To the Graduate Council:

I am submitting herewith a thesis written by Xia Liu entitled "A Laboratory-Scale Contactor for Osmotic Dehydration of Fresh Fruits and Vegetables." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

Fred D. Tompkins, Major Professor

We have read this thesis
and recommend its acceptance:

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A LABORATORY-SCALE CONTACTOR FOR OSMOTIC DEHYDRATION OF FRESH FRUITS AND VEGETABLES

A Thesis

Presented for the

Master of Science

Degree

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Xia Liu

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ABSTRACT

Data from small-scale batch experiments involving osmotic dehydration of green beans in aqueous solutions of sodium chloride were analyzed, and regression models based upon these data were developed. A laboratory-scale contactor was designed and fabricated to allow batch-type osmotic dehydration of fruits and vegetables. The contactor was then employed to dehydrate green beans in sodium chloride water solutions. Effects of processing variables, including salt solution concentration (5%, 10%, 15%, and 20%), solution temperature (10°C, 20°C, and 30°C), and time of exposure (0, 15, 30, 45, and 60 minutes) on the moisture loss and salt uptake of green beans were evaluated. Regression models of moisture loss and salt uptake were also developed. Models based upon both small-scale batch processing and processing in the contactor were compared in terms of parameters in the models. Small-batch treatments removed moisture more rapidly at the beginning of the processing than did processing in the larger- scale contactor. Overall, more moisture was removed and less salt was taken up by the green beans during contactor processing as compared to the small batch processing. Green bean pods could lose 26% their original moisture while taking on 8% salt by weight when immersed in a 20% NaCl solution at 30°C for one hour during processing in the

contactor. Differences in results between the two processing methods may be attributable to (1) different mass ratios for the two experiments and (2) physical differences in the green beans used in the two processes.

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CHAPTER I

INTRODUCTION

About 90,000 ha of green beans were harvested in the United States in 1985. Approximately 637,000 metric tons of these beans were processed to extend their usefulness as food products (USDA, 1985). As is the case with most vegetables or fruit materials, once green beans are harvested, most natural resistance to the action of spoilage microorganisms is lost. Enzymatic changes may actually accelerate the activity of spoilage organisms (Van Arsdel et al., 1973).

Major economic losses may occur during commodity transport or storage because of the degradation resulting from respiration. Even at reduced temperatures of 3 to 6 °C, however, green bean pods can only be stored for about ten days. Freshly harvested produce should be cooled as rapidly as possible to prevent pod deterioration. A conventional approach is to refrigerate the produce to reduce the rate of respiration. Another method involves partial dehydration of the tissue shortly after harvesting. This is accomplished by removing a portion of the moisture, thus reducing produce respiration (Biswal et al., 1990). A fresh green bean pod is by weight about 90 percent water. Removal of a portion of this water can be accomplished through osmotic dehydration.

Osmotic dehydration involves the immersion of the foodstuffs in liquids with a water activity lower than that of the foodstuffs (Biswal and Bozorgmehr, 1988). When salt or sugar solutions are used as the osmotic agent, two simultaneous mass flows take place: solute (salt or sugar) diffuses from the liquid solution into the food, and water diffuses out of the foodstuffs into the solution. Compared with other drying methods, the osmotic dehydration technique has many important advantages, including minimized heat damage to color and flavor and less discoloration of the vegetable and fruit by enzymatic oxidative browning. Ponting (1973) described osmotic drying for dehydration of fruit pieces, slices, and chunks. Fruits such as apples (Ponting et al., 1966; Ponting, 1973), peaches, and bananas (Bongirwar and Sreenivasan, 1977) have reportedly been dehydrated with significantly improved flavor and excellent color. Use of the osmotic dehydration process also has been studied by Pear and Richberg (1968), Lerici and Pinnavaia (1985), Biswal and Bozorgmehr (1988), Biswal and Le Maguer (1989), Hawkes and Flink (1978), and Kim and Toledo (1987).

The objective of this study was to design a laboratory-scale osmotic contactor based upon the results of research involving osmotic dehydration of green beans in sodium chloride solutions (Biswal and Bozorgmehr, 1988). Specific objectives of this study were: (1) to design and develop a laboratory-scale prototype contactor for osmotic dehydration of green beans and (2) to develop regression models for osmotic dehydration of green beans based upon processing in the laboratory-scale contactor.

CHAPTER II

REVIEW OF LITERATURE

I. DRYING PROCESSES

The dehydration process was probably the earliest method of food preservation. As water is removed from produce, the moisture content finally reaches a level where it is below that needed for the growth of microorganisms. After dehydration, the cost for transportation, handling, and storage are substantially lowered, because the need of costly refrigeration during transportation and storage is reduced or eliminated.

There are a number of methods used to remove moisture. Generally, the ways of directly removing moisture from fruits and vegetables can be divided into two categories: natural means such as sun and wind drying, and artificial means such as using forced air. In this century, natural sun and wind drying have largely been replaced by mechanical means such as forced air drying, vacuum drying, and dehydrofreezing because natural drying depends on overall climate and daily conditions. Some drying methods are reviewed in the following.

Freeze Drying

The process of freeze drying is characterized by heating a frozen product in a vacuum chamber maintained at an absolute pressure below the vapor pressure of the ice within the product. When heat is applied to the frozen product, the water contained within the product in the form of ice changes from the solid ice phase directly into the vapor phase. This inhibits undesirable chemical and biochemical reactions and minimizes loss of volatile aromatic compounds (Van Arsdel et al., 1973).

Spray Drying

Spray drying involves the dispersion of liquid or slurry in a stream of heated air. Dried particles are collected after separation from the air. The process is widely used to dehydrate fruit juices and has several features to produce high quality products. The fine dispersion of the particles provides large surface area, resulting in short drying times with high heat transfer rates. The final dried product is delivered as a free flowing powder. Besides allowing rapid drying, this process is continuous and simple to operate (Van Arsdel et al., 1973).

Tunnel Drying

Tunnel drying is one of the most popular methods for moisture reduction in fruits and vegetables. In tunnel drying, fresh materials are moved at intervals into one end of the tunnel. Hot air is pumped into the tunnel. This drying method is being used in more and more food dehydration plants and now is applied to the drying of such materials as apples, beets, carrots, onions and potatoes (Van Arsdel et al., 1973).

Freeze drying and spray drying are effective methods for removing moisture from products. However, those processes are very expensive. Tunnel drying works well, is relatively inexpensive, but requires considerable space. Another drying method which is relatively inexpensive and has a reduced space requirement is osmotic dehydration.

Osmotic Dehydration

Osmotic dehydration is a water removal process based on placing foodstuffs, such as pieces of fruit materials or vegetables, in a concentrated solution. The pressures of two solutions, one on either side of the cell membrane, generates a driving force, termed the osmotic pressure. Thus, under proper conditions, the water within the vacuole migrates out of the cell, and the solute in the external solution diffuses into the cell (Van Arsdel et al., 1973). The advantages claimed for osmotic dehydration are superior quality and little or no need for sulfur treatment (Farkas and Lazar, 1969). The following are additional advantages of the osmotic dehydration technique.

First, most vegetables must be blanched before the freezing or drying process to prevent development of undesirable flavors during subsequent storage (Baardseth 1978; Bottcher 1975). However, if osmotic dehydration is employed, it may be possible to eliminate the blanching process prior to freezing (Biswal and Bozorgmehr, 1989).

Second, Lerici and Pinnavaia (1985) noted that, in comparison with other drying processes, this process minimized heat damage to color and flavor and resulted in less discoloration of the fruits by enzymatic oxidative browning.

Third, the method is less expensive and consumes less energy than freeze drying.

II. LEACHING EQUIPMENT

The following review emphasizes a number of equipment items and technologies pertinent to osmotic dehydration. Countercurrent extraction, or diffusion extraction as it is sometimes called, was conceived in the sugar industry for extraction of sugar from sugar beets (Casimir, 1983). The following illustrates both similarities in principle and differences in equipment used for osmotic processing.

Fixed-bed Leaching

Fixed-bed leaching is used in the beet sugar industry. Figure 1 illustrates a typical sugar beet diffuser or extractor (Geankoplis, 1978). The cover is removable, so that sugar beet slices can be dumped into the bed. Heated water flows into the bed to leach out the sugar. The leached sugar solution flows out

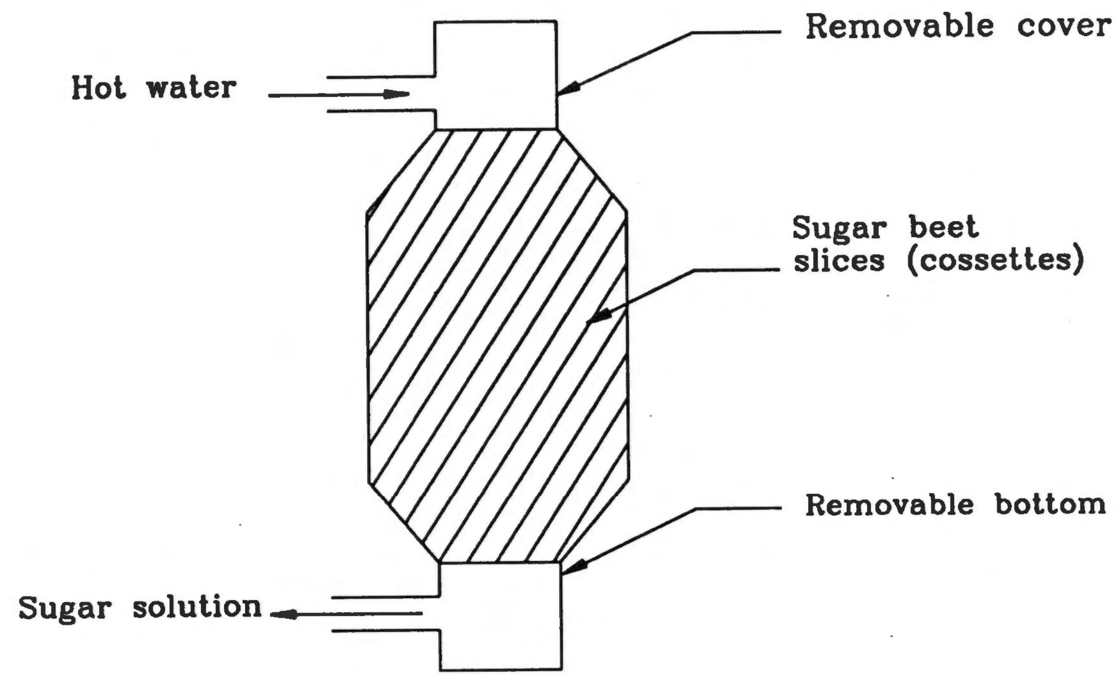

Figure 1. Typical fixed-bed apparatus for sugar beet leaching

the bottom into the next tank in the series. The top and bottom covers are removable so that the leached beets can be removed and a fresh charge can be added.

Moving-bed Leaching

There are a number of devices available for stagewise countercurrent leaching where the bed or stage moves instead of being stationary. The HILDEBRANDT extractor, as shown in Figure 2, consists of three screw conveyors arranged in a "U" shape. The solids enter the system at the top right, are conveyed downward and across the bottom, and then upward to the other leg. The solvent flows countercurrently (Geankoplis, 1978).

The De danske Sukkerfabrikker (D.d.S.) extractor, as illustrated in Figure 3, is one of the most widely used machines (Casimir, 1983). Its body slopes to permit gravity flow of water and to extract juice through a counter moving bed of solids. The solids are propelled through the extractor by double screw conveyors running in parallel, cylindrical troughs. The screws rotate in opposite directions, but are oppositely pitched so that they both provide forward motion toward the solids elevator. In one model of the D.d.S. extractor, the screw flights are formed of metal ribbons with slight gaps between them to permit flow of extract through the screw surface. The D.d.S. extractor has been recently used to extract apple juice from apple slices (Casimir, 1983).

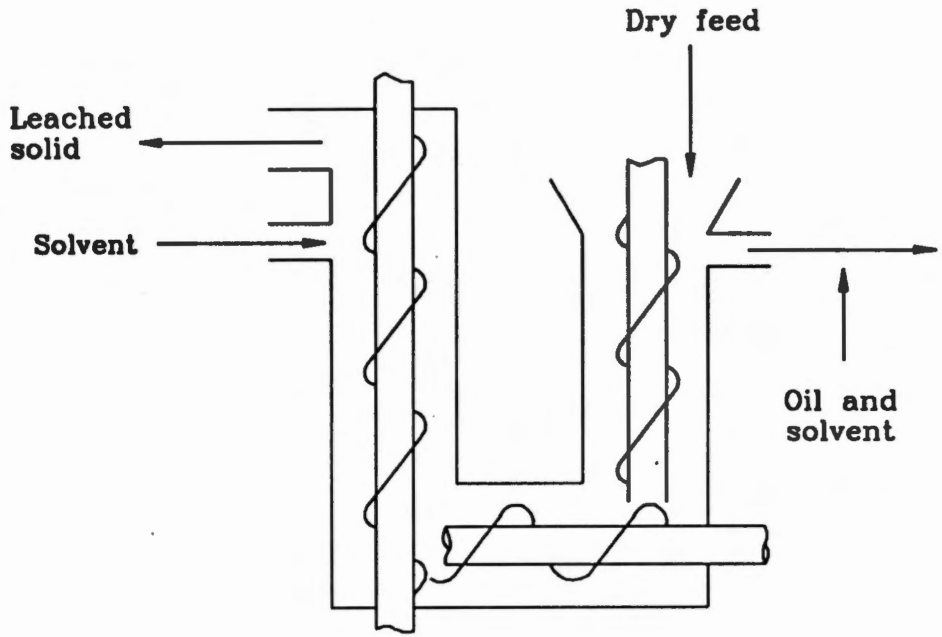

Figure 2. The Hildebrandt screw-conveyor extractor

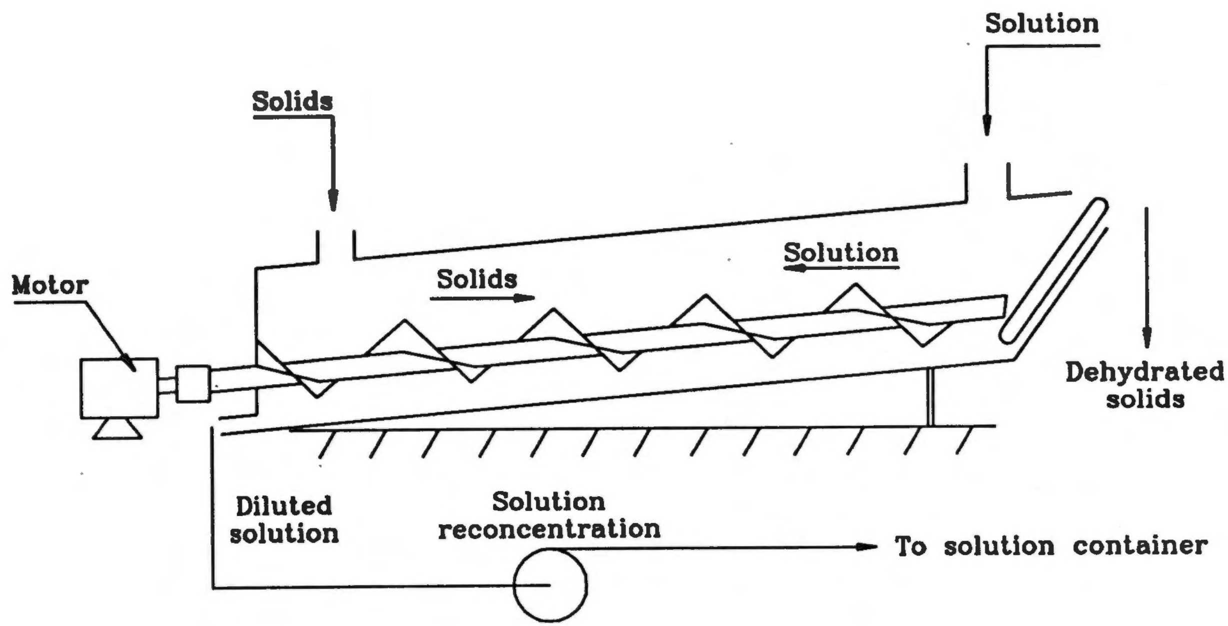

Figure 3. The De danske Sukkerfabrikker (D. d. S.) extractor

For the research reported herein, a batch process employing fluid recirculation will be incorporated in the design of a prototype osmotic dehydrator for green beans.

CHAPTER III

DEVELOPMENT OF MODELS FOR OSMOTIC DEHYDRATION OF GREEN BEANS

I. REGRESSION MODELS

Regression analysis was used to provide quantitative relationships describing the osmotic dehydration process for green beans. Biswal and Bozorgmehr (1988) conducted a small-scale experiment on osmotic dehydration of green beans in a sodium chloride solution. Processing variables included sodium chloride solution concentration, processing temperature, and the time of exposure of green beans to a salt water solution. The experimental data are shown on Appendix A.

Figure 4 is based upon the data collected by Biswal and Bozorgmehr (1988) and shows moisture loss versus processing time at different solution concentrations and temperatures. Total moisture loss from the bean pod increased with contacting time and with processing temperature. Moisture loss, expressed as a percentage of the original moisture present in the material, is given by the following equation (Biswal and Bozorgmehr, 1988):

$$M\ (\%) = \{ 1 - (m_\theta/m_0)\ (w_\theta/w_0)\} \times 100 \qquad (1)$$

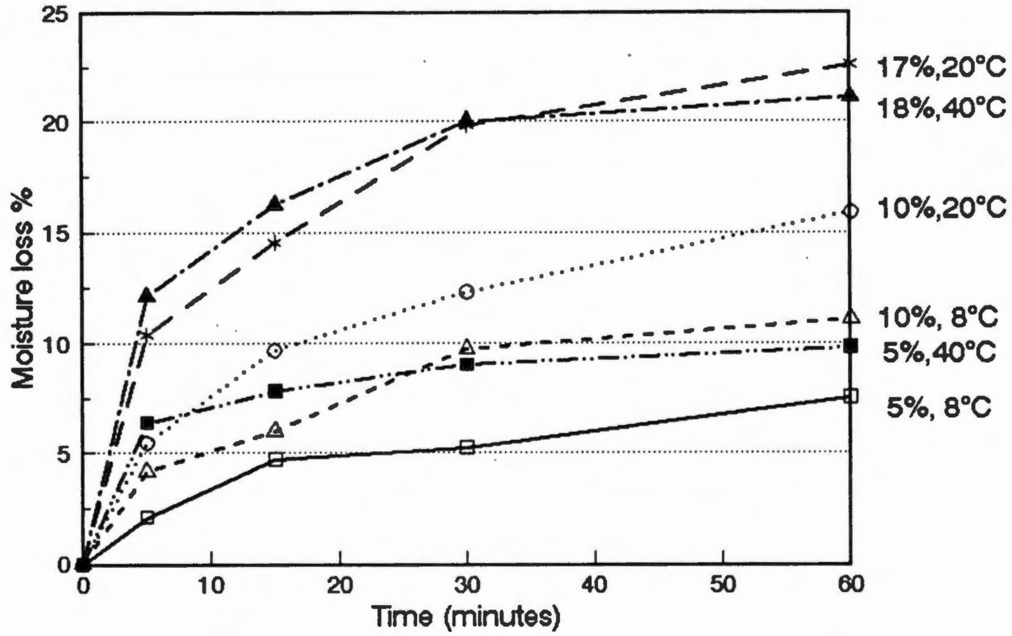

Figure 4. Moisture loss as a function of time for various processing temperatures and contacting solution concentrations in small-batch laboratory experiments with green beans.

where m_θ/m_0 is the reduction in mass of green beans at time θ, and w_0 and w_θ are masses of water in the green beans at times 0 and θ. Figure 4 also indicates that total moisture loss increased with increases in the salt concentration in the NaCl solution. An exponential relation was chosen to relate moisture loss to the processing variables.

The model equation was:

$$M\ (\%) = a_0\ C^{a_1}\ e^{\frac{-a_2}{\sqrt{TX}}} \tag{2}$$

where a_0, a_1 and a_2 were coefficients to be determined. C was solution concentration (% salt by weight), T represented the processing temperature (°C), and X was time (minutes). M, as used in Equation 2, describes the percentage of the original pod moisture removed during contacting. For example, a loss of 20 mg from a sample originally containing 100 mg of water would result in M = 20%.

Figure 5 illustrates a typical experimental data plot of observed salt uptake, expressed as percentage of total pod weight after processing, as a function of moisture loss. The figure indicates that there was, in general, a linear relationship between the salt uptake (S) and the moisture loss from the pod with residual variations due to bath composition, processing temperature, and time of contacting.

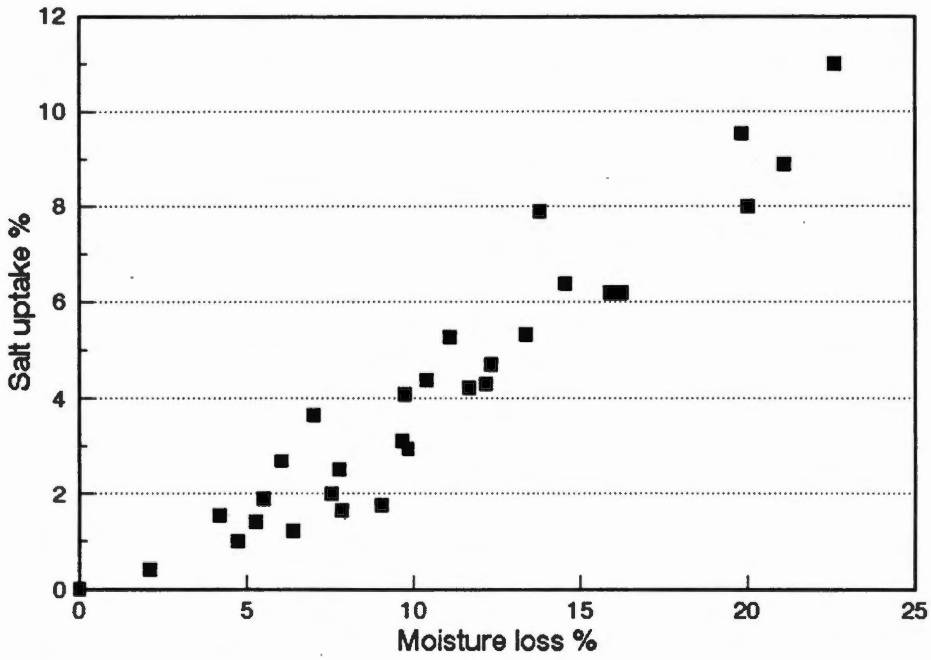

Figure 5. Observed salt uptake by green bean pods as a function of moisture loss in small-batch experiments.

The model equation was:

$$S\ (\%) = (b_0 - b_1T + b_2X)\ \sqrt{C}\ M \qquad (3)$$

where b_0, b_1 and b_2 were coefficients to be determined. M represented the moisture loss by green beans as given by Equation 2. Salt uptake (S) is defined as the mass percentage of salt in the green beans following processing and is expressed as follows:

$$S\ (\%) = \frac{mass\ NaCl}{total\ mass\ of\ green\ beans\ following\ contacting} \times 100. \qquad (4)$$

Model 3 was thus developed to predict the salt uptake (S) by the green beans as a function of moisture loss (M) and the other processing variables.

Linear regression (Proc Reg) within the Statistical Analysis System (SAS, 1985) was employed to estimate coefficients for both models. Since Model 2 was in exponential form, the equation was transformed to a linear form before applying the regression analysis.

II. RESULTS AND DISCUSSION

Values of coefficients used in the two models above were estimated by the regression analysis as: a_0 = 4.24, a_1 = 0.65, a_2 = 10.45, b_0 = 0.1314, b_1 =

0.103×10^{-2}, and $b_2 = 0.214 \times 10^{-3}$. The coefficient of determination (R^2) in the case of each model was 0.99, indicating that 99 percent of the total variation in the values of moisture loss and salt uptake was explained by the variables considered. P-values for each individual processing variable test were less than 0.05. This indicated that there was strong evidence of significant effects of salt solution concentration, temperature, and processing time upon moisture loss and salt uptake of green beans.

To test for potential problems in each regression model, influence and collinearity diagnostics were employed. Results of those diagnostic are described below.

Influence Diagnostic

The influence diagnostic technique was used to detect the most influential outlying data points within the scatter. These outlying points might occur due to improperly recorded data, calculation errors, or observation errors. Such errors might have a disproportionate influence on the parameter estimates and would be of concern in any regression analysis. Results of the diagnostic indicated that some observations might indeed have a significant influence on the parameter estimates. Those observations with higher influence values were temporarily deleted from the data set. Models were again developed as previously described using the data set with certain observations deleted. Model results thus obtained were similar, indicating that the deleted observations did not appreciably affect the form of the model. Thus, all observations were retained in the data set.

Collinearity Diagnostic

The collinearity diagnostic was used to further test both models. Collinearity diagnostic output is shown in Tables 1 and 2. Results suggest that no substantial collinearity problem existed within the models. First, correlations among the processing variables for both models were less than 0.90. Second, as indicated in Table 2, all condition numbers for both models were less than thirty. Belsley et al. (1980) noted that any condition index greater than or equal to thirty suggested the presence of moderate to severe collinearity. Third, in Table 2, the third row involved two loadings greater than 0.5 which correspond to the smallest eigenvalues. Since the smallest eigenvalues had condition numbers 6.54 (less than the warning level of 30 for moderate collinearity), the proportion pattern did not indicate any major problem.

In summary, all diagnostics showed that there were no substantial problems in fitting the models to the data. Further, both regression models based upon the experimental data described the osmotic dehydration process very well. Therefore, for this small-scale experiment, the models could be expressed in final forms as follows:

Table 1. Regression Diagnostic Results I. Correlation among the processing variables in the small-batch experiments

Corr	Correlation of Estimates				
	X_0	X_1	X_2	Y_1	Y_2
X_0	1.00	-0.77	-0.60		
X_1	-0.77	1.00	0.07		
X_2	-0.60	0.07	1.00		
Y_1				1.00	0.05
Y_2				0.05	1.00

Table 2. Regression Diagnostic Results II. Collinearity of the processing variables in the small-batch experiments

No.	Eigenvalue	Condition No.	Variable Proportion				
			X_0	X_1	X_2	Y_1	Y_2
1	2.72	1.00	0.013	0.019	0.029		
2	0.22	3.51	0.009	0.261	0.674		
3	0.06	6.54	0.978	0.720	0.298		
4	0.20	3.69				0.044	0.911
5	0.23	11.40				0.950	0.059

$X_0 = C^{0.5} M$, $X_1 = C^{0.5} M T$, $X_2 = C^{1.5} M$, $Y_1 = C$, and $Y_2 = -(T X)^{-0.5}$.

$$M\ (\%) = 4.24\ C^{0.65}\ e^{\frac{-10.45}{\sqrt{T X}}} \tag{5}$$

and

$$S\ (\%) = (0.1314 - 0.00103T + 0.000214X)\ \sqrt{C}\ M. \tag{6}$$

CHAPTER IV

DESIGN OF A PROTOTYPE CONTACTOR FOR OSMOTIC DEHYDRATION OF GREEN BEANS

Based upon the results of small-scale batch experiments involving osmotic dehydration of green beans in sodium chloride solutions, a recirculation-type laboratory-scale batch contactor was designed and developed.

I. THE PROTOTYPE CONTACTOR

Tank and Frame

The processing vessel was a PVC weldment measuring 1200 mm long by 340 mm wide and 200 mm deep with a capacity of about 0.08 m^3 of salt solution. The tank was supported by an angle iron frame. Four parallel pipes were installed along the length of the tank at a position just above the bottom surface. These pipes had a series of holes drilled along their lengths. The line of holes in each pipe was oriented upward.

Baskets

Mesh baskets of about 0.5-kg capacity and used commercially for deep frying in restaurants were employed as containers for holding the green beans as batches and for keeping the pod segments completely immersed in the salt solution. A rack was provided along the walls of the contactor vessel for supporting the baskets containing the produce to be dehydrated.

Temperature Control System

The temperature control system consisted of an ice box and a 1500-watt immersion heater. Processing temperature was maintained near constant by using a series of hand-operated valves to direct flow through heating or cooling baths as needed (Figure 6). After some practice, this manual temperature regulation system was easily operated so as to maintain the solution temperature within 1°C of the prescribed level for at least one hour.

II. OPERATION OF THE CONTACTOR

Figure 7 illustrates the prototype contactor system. Pressurized fluid entered the tank at one end. This flow was routed into a set of four parallel pipes. Fluid discharged from the pipes was directed upward through the fluid already in the tank. When the system was stabilized at the designated processing temperature, the baskets with bean pods were immersed in the salt solution. Fluid discharged from the sparger pipes and fluid movement along the length of the vessel provided ample agitation to assure fluid movement in and around the baskets of bean pods during processing.

Fluid exited the tank through a series of drain ports on the opposite end of the tank. These drain ports were installed just below the top edge of the tank

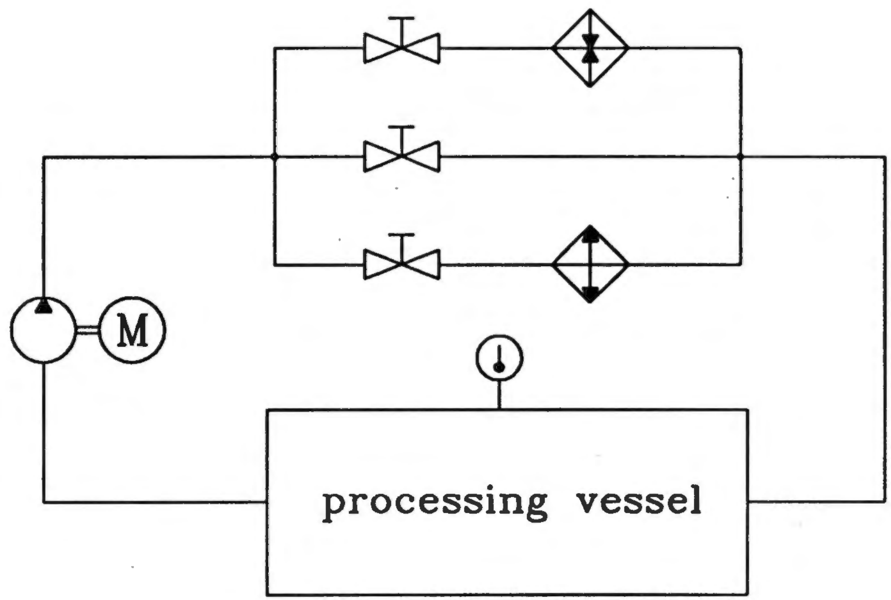

Figure 6. Schematic of the prototype contactor liquid recirculation system.

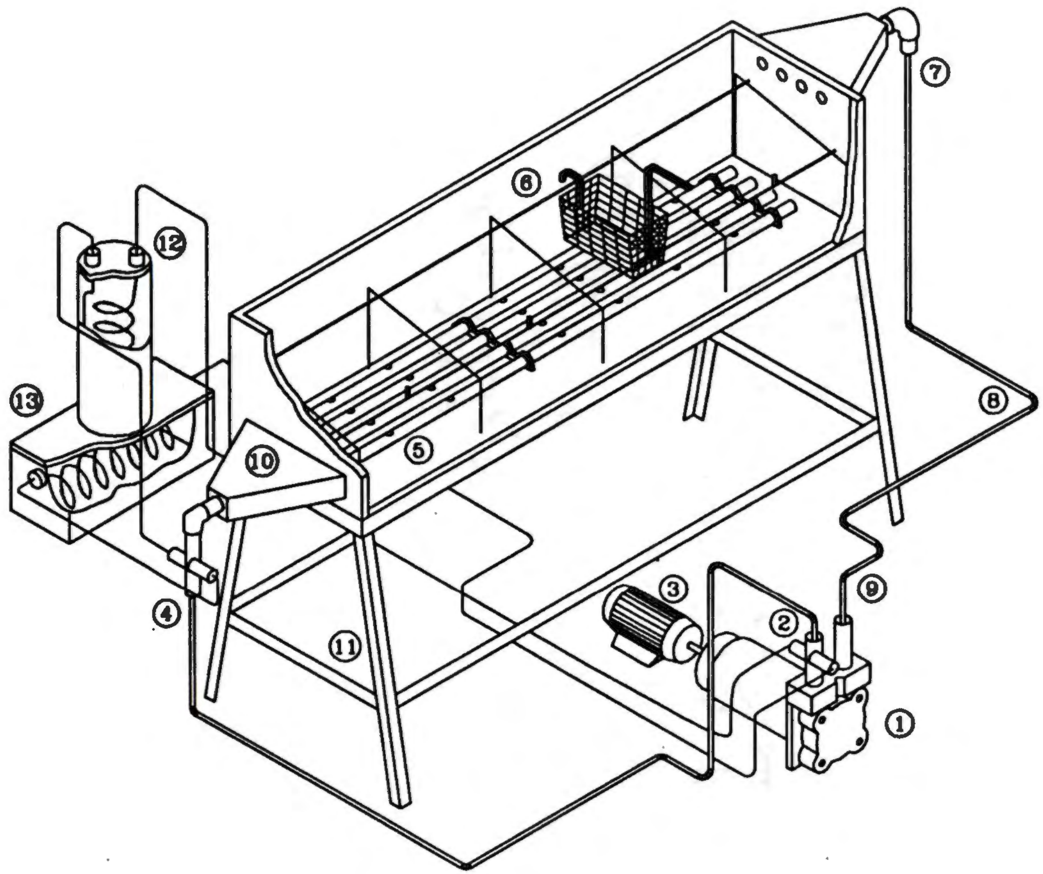

Figure 7. An experimental laboratory-scale osmotic dehydration contactor: (1) pump; (2) pump outlet; (3) motor; (4) vessel inlet; (5) inlet pipes; (6) basket and rack; (7) vessel outlet; (8) conduits; (9) pump inlet; (10) processing vessel; (11) frame; (12) heater bath; and (13) cooler bath.

end plate to establish the desired liquid level for produce processing. Fluid exiting the tank returned directly to the inlet of a centrifugal recirculation pump. Output flow from this pump could be divided along three paths by manipulating the hand-operated valves (Figure 6). First, flow could be returned directly to the processing vessel inlet. The other two paths were designed to provide control of the processing solution temperature. In one instance, a portion or all of the pump outlet flow could be directed through a heat exchanger immersed in a container of heated water. This route was chosen if the temperature of the contacting solution as indicted by a thermometer in the processing tank began to fall below the desired level. After passing through the exchanger, the heated fluid then entered the processing vessel. Similarly, fluid could be routed through a second heat exchanger immersed in an ice bath. This flow path could be employed if the solution temperature began to rise above the specified level.

CHAPTER V

CONTACTOR PERFORMANCE

After the contactor was designed and fabricated, it was then employed to process green beans in the sodium chloride solution to remove moisture. Processing variables include sodium chloride solution concentration, processing temperature, and time of green bean exposure to the salt water solution. Data from this contactor processing were collected and analyzed.

I. MATERIALS AND METHODS

Green beans used in the test were purchased from a local market. They were graded, cleaned, and standardized by soaking them in tap water at room temperature for one hour. The beans were cross cut into pieces approximately 2.5 cm in length and then sliced lengthwise into halves by hand.

The prototype contactor was used to dehydrate the green beans at four different salt solution concentrations (5%, 10%, 15%, and 20% by weight) and three different temperatures (10°C, 20°C, and 30°C). Salt uptake by and moisture loss from the green beans were analyzed for contacting durations of 0, 15, 30, 45, and 60 minutes. Each combination of processing variables was replicated four times. In each replicate, about 1 kg of beans were processed in the contactor, about 0.25 kg in each of four baskets. Since the volume of the contactor was fixed, the mass ratio of green beans to salt solution was maintained at about 1 to 80.

Following initiation of processing, a basket of bean pods was removed from the salt solution after each 15-minute interval. The beans were quickly rinsed in tap water to remove any solution remaining on the surface, and blotted dried. The entire batch of beans was then analyzed for reduction in mass. Three samples (approximately 2 grams each) of bean tissue were randomly collected from each basket representing a combination of variables. These samples were analyzed reduction in moisture content by drying the samples in a vacuum oven for six hours at 70 ± 1°C under a pressure 100 mm Hg (AOAC, 1984). Sodium chloride content was determined by using a titration method (AOAC, 1984). The percentage of original moisture lost from the green beans was calculated by using Equation 1 in Chapter 3. The experimental data are tabulated in Appendix B.

II. MODEL DEVELOPMENT

Moisture Loss Model

Typical experimental data of moisture loss versus time are illustrated in Figure 8. Total moisture loss from the pod increased with contacting time and with process temperature. Figure 8 also indicates that total moisture loss increased with increases in the salt concentration of the NaCl contacting

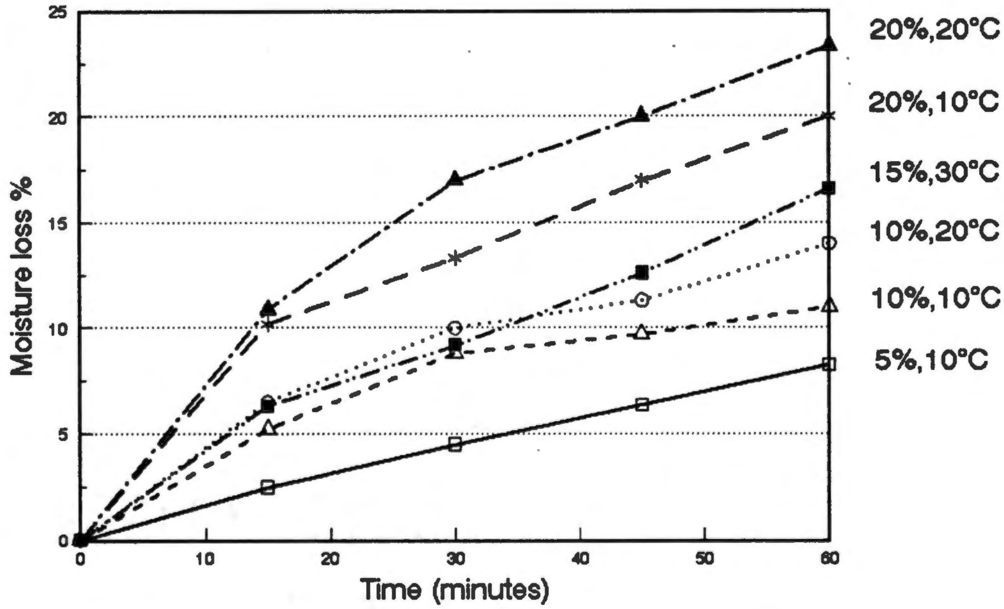

Figure 8. Moisture loss as a function of time for various processing temperatures and contacting solution concentrations using the prototype contactor.

solution. Thus, an exponential relationship between moisture loss and the processing variables was used to develop the model equation. Since the mass ratio of the green beans to the salt solution was maintained at 1 to 80, the assumption was made that the solution concentration was constant during the process. The relationship between moisture loss and the processing variables could be expressed using an equation of the form shown in Chapter 3, Equation 2.

Salt Uptake Model

Figure 9 indicates that there was, in general, a linear relationship between the salt uptake and moisture loss of the pod with residual variations due to bath composition, temperature and contacting time. Thus, the model equation describing the process could be expressed as shown by the relationship in Chapter 3, Equation 3.

III. RESULTS AND DISCUSSION

The Statistical Analysis System (SAS, 1985) was employed to estimate coefficients for both of the models specified above. Values of coefficients were estimated by the regression analysis as: $a_0 = 13.84$, $a_1 = 0.43$, $a_2 = 27.88$, $b_0 = 0.082$, $b_1 = 0.905 \times 10^{-3}$, and $b_2 = 0.23 \times 10^{-3}$. The coefficient of determination (R^2)

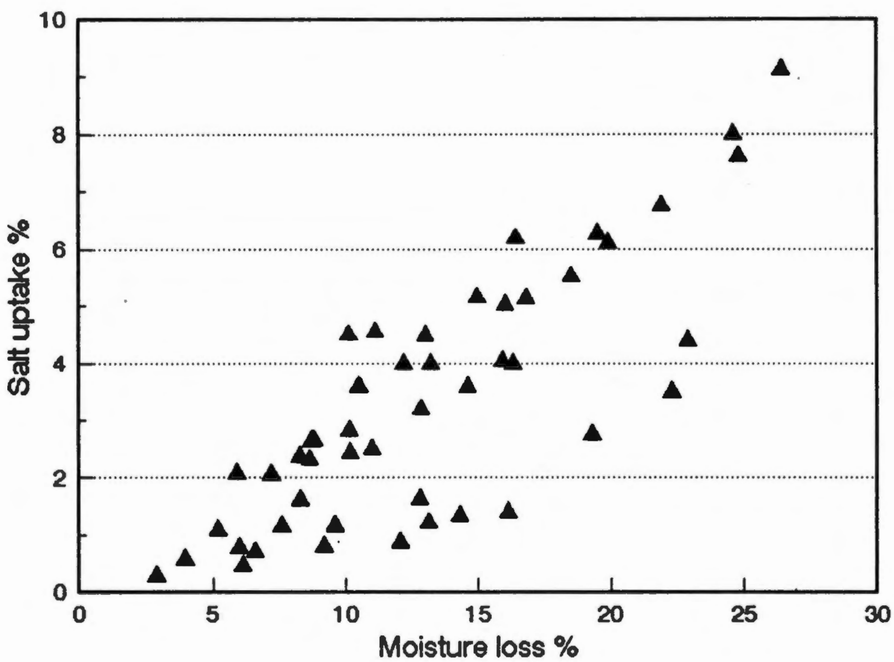

Figure 9. Observed salt uptake by green bean pods as a function of moisture loss using the prototype contactor.

in the case of each model was 0.98. Thus, the regression models were expressed as:

$$M\ (\%) = 13.84\ C^{0.43}\ e^{\frac{-27.88}{\sqrt{TX}}} \tag{7}$$

and

$$S\ (\%) = (0.082 - 0.000905T + 0.00023X)\ \sqrt{C}\ M \tag{8}$$

Figures 10 and 11 show the experimental data versus the predicted values. The data points and predicted values are scattered along the "diagonal" lines.

The influence and collinearity diagnostics were also employed to test models 7 and 8. Test procedures were identical to those described in Chapter 3. Tables 3 and 4 show the test results for models 7 and 8. All diagnostic tests indicated that there were no substantial problems in fitting the models to the data.

In comparing the small batch process to contactor processing, recall that moisture loss could be generally expressed as:

$$M\ (\%) = a_0\ C^{a_1}\ e^{\frac{-a_2}{\sqrt{TX}}} \tag{9}$$

The parameter a_0 in the model is an indication of the total amount of moisture removed during processing. Larger values of a_0 indicate that more

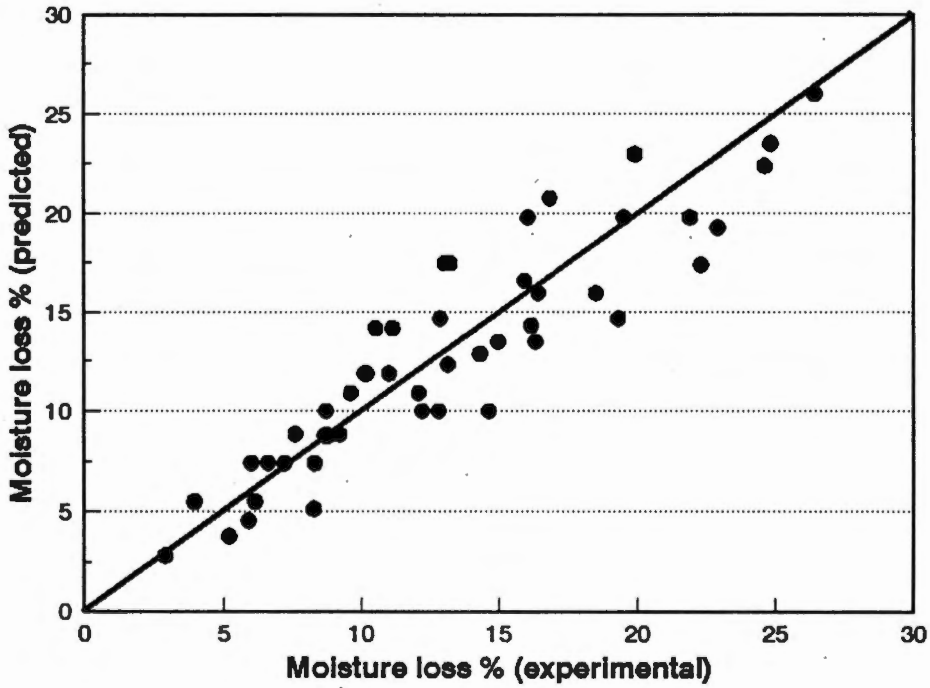

Figure 10. Predicted moisture loss versus measured moisture loss for the prototype contactor.

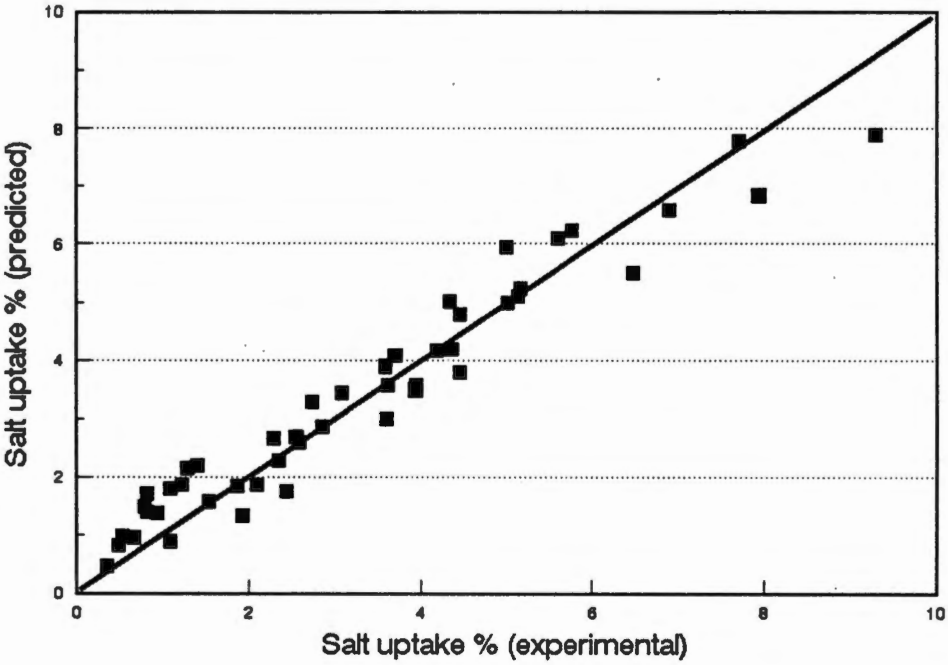

Figure 11. Predicted salt uptake versus measured salt uptake for the prototype contactor.

Table 3. Regression Diagnostic Results I. Correlation among the processing variables for the prototype contactor experiments

	Correlation of Estimates				
Corr	X_0	X_1	X_2	Y_1	Y_2
X_0	1.00	-0.73	-0.67		
X_1	-0.73	1.00	0.04		
X_2	-0.67	0.04	1.00		
Y_1				1.00	0.00
Y_2				0.00	1.00

Table 4. Regression Diagnostic Results II. Collinearity of the processing variables for the prototype contactor experiments

			Variable Proportion				
No.	Eigenvalue	Condition No.	X_0	X_1	X_2	Y_1	Y_2
1	2.87	1.00	0.006	0.010	0.012		
2	0.10	5.35	0.002	0.395	0.567		
3	0.03	9.49	0.993	0.595	0.421		
4	0.09	5.69				0.139	0.855
5	0.02	11.92				0.856	0.132

$X_0 = C^{0.5} M$, $X_1 = C^{0.5} M T$, $X_2 = C^{1.5} M$, $Y_1 = C$, and $Y_2 = -(T X)^{-0.5}$.

moisture was removed. The parameter a_2 is associated with the moisture loss near the beginning of the process. Smaller values correspond to higher initial moisture removal rates. Table 5 illustrates the parameter comparison of the two processing methods.

Table 5. Parameter Comparison for Small and Large-Scale Processes

	a_0	a_1	a_2
Small Batch	4.24	0.65	10.45
Contactor	13.84	0.43	27.88

In small batch processing, moisture was removed rapidly at the beginning of the process, as indicated by the small value of a_2 associated with the small batch processing equation. Over the total contacting period, more moisture could be removed by using the contactor, since contactor processing had a larger value of a_0. For example, given processing conditions of salt solution concentration = 5% NaCl, temperature = 30°C, and processing time = 30 minutes, the moisture loss was 8.5% (by weight) for batch processing and 11% (by weight) for the contactor processing. An explanation for the difference might be found in the differences between the contacting experiments. For the small-scale batch experiment, the ratio of green beans to solution was 1 to 3 on a mass basis. As processing continued, salt solution concentration was reduced. Thus, the driving force was reduced over time. As a result, the rate of moisture loss from green beans was diminished. However, for contactor processing, the mass ratio of green beans to solution was 1 to 80. Thus, changes in salt concentration in the solution over time were negligible. The driving force remained relatively constant. As a result, more total moisture was removed over the processing period. The difference between the two processes at a salt concentration of 5% and a temperature of 30°C is illustrated in Figure 12.

Figure 13 compares the two processes in terms of salt uptake. Small-scale batch processing resulted in greater salt uptake by the pods than did contactor processing. For example, at a solution concentration = 5% NaCl, temperature = 30°C, and time = 30 minutes, model 6 predicts salt uptake of 4.5% (by weight) while model 8 indicates 2.6% (by weight).

In summarizing the two osmotic dehydration techniques, contactor processing had, in general, greater moisture removal and less salt uptake than did batch processing. The differences in results produced by the two processes may be attributable to two things. First, the mass ratio of green beans to NaCl solution was very different in the two sets of experimentation. Second, the green beans used in the two sets of tests probably were quit different. Freshly harvested Bush Blue Lake - 47 snap beans were used in the small-scale batch

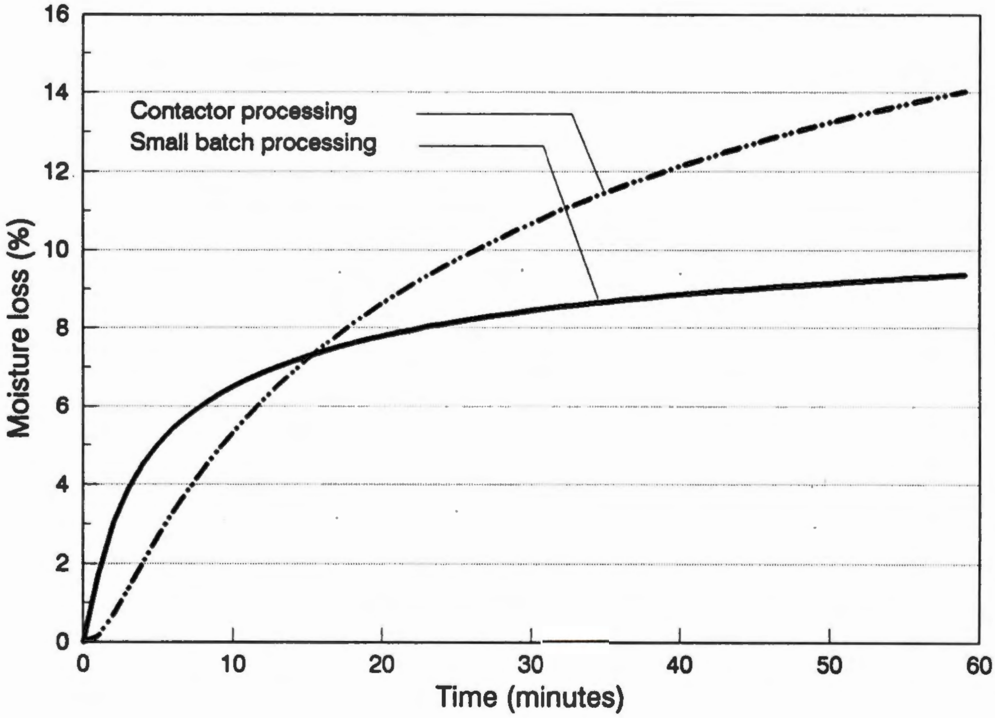

Figure 12. Comparison of moisture loss in small and large scale processes at a salt concentration = 5% and temperature = 30°C.

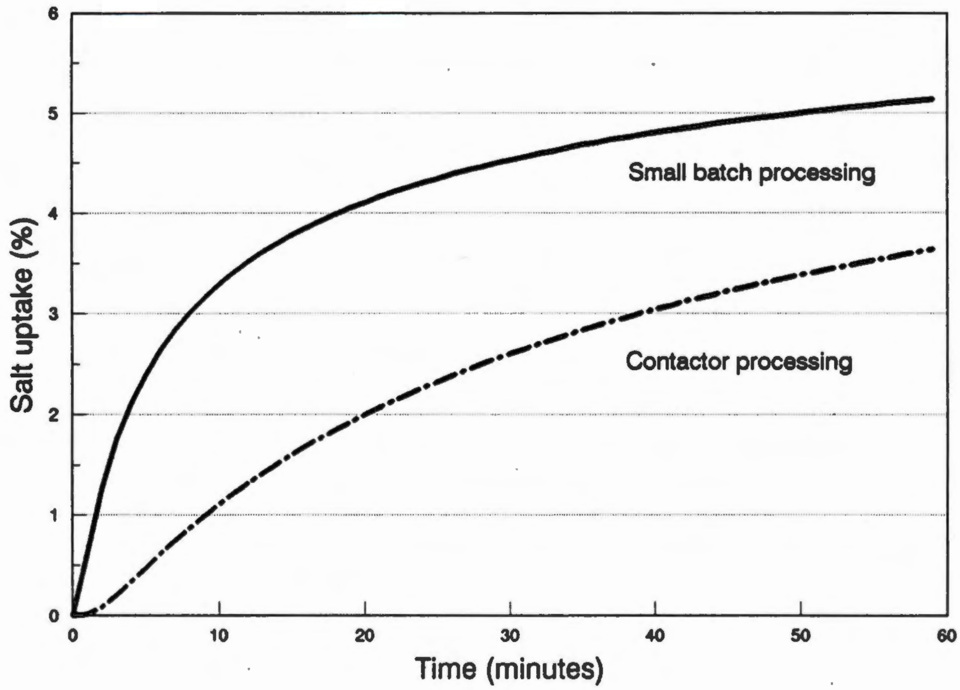

Figure 13. Comparison of salt uptake in small and large scale processes at a salt concentration = 5% and temperature = 30°C.

experiments. The beans processed in the prototype contactor were purchased from a local produce market. The history of those beans, including variety, time since harvest, and storage and transport conditions, were unknown.

CHAPTER VI

SUMMARY AND CONCLUSION

I. SUMMARY

Small-scale experiments conducted by Biswal and Bozorgmehr (1988) involved osmotic dehydration of green beans in sodium chloride solutions. Green beans were dehydrated in several laboratory beakers using a very small scale batch process. Processing variables for this study included concentration of NaCl solution, processing temperature, and the process duration. Data describing moisture loss from and salt uptake by the green beans were analyzed. Two regression models based upon the experimental data were developed. They were:

$$M\ (\%) = 4.24\ C^{0.65}\ e^{\frac{-10.45}{\sqrt{T\,X}}} \qquad (10)$$

$$S\ (\%) = (0.1314 - 0.00103T + 0.000214X)\ \sqrt{C}\ M \qquad (11)$$

Coefficients of determination (R^2) for both models were 0.99.

To allow larger-scale batch-type processing, a laboratory contactor was designed to osmotically dehydrate green beans. The contactor was then employed to dehydrate green beans in NaCl solution. Laboratory experiments were conducted at four different solution concentrations and three different processing temperatures. Green bean samples were analyzed after being exposed to the NaCl solution for 0, 15, 30, 45, or 60 minutes. Moisture loss from and salt uptake by the green bean tissue were analyzed using standard laboratory techniques. Regression models based upon the contactor processing data were developed as follows:

$$M\ (\%) = 13.84\ C^{0.43}\ e^{\frac{-27.88}{\sqrt{T\,X}}} \tag{12}$$

$$S\ (\%) = (0.082 - 0.000905T + 0.00023X)\ \sqrt{C}\ M \tag{13}$$

R^2 for each of the above models was 0.98.

In comparing small-scale batch processing models with the contactor processing models, contactor processing was found to remove more moisture and resulted in less salt uptake then the small scale batch process. However, the small-scale batch processing resulted in more rapid removal of moisture at the beginning of the processing period.

Differences in results produced by the two processing methods may be associated with (1) differences in mass ratios of beans to solution used in the two systems and (2) physical differences in the green beans used in the two sets of tests.

II. CONCLUSIONS

For this research, major conclusions were made as follows:

1. Salt solution concentration, solution temperature, and time of green bean exposure to the salt water solution each had a significant effect on moisture loss from, and salt uptake by, green beans during osmotic contacting.
2. An exponential model predicting moisture loss from green beans during osmotic contacting with an aqueous solution of sodium chloride appears suitable for practical use.
3. A linear model for predicting salt uptake by green beans during osmotic contacting with an aqueous solution of sodium chloride describes the process well.
4. The batch contactor developed for this study worked well in the laboratory and may serve as the basis for the development of a semi-continuous or continuous processing unit.

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APPENDIXES

APPENDIX A

Table 6. Mass Transfer Data for Osmotic Dehydration of Green Beans in Aqueous Solutions of Sodium Chloride. Experiments involved small-batches of green beans contacted in laboratory beakers as described by Biswal and Bozorgmehr (1988).

rep. #	expt.condi °C/%NaCl	time min.	m_θ/m_0	salt %	w_θ	moisture loss %
1	8/5	0	1.000	0.00	0.907	0.00
1		5	0.980	0.40	0.906	2.11
1		15	0.960	1.00	0.900	4.74
1		30	0.960	1.40	0.895	5.27
1		60	0.940	2.00	0.892	7.55
2	8/5	0	1.000	0.00	0.907	0.00
2		5	0.981	0.60	0.906	2.01
2		15	0.969	1.17	0.895	4.38
2		30	0.958	1.34	0.895	5.47
2		60	0.939	1.99	0.892	7.65
3	8/5	0	1.000	0.00	0.907	0.00
3		5	0.974	0.41	0.905	2.81
3		15	0.947	1.17	0.894	6.66
3		30	0.946	1.46	0.887	7.49
3		60	0.934	1.87	0.891	8.25
1	8/9.62	0	1.000	0.00	0.907	0.00
1		5	0.971	1.55	0.895	4.18
1		15	0.961	2.69	0.887	6.02
1		30	0.942	4.09	0.869	9.75
1		60	0.942	5.26	0.856	11.10
1	8/16.90	0	1.000	0.00	0.907	0.00
1		5	0.950	3.65	0.888	6.99
1		15	0.924	4.91	0.861	12.29
1		30	0.919	7.89	0.851	13.77
1		60	0.884	8.94	0.832	18.91

Table 6. (continued)

rep. #	expt.condi °C/%NaCl	time min.	m_θ/m_0	salt %	w_θ	moisture loss %
1	20/9.62	0	1.000	0.00	0.907	0.00
1		5	0.960	1.90	0.893	5.48
1		15	0.930	3.10	0.881	9.67
1		30	0.910	4.70	0.874	12.31
1		60	0.890	6.20	0.857	15.90
2	20/9.62	0	1.000	0.00	0.907	0.00
2		5	0.963	1.93	0.897	4.76
2		15	0.930	3.39	0.887	9.05
2		30	0.892	4.33	0.871	14.34
2		60	0.890	6.31	0.858	15.80
3	20/9.62	0	1.000	0.00	0.907	0.00
3		5	0.947	2.10	0.887	7.39
3		15	0.913	3.57	0.877	11.72
3		30	0.901	4.68	0.864	14.17
3		60	0.877	6.25	0.855	17.33
1	20/16.90	0	1.000	0.00	0.907	0.00
1		5	0.933	4.38	0.871	10.40
1		15	0.900	6.37	0.861	14.56
1		30	0.875	9.53	0.831	19.83
1		60	0.857	10.99	0.819	22.61
1	40/4.91	0	1.000	0.00	0.907	0.00
1		5	0.955	1.23	0.889	6.39
1		15	0.937	1.65	0.892	7.85
1		30	0.928	1.75	0.889	9.04
1		60	0.921	2.92	0.888	9.83
1	40/9.62	0	1.000	0.00	0.907	0.00
1		5	0.956	2.51	0.875	7.77
1		15	0.925	4.21	0.866	11.68
1		30	0.916	5.32	0.858	13.35
1		60	0.905	6.78	0.856	14.59

Table 6. (continued)

rep. #	expt.condi °C/%NaCl	time min.	m_θ/m_0	salt %	w_θ	moisture loss %
1	40/17.8	0	1.000	0.00	0.907	0.00
1		5	0.920	4.30	0.866	12.16
1		15	0.900	6.20	0.844	16.25
1		30	0.890	8.00	0.815	20.03
1		60	0.890	8.90	0.804	21.11
2	40/17.8	0	1.000	0.00	0.907	0.00
2		5	0.925	4.13	0.862	12.09
2		15	0.902	6.66	0.839	16.56
2		30	0.892	7.52	0.826	18.77
2		60	0.890	9.99	0.804	21.11
3	40/17.8	0	1.000	0.00	0.907	0.00
3		5	0.938	4.07	0.864	10.65
3		15	0.914	6.29	0.825	16.86
3		30	0.883	7.64	0.824	19.78
3		60	0.885	8.88	0.808	21.16

m_θ/m_0 : mass reduction of green beans at time θ;
w_θ : weight fraction of water content in green beans at time θ.

APPENDIX B

Table 7. Mass Transfer Data for Osmotic Dehydration of Green Beans in Aqueous Solutions of Sodium Chloride Using a Prototype Contactor

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	5	10	0	0.00	1.000	0.897320	0.897320	0.0000
1	5	10	15	0.35	0.978	0.894330	0.897320	2.5259
1	5	10	30	0.53	0.968	0.885750	0.897320	4.4481
1	5	10	45	0.93	0.957	0.883560	0.897320	5.7675
1	5	10	60	0.82	0.948	0.881310	0.897320	6.8914
2	5	10	0	0.00	1.000	0.901330	0.901330	0.0000
2	5	10	15	0.29	0.979	0.893430	0.901330	2.9581
2	5	10	30	0.58	0.975	0.887780	0.901330	3.9658
2	5	10	45	0.78	0.958	0.883960	0.901330	6.0462
2	5	10	60	1.16	0.946	0.880220	0.901330	7.6156
3	5	10	0	0.00	1.000	0.904560	0.904560	0.0000
3	5	10	15	0.35	0.981	0.899190	0.904560	2.4824
3	5	10	30	0.63	0.969	0.891540	0.904560	4.4948
3	5	10	45	0.80	0.958	0.884250	0.904560	6.3510
3	5	10	60	0.99	0.943	0.880000	0.904560	8.2604
4	5	10	0	0.00	1.000	0.907550	0.907550	0.0000
4	5	10	15	0.39	0.982	0.897800	0.907550	2.8550
4	5	10	30	0.64	0.976	0.895240	0.907550	3.7238
4	5	10	45	0.83	0.964	0.884970	0.907550	5.9984
4	5	10	60	0.88	0.944	0.880520	0.907550	8.4116

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	5	20	0	0.00	1.000	0.915040	0.915040	0.0000
1	5	20	15	0.49	0.961	0.906160	0.915040	4.8326
1	5	20	30	0.82	0.942	0.901630	0.915040	7.1805
1	5	20	45	1.09	0.934	0.894870	0.915040	8.6588
1	5	20	60	1.28	0.899	0.892210	0.915040	12.3430
2	5	20	0	0.00	1.000	0.913100	0.913100	0.0000
2	5	20	15	0.47	0.960	0.892830	0.913100	6.1311
2	5	20	30	0.81	0.939	0.883020	0.913100	9.1933
2	5	20	45	1.17	0.935	0.882710	0.913100	9.6119
2	5	20	60	1.22	0.901	0.880190	0.913100	13.1474
3	5	20	0	0.00	1.000	0.901690	0.901690	0.0000
3	5	20	15	0.53	0.959	0.899980	0.901690	4.2819
3	5	20	30	0.79	0.942	0.883670	0.901690	7.6826
3	5	20	45	1.19	0.926	0.880700	0.901690	9.5556
3	5	20	60	1.26	0.908	0.879050	0.901690	11.4798
4	5	20	0	0.00	1.000	0.915350	0.915350	0.0000
4	5	20	15	0.58	0.958	0.899250	0.915350	5.8850
4	5	20	30	0.91	0.941	0.899010	0.915350	7.5798
4	5	20	45	1.11	0.920	0.887910	0.915350	10.7579
4	5	20	60	1.52	0.911	0.884850	0.915350	11.9355

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	5	30	0	0.00	1.000	0.904260	0.904260	0.0000
1	5	30	15	0.67	0.949	0.898740	0.904260	5.6793
1	5	30	30	0.79	0.895	0.885370	0.904260	12.3697
1	5	30	45	1.22	0.879	0.884240	0.904260	14.0461
1	5	30	60	1.40	0.865	0.874190	0.904260	16.3764
2	5	30	0	0.00	1.000	0.903830	0.903830	0.0000
2	5	30	15	0.70	0.939	0.898970	0.903830	6.6049
2	5	30	30	0.88	0.895	0.887960	0.903830	12.0715
2	5	30	45	1.34	0.873	0.886990	0.903830	14.3266
2	5	30	60	1.41	0.866	0.875320	0.903830	16.1317
3	5	30	0	0.00	1.000	0.908270	0.908270	0.0000
3	5	30	15	0.74	0.940	0.899200	0.908270	6.9387
3	5	30	30	0.99	0.886	0.895970	0.908270	12.5998
3	5	30	45	1.40	0.872	0.888340	0.908270	14.7134
3	5	30	60	1.59	0.859	0.875090	0.908270	17.2380
4	5	30	0	0.00	1.000	0.911623	0.911623	0.0000
4	5	30	15	0.73	0.948	0.894034	0.911623	7.0291
4	5	30	30	0.86	0.904	0.888207	0.911623	11.9220
4	5	30	45	1.36	0.872	0.884258	0.911623	15.4176
4	5	30	60	1.43	0.858	0.876353	0.911623	17.5195

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	10	10	0	0.00	1.000	0.908043	0.908043	0.0000
1	10	10	15	1.09	0.965	0.902135	0.908043	4.1279
1	10	10	30	2.09	0.957	0.879480	0.908043	7.3103
1	10	10	45	2.59	0.950	0.873925	0.908043	8.5694
1	10	10	60	2.74	0.945	0.870033	0.908043	9.4557
2	10	10	0	0.00	1.000	0.899761	0.899761	0.0000
2	10	10	15	1.10	0.962	0.886457	0.899761	5.2224
2	10	10	30	2.07	0.953	0.876077	0.899761	7.2085
2	10	10	45	2.65	0.946	0.868375	0.899761	8.6999
2	10	10	60	2.82	0.939	0.860981	0.899761	10.1471
3	10	10	0	0.00	1.000	0.910559	0.910559	0.0000
3	10	10	15	1.13	0.968	0.891401	0.910559	5.2367
3	10	10	30	2.22	0.951	0.873423	0.910559	8.7785
3	10	10	45	2.64	0.947	0.867791	0.910559	9.7480
3	10	10	60	2.89	0.941	0.860585	0.910559	11.0645
4	10	10	0	0.00	1.000	0.906065	0.906065	0.0000
4	10	10	15	1.18	0.965	0.895611	0.906065	4.6134
4	10	10	30	2.00	0.948	0.875112	0.906065	8.4386
4	10	10	45	2.55	0.943	0.870707	0.906065	9.3799
4	10	10	60	2.80	0.939	0.863278	0.906065	10.5342

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	10	20	0	0.00	1.000	0.896356	0.896356	0.0000
1	10	20	15	1.53	0.942	0.882955	0.896356	7.2083
1	10	20	30	2.28	0.938	0.875585	0.896356	8.3736
1	10	20	45	3.08	0.922	0.865263	0.896356	10.9983
1	10	20	60	3.70	0.913	0.847055	0.896356	13.7216
2	10	20	0	0.00	1.000	0.901559	0.901559	0.0000
2	10	20	15	1.62	0.939	0.880228	0.901559	8.3217
2	10	20	30	2.50	0.929	0.863552	0.901559	11.0164
2	10	20	45	3.20	0.914	0.859638	0.901559	12.8499
2	10	20	60	4.04	0.895	0.846333	0.901559	15.9824
3	10	20	0	0.00	1.000	0.896430	0.896403	0.0000
3	10	20	15	1.52	0.944	0.887840	0.896403	6.5018
3	10	20	30	2.30	0.925	0.872014	0.896403	10.0167
3	10	20	45	3.04	0.921	0.862903	0.896403	11.3419
3	10	20	60	3.65	0.908	0.849791	0.896403	13.9215
4	10	20	0	0.00	1.000	0.889479	0.889479	0.0000
4	10	20	15	1.68	0.937	0.881558	0.889479	7.1205
4	10	20	30	2.25	0.919	0.867430	0.889479	10.3781
4	10	20	45	3.12	0.912	0.859091	0.889479	11.9157
4	10	20	60	3.52	0.910	0.848974	0.889479	13.1439

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	10	30	0	0.00	1.000	0.916879	0.916879	0.0000
1	10	30	15	1.87	0.890	0.889743	0.916879	13.6340
1	10	30	30	2.86	0.864	0.857689	0.916879	19.1776
1	10	30	45	3.62	0.855	0.847889	0.916879	20.9334
1	10	30	60	4.36	0.843	0.842970	0.916879	22.4954
2	10	30	0	0.00	1.000	0.917713	0.917713	0.0000
2	10	30	15	1.64	0.910	0.879343	0.917713	12.8048
2	10	30	30	2.76	0.864	0.857530	0.917713	19.2661
2	10	30	45	3.50	0.841	0.847825	0.917713	22.3046
2	10	30	60	4.40	0.838	0.844191	0.917713	22.9136
3	10	30	0	0.00	1.000	0.907729	0.907729	0.0000
3	10	30	15	1.88	0.892	0.891253	0.907729	12.4191
3	10	30	30	2.74	0.863	0.874668	0.907729	16.8432
3	10	30	45	3.65	0.842	0.850898	0.907729	21.0716
3	10	30	60	4.26	0.838	0.842040	0.907729	22.2643
4	10	30	0	0.00	1.000	0.909446	0.909446	0.0000
4	10	30	15	1.79	0.894	0.894418	0.909446	12.0773
4	10	30	30	2.94	0.872	0.883086	0.909446	15.3275
4	10	30	45	3.43	0.851	0.856973	0.909446	19.8101
4	10	30	60	4.29	0.839	0.847798	0.909446	21.7873

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	15	10	0	0.00	1.000	0.914041	0.914041	0.0000
1	15	10	15	1.92	0.958	0.896499	0.914041	6.0386
1	15	10	30	2.54	0.939	0.883309	0.914041	9.2571
1	15	10	45	4.45	0.939	0.854430	0.914041	12.2239
1	15	10	60	4.45	0.896	0.874851	0.914041	14.2416
2	15	10	0	0.00	1.000	0.920108	0.920108	0.0000
2	15	10	15	2.08	0.962	0.899987	0.920108	5.9037
2	15	10	30	2.66	0.952	0.881229	0.920108	8.8227
2	15	10	45	4.50	0.950	0.870613	0.920108	10.1103
2	15	10	60	4.55	0.941	0.869088	0.920108	11.1178
3	15	10	0	0.00	1.000	0.913703	0.913703	0.0000
3	15	10	15	1.92	0.956	0.894181	0.913703	6.4426
3	15	10	30	2.74	0.940	0.884502	0.913703	9.0041
3	15	10	45	4.48	0.931	0.871258	0.913703	11.2249
3	15	10	60	4.64	0.921	0.855001	0.913703	13.8171
4	15	10	0	0.00	1.000	0.916591	0.916591	0.0000
4	15	10	15	1.74	0.954	0.899756	0.916591	6.3522
4	15	10	30	2.58	0.936	0.888105	0.916591	9.3089
4	15	10	45	4.48	0.931	0.875477	0.916591	11.0760
4	15	10	60	4.62	0.923	0.858834	0.916591	13.5161

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	15	20	0	0.00	1.000	0.914096	0.914096	0.0000
1	15	20	15	2.34	0.943	0.882023	0.914096	9.0087
1	15	20	30	3.59	0.914	0.871203	0.914096	12.8888
1	15	20	45	4.34	0.912	0.849091	0.914096	15.2856
1	15	20	60	5.00	0.892	0.846139	0.914096	17.4314
2	15	20	0	0.00	1.000	0.921214	0.921214	0.0000
2	15	20	15	2.32	0.942	0.893274	0.921214	8.6570
2	15	20	30	3.60	0.940	0.877507	0.921214	10.4598
2	15	20	45	4.49	0.929	0.861945	0.921214	13.0770
2	15	20	60	5.03	0.911	0.848983	0.921214	16.0430
3	15	20	0	0.00	1.000	0.921054	0.921054	0.0000
3	15	20	15	2.27	0.943	0.900690	0.921054	7.7849
3	15	20	30	3.44	0.921	0.878843	0.921054	12.1209
3	15	20	45	4.32	0.908	0.858623	0.921054	15.3546
3	15	20	60	4.87	0.891	0.854373	0.921054	17.3505
4	15	20	0	0.00	1.000	0.919049	0.919049	0.0000
4	15	20	15	2.39	0.938	0.900076	0.919049	8.1364
4	15	20	30	3.71	0.920	0.876618	0.919049	12.2475
4	15	20	45	4.40	0.900	0.867089	0.919049	15.0883
4	15	20	60	5.04	0.880	0.860210	0.919049	17.6339

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	15	30	0	0.00	1.000	0.914130	0.914130	0.0000
1	15	30	15	2.56	0.890	0.875712	0.914130	14.7404
1	15	30	30	4.19	0.871	0.854275	0.914130	18.6031
1	15	30	45	5.16	0.861	0.842516	0.914130	20.6452
1	15	30	60	5.95	0.840	0.777538	0.914130	28.5515
2	15	30	0	0.00	1.000	0.918550	0.918550	0.0000
2	15	30	15	2.45	0.923	0.893788	0.918550	10.1882
2	15	30	30	4.00	0.913	0.872693	0.918550	13.2580
2	15	30	45	5.13	0.902	0.847001	0.918550	16.8260
2	15	30	60	6.10	0.869	0.845825	0.918550	19.9802
3	15	30	0	0.00	1.000	0.915195	0.915195	0.0000
3	15	30	15	2.58	0.919	0.879842	0.915195	11.6500
3	15	30	30	4.21	0.882	0.859120	0.915195	17.2041
3	15	30	45	5.15	0.878	0.850379	0.915195	18.4182
3	15	30	60	6.08	0.865	0.841094	0.915195	20.5037
4	15	30	0	0.00	1.000	0.917095	0.917095	0.0000
4	15	30	15	2.41	0.911	0.879379	0.917095	12.6465
4	15	30	30	4.09	0.867	0.865526	0.917095	18.1752
4	15	30	45	5.20	0.859	0.848853	0.917095	20.4919
4	15	30	60	6.05	0.839	0.840836	0.917095	23.0765

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	20	10	0	0.00	1.000	0.915972	0.915972	0.0000
1	20	10	15	2.44	0.952	0.883491	0.915972	8.1759
1	20	10	30	3.95	0.945	0.865796	0.915972	10.6766
1	20	10	45	5.01	0.923	0.856754	0.915972	13.6672
1	20	10	60	5.76	0.914	0.850313	0.915972	15.1518
2	20	10	0	0.00	1.000	0.922659	0.922659	0.0000
2	20	10	15	2.37	0.951	0.890009	0.922659	8.2653
2	20	10	30	4.00	0.938	0.863365	0.922659	12.2280
2	20	10	45	5.15	0.919	0.853903	0.922659	14.9483
2	20	10	60	6.19	0.904	0.852982	0.922659	16.4268
3	20	10	0	0.00	1.000	0.915469	0.915469	0.0000
3	20	10	15	2.69	0.953	0.899759	0.915469	6.3354
3	20	10	30	3.86	0.946	0.878956	0.915469	9.1731
3	20	10	45	5.00	0.932	0.858179	0.915469	12.6325
3	20	10	60	5.80	0.912	0.837284	0.915469	16.5889
4	20	10	0	0.00	1.000	0.922122	0.922122	0.0000
4	20	10	15	2.62	0.953	0.897826	0.922122	7.2110
4	20	10	30	4.08	0.940	0.874768	0.922122	10.8272
4	20	10	45	5.11	0.922	0.861395	0.922122	13.8719
4	20	10	60	6.14	0.910	0.853544	0.922122	15.7676

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	20	20	0	0.00	1.000	0.922451	0.922451	0.0000
1	20	20	15	3.61	0.941	0.876174	0.922451	10.6208
1	20	20	30	5.13	0.919	0.855572	0.922451	14.7629
1	20	20	45	6.90	0.889	0.844709	0.922451	18.5923
1	20	20	60	7.70	0.874	0.817044	0.922451	22.5871
2	20	20	0	0.00	1.000	0.921332	0.921332	0.0000
2	20	20	15	3.59	0.895	0.878524	0.921332	14.6585
2	20	20	30	5.51	0.884	0.849364	0.921332	18.5052
2	20	20	45	6.75	0.858	0.838032	0.921332	21.9574
2	20	20	60	8.03	0.839	0.828306	0.921332	24.5713
3	20	20	0	0.00	1.000	0.921285	0.921285	0.0000
3	20	20	15	3.63	0.934	0.878698	0.921285	10.9175
3	20	20	30	5.50	0.905	0.844809	0.921285	17.0124
3	20	20	45	6.72	0.882	0.833261	0.921285	20.2271
3	20	20	60	7.37	0.862	0.820138	0.921285	23.2638
4	20	20	0	0.00	1.000	0.923978	0.923978	0.0000
4	20	20	15	3.70	0.920	0.876717	0.923978	12.7058
4	20	20	30	4.94	0.899	0.856310	0.923978	16.6839
4	20	20	45	7.08	0.891	0.852498	0.923978	17.7929
4	20	20	60	7.45	0.873	0.823964	0.923978	22.1496

Table 7. (continued)

rep #	NaCl %	temp. °C	time min.	salt %	m_θ/m_0	w_θ	w_0	moisture loss %
1	20	30	0	0.00	1.000	0.916611	0.916611	0.0000
1	20	30	15	3.94	0.894	0.874416	0.916611	14.7154
1	20	30	30	6.48	0.865	0.846164	0.916611	20.1480
1	20	30	45	7.94	0.832	0.827979	0.916611	24.8451
1	20	30	60	9.30	0.828	0.807722	0.916611	27.0362
2	20	30	0	0.00	1.000	0.916019	0.916019	0.0000
2	20	30	15	4.03	0.891	0.860217	0.916019	16.3278
2	20	30	30	6.26	0.872	0.845516	0.916019	19.5115
2	20	30	45	7.60	0.836	0.823529	0.916019	24.8411
2	20	30	60	9.12	0.831	0.811129	0.916019	26.4155
3	20	30	0	0.00	1.000	0.917600	0.917600	0.0000
3	20	30	15	3.89	0.900	0.868625	0.917600	14.8036
3	20	30	30	6.49	0.861	0.837482	0.917600	21.4176
3	20	30	45	7.68	0.838	0.831434	0.917600	24.0691
3	20	30	60	8.90	0.823	0.816100	0.917600	26.8036
4	20	30	0	0.00	1.000	0.908442	0.908442	0.0000
4	20	30	15	4.00	0.895	0.870371	0.908442	14.2508
4	20	30	30	6.50	0.858	0.840791	0.908442	20.5895
4	20	30	45	7.57	0.834	0.838569	0.908442	23.0147
4	20	30	60	9.20	0.821	0.812105	0.908442	26.6064

m_θ/m_0: mass reduction of green beans at time θ;
w_0, w_θ: weight fraction of water content in green beans at times 0 and θ.

VITA

Xia Liu was born in Chongqing city, P.R. China, on January 29, 1960. She began her early education in No.12 Elementary school in that city in 1966. In 1974, she entered No. 98 high school in the same city and graduated on July, 1976. On September, 1976, she was sent to the suburb of Chongqing city and worked on a farm until September, 1978.

In September,1978 she was admitted to the Agricultural Engineering Department, Southwestern Agricultural University, Chongqing, P. R. China and majored in Agricultural Mechanization. She received a Bachelor of Science degree in Agricultural Engineering in August of 1982. She then taught in that university for five years.

In December, 1986, she obtained a scholarship from her government and began study toward a Master of Science degree in Agricultural Engineering at The University of Tennessee, Knoxville. This degree was awarded in May, 1991.

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