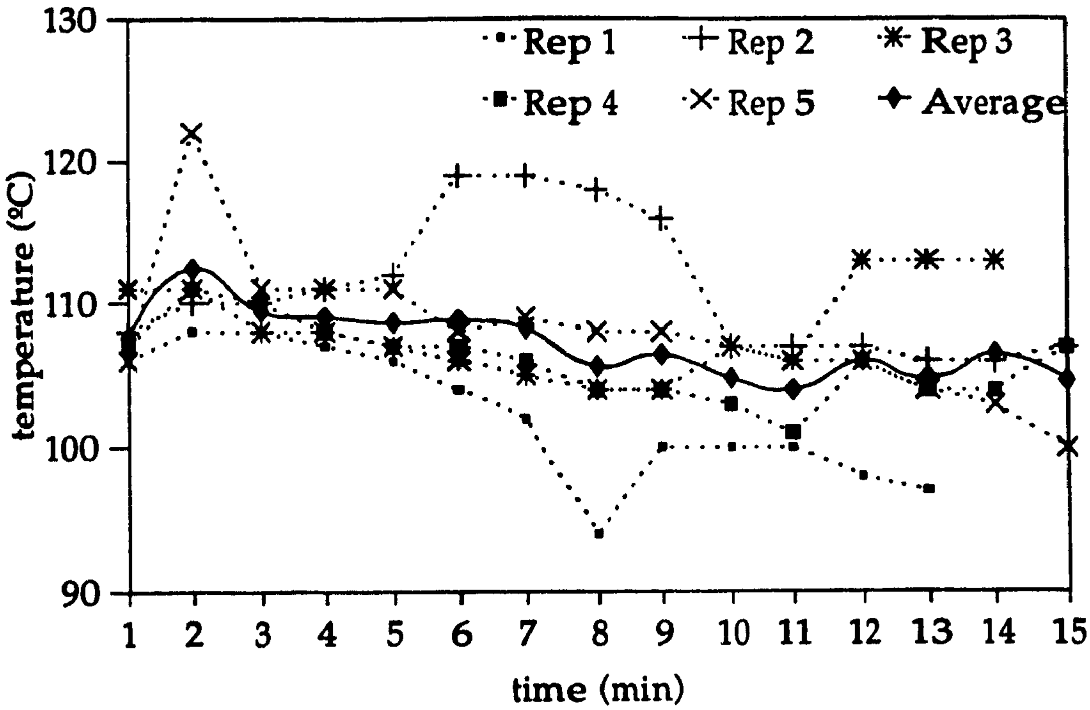
Moisture Content: 23%
Salt Temperature: 225°C   Residence time: 30 s



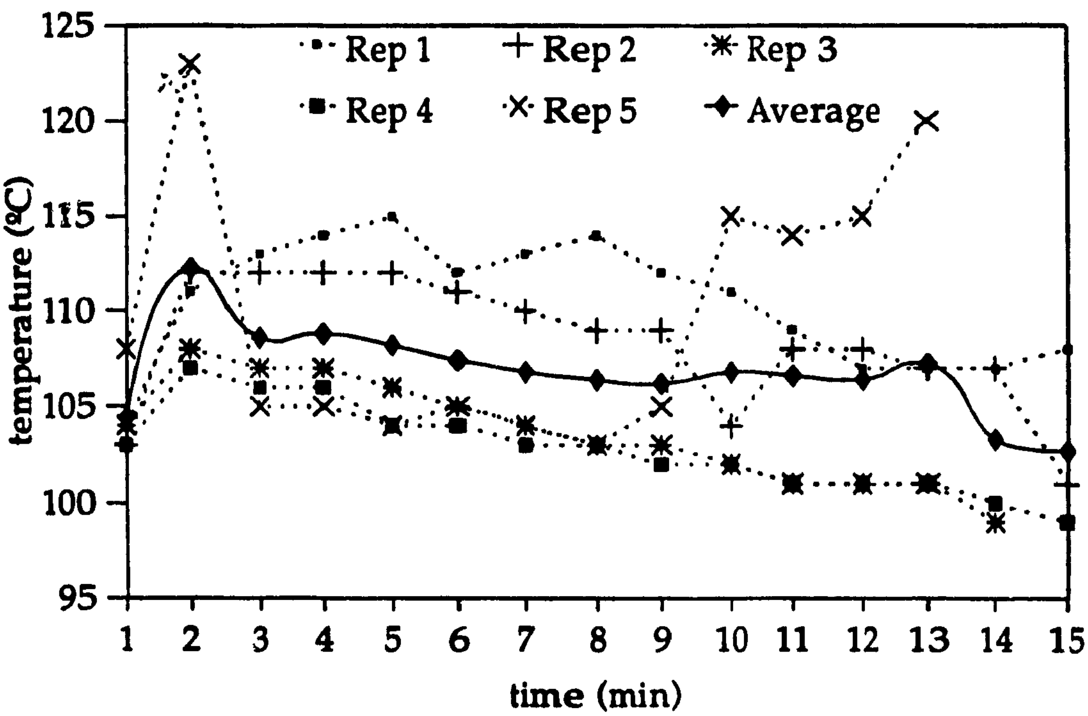
Moisture Content: 23%
Salt Temperature: 225°C Residence time: 60 s



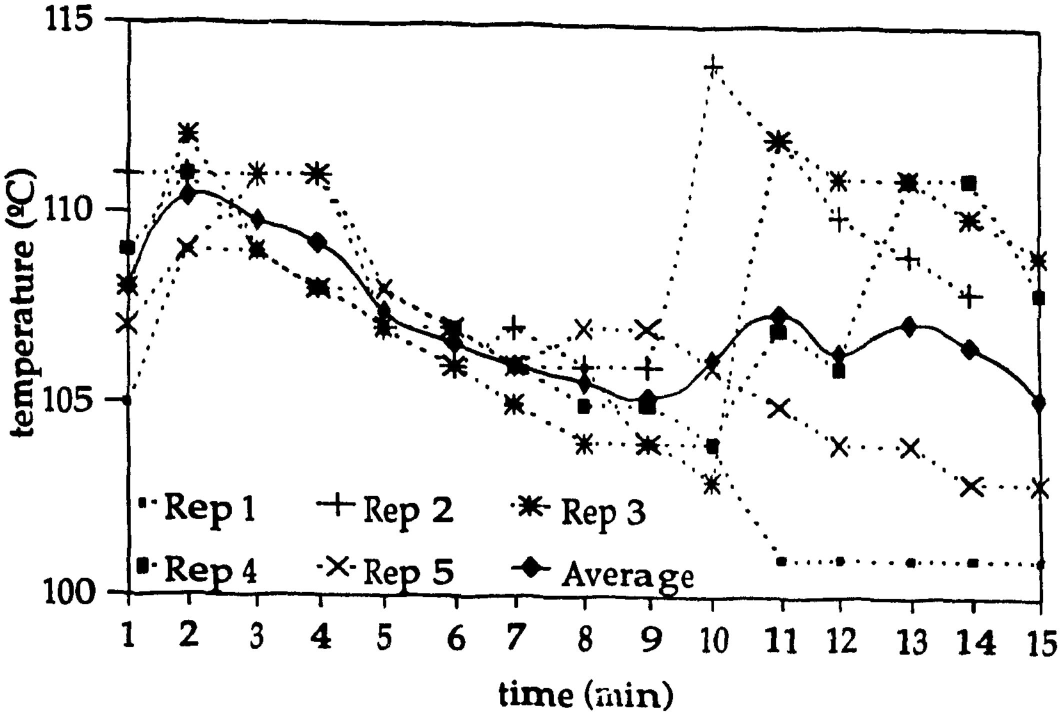
Moisture Content: 23%
Salt Temperature: 250°C Residence time: 15 s



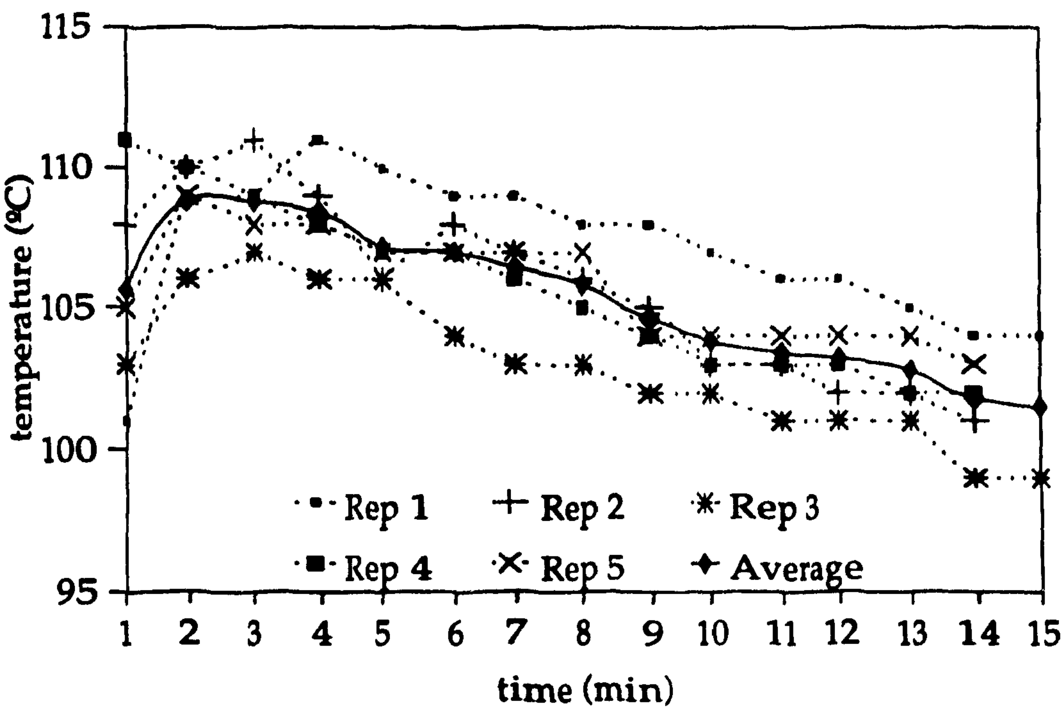
Moisture Content: 23%
Salt Temperature: 250°C Residence time: 30 s



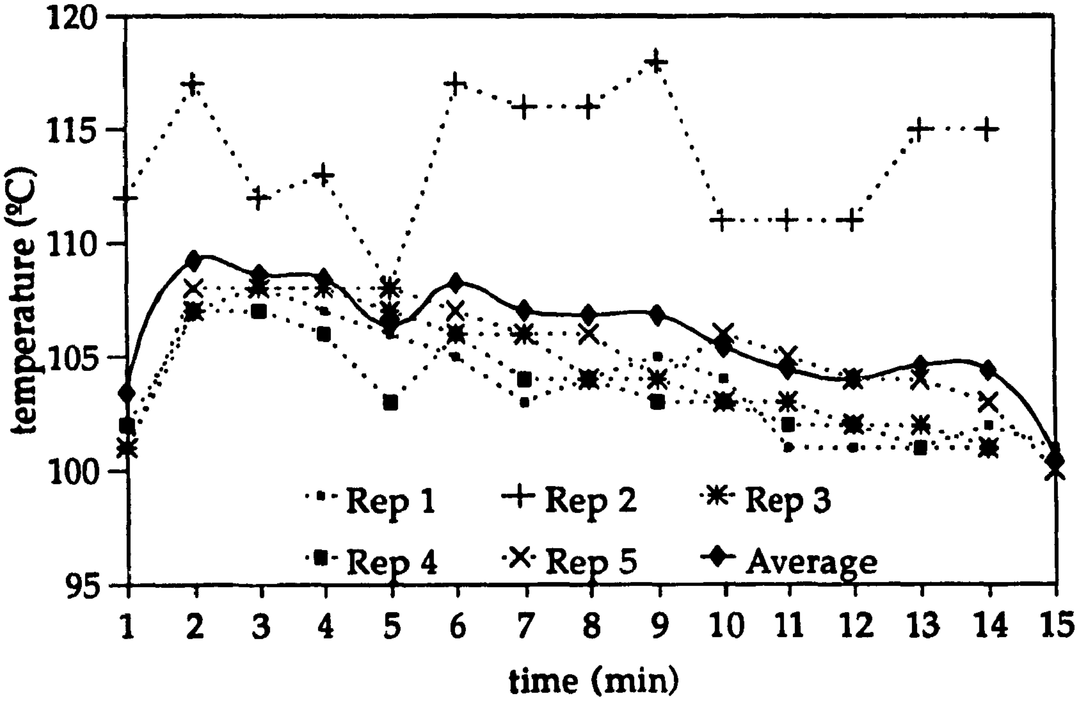
Moisture Content: 23%
Salt Temperature: 250°C Residence time: 60 s



Moisture Content: 23%
Salt Temperature: 275°C Residence time: 15 s



Moisture Content: 23%
Salt Temperature: 275°C Residence time: 30 s



Moisture Content: 23%
Salt Temperature: 275°C Residence time: 60 s