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MICROCOMPUTER-BASED CONTROL OF EXHAUST AIR RECIRCULATION IN A FRUIT DEHYDRATOR

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Lihan Huang

May 1994

To:

My wife Ying Chen for her love, understanding, patience, and prayers throughout my graduate program.

My parents, Mr. Xuanliang Huang and Mrs. Ruiping Zheng for their encouragement and support over the past 30 years.

My daughter, Jiexin Huang for her being a very nice girl.

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ABSTRACT

A microcomputer-based control system was developed to monitor and control the exhaust air recirculation in a batch-type fruit dehydrator. The purpose of this system was to increase the recirculation of the exhaust air gradually as dehydration progressed. The system was able to maintain the humidity ratio of the drying air at different specified levels at different stages of drying. Type T thermocouples were used as temperature sensors to measure the dry and wet bulb temperatures of the drying air. The humidity ratio of the drying air was determined by the dry and wet bulb temperatures. Control of the humidity ratio of the drying air was accomplished by adjustment of the exhaust air recirculation. A stepping motor and valve mechanism were used to adjust the recirculation ratio. A microcomputer was used to control the motor through the I/O of a multifunction board and a stepping motor driver. The number of steps and direction for the motor were determined by the difference between the measured humidity ratio and the set point. The effects of proportional coefficients and sampling periods on the humidity control were investigated. The control system was able to maintain the humidity ratio of the drying air at an accuracy of ±0.001 kg water/kg dry air.

The system was tested under actual drying conditions to evaluate its performance. The dehydration started with an initial recirculation rate (70%) and was programmed to maintain the humidity ratio of the drying air at different specified levels as dehydration progressed. After the drying sample weight dropped to 70% of its original weight, the system adjusted to maintain the humidity ratio of the drying air at the set point of 0.025 kg water/kg dry air. Approximately five minutes were needed for the system to stabilize

at the set point after the adjustment. The recirculation of the exhaust air was increased gradually as dehydration progressed. The energy savings with this system was approximately 31% over the dehydration without air recirculation.

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CHAPTER I

INTRODUCTION

Air drying of food materials, along with other unit operations such as freezing and evaporation, is one of the more energy-intensive operations in the food industry. With the increasing cost of energy in modern industry, more and more attention has been directed to improving the efficiency of energy utilization to lower the costs of drying operations. Better understanding of the principles of drying, improving the performance of drying equipment, and developing revolutionary drying concepts may lead to improved energy conservation in the food industry. Among these alternatives, improving the performance of the food drying equipment appears to be the most practical and acceptable method to the food industry.

The temperature of food dehydrator exhaust air generally is higher than that of the ambient air. Thus, it is possible to recover and reuse a portion of energy used in the drying operation by mixing part of the unsaturated hot exhaust air with the fresh ambient air and recirculating it through the dehydrator. Depending upon the difference between the ambient and exhaust air temperatures and the degree of saturation in the exhaust air, a considerable amount of heat energy can be reclaimed. This recovery is technically feasible and economically significant.

Bakker-Arkema et al. (1974) reported a 16% difference in the dryer energy utilization index (total energy required by a dryer to remove 1 lb of moisture from grain under specified conditions) between a conventional and a modified cross flow grain dryer. Baski et al. (1978) recovered the heat energy in an air recirculating cross flow rice dryer by recycling the exhaust air one or more times. Walker (1992) studied the effect of air recirculation upon energy use of batch food dehydrators. He found energy savings up to 53% and 46% for peaches and apples, respectively, with an air recirculation rate of 75%. Recirculation did not affect the drying time and there was no identifiable loss of product quality.

Besides the energy-saving aspect of exhaust air recirculation, the absolute humidity of the exhaust air is higher than that of the ambient fresh air. The mixture of the exhaust and fresh air would provide a higher humidity drying medium, which in turn could decrease the drying rate and reduce the physical and chemical damages to the product. In the early stage of drying, the rate of moisture removal is determined by external conditions such as temperature, air velocity, and vapor pressure, etc. (Okos et al., 1992). Water is always available on the surface of drying materials at this stage (Sokhansanj and Jayas, 1987). As drying progresses, the drying rate begins to fall. The removal of moisture then is determined by the rate of moisture diffusion within the drying materials. The resistance of internal moisture transfer controls the process of drying in the falling rate stage (Okos et al., 1992). If the air humidity ratio is very low at this stage, the rate of moisture evaporation from the surface would be higher than the rate of moisture diffusion to the surface of the food. A steep moisture gradient may be established between the surface and the center of the drying materials (Van Arsdel and Copley, 1964). As a result, the surface of the food would become very dry, while the center may remain at a high moisture level. Severe physical damage, such as cracks, shrinkage, or case hardening, may then retard the drying process. Reducing the drying rate by increasing moisture in the drying air would help prevent the undesirable physical damage and the formation of case hardening (Van Arsdel and Copley, 1964). Since the moisture content of the exhaust air is higher than that of the fresh air, partial recirculation of exhaust air through the dryer may achieve this goal. Brooker et al. (1974) showed that a high drying rate and excessive drying temperatures could cause damage in both physical and chemical properties of grain. Drying with recirculated exhaust air would help alleviate this problem to some extent. Improved product quality has been reported by Young (1986) for peanuts dried with recirculated air. Wiegand (1923) indicated that drying with recirculated exhaust air increased the product quality.

Extensive efforts have been made in the automatic control of drying operations. Almost all of these controls have been applied to the drying temperature, air flow rate, drying time, mass flow of drying materials, and the moisture content of the final products (Agness and Isaac, 1967; Holtman and Zachariah, 1969; Walfer and Warnock, 1982; Bakker-Arkema, 1984). However, very few efforts have been made to automatically control the recirculation of exhaust air (Stone and Kranzler, 1981; Hansmann and Noort, 1992). The development a microcomputer-based automatic control for recirculated air could improve both dryer performance and product quality.

OBJECTIVES

The objectives of this study were:

1) To develop a microcomputer-based control system for a fruit dehydrator to automatically control the recirculation of exhaust air in the drying operation.

2) To test the microcomputer-based control system under drying conditions.

3) To compare the performance of a fruit dehydrator with microcomputer-based recirculation control with the performance of a similar dehydrator with no recirculated air.

CHAPTER II

REVIEW OF LITERATURE

Water in Foods and Water Activity

Several basic components exist in living biological systems. These components include proteins, carbohydrates, lipids, nucleic acids, vitamins, minerals, and water. Of all these basic components, water is the most ubiquitous and plays a fundamental role in the existence of living organisms. Water often comprises 50 to 90% of plant and animal weight (Zapsalis and Beck, 1985). As a result, water becomes a major component of most food (Table 1).

Perishability and spoilage of fresh or processed foods are associated closely with the existence of excess water within the foods. Perhaps one of the earliest discoveries about food preservation was the fact that the removal of excess water may prevent or at least defer the spoilage of the food (Van Arsdel, 1973a). Although people in ancient times did not actually know that growth of microbes in food with high water activity was responsible for the spoilage, they found that dried foods did not mold easily. As a result, drying has become one of the most traditional, successful, and widely used methods of food preservation. Sun drying, one of the most ancient techniques of food preservation, still finds application in the modern food industry.

Although foods with the same water content do not show the same ability to resist

Table 1. Water contents of various materials

Plant	Water (%, w.b.)	Animal	Water (%, w.b.)
Foods, fruits		Foods, fluid	
Apple	85	Milk, cow, whole, 3.5% fat	87.4
Berries	80-85	Milk, cow, fat-free	90.5
Cherries, red, sour	84	Eggs, chicken, whole	74
Grapes	81	Eggs, chicken, yolk	51
Grapefruits, pulp	88	Eggs, chicken, white	88
Oranges, peeled, fresh	86		
Peaches	89	Foods, tissue	
Pears	83	Beef, raw, retail, cuts	50-70
Rhubarb	95	Chicken, all classes, raw meat w/o skin	74
Strawberries	90	Pork, raw, complete of trimmed, lean cuts	55-60
Tomatoes	94	Fish, muscle portions	65-81
Foods, vegetables		Other biological materials	
Asparagus	92	Human components	
Avocado	74	Whole brains	76-78
Bananas	76	Eye lens	68
Bean, green	90	Liver	73-77
Beets	87	Pancreas	75
Broccoli	89	Whole heart	71-80
Cabbage	92	Kidney	78-89
Carrots	88	Muscle	76
Cauliflower	91	Bone	44
Lettuce	95	Skin	68-76
Peas, green, immature	78	Bloods, adult, whole	80.5-80.8
Potatoes	80	Erythrocytes	64
		Plasma or serum	93-95
Other biological materials		Milk, U.S.	85.2
Leaves	75-85	Mammal, whole	63-68
Stems	50-60	Earthworm	84
Tips of growing shoots	91-93	Jellyfish	95-98
Bacteria	ca. 80	Insects	
		Adult	45-65
		Larva	58-90

(Source: Fennema et al., 1973)

the spoilage, foods do become more stable when their water content is greatly reduced (van den Berg and Bruin, 1981). Water activity (a_w) is theoretically defined as the ratio of the partial pressure of water vapor above the food under equilibrium conditions and the vapor pressure of pure water at the same temperature (Troller and Christian, 1978; Fennema, 1985). Water activity is actually more closely interrelated with the stability of fresh or processed foods than moisture content.

Water activity varies from 0 to 1 and is an indicator of the availability of free water in the food system that can be utilized by microbes. In general, foods with a high concentration of solutes, in which most of the water is bound, show a low water activity value. For most foods, the higher the water activity, the more perishable the food.

The water activity of fresh fruits and vegetables ranges from 0.95 to 1.0, which is a condition highly suitable for the growth of most microorganisms (Karen, 1975; Troller and Christian, 1978). Most microorganisms stop growing when water activity in the food system is below 0.5 (Karen, 1975; Fennema, 1985; Troller, 1991). Lowering water activity in the food and maintaining it at a low level can prevent the growth of microorganisms and thus prolong shelf life.

Several methods are used for lowering water activity. Dehydration, freezing, and salting are commonly used methods in the food industry and in home preservation of fresh fruits, vegetables, and meat.

Preservation of Fruits by Dehydration

Dehydration of fruits is a water removal process in which excess water is removed. The most commonly used drying medium is heated air. Sun drying, an ancient method of dehydration, utilizes solar energy to remove water. This method is still used in various areas of the world, particularity in the developing countries (Troller and Christian, 1978). Artificial dehydration, a major method of drying in the modern food and agricultural industries, uses heated air to remove water by circulating the hot air over the surface of the food (Menon and Mujumdar, 1987).

Some common drying methods include sun drying, cabinet drying, tunnel drying, spraying drying, and fluidized-bed drying, among others. However, the fundamental principle of food preservation remains the same for all methods. With the removal of excess water, the concentration of solutes in the food rises, and water activity decreases. The final water activity level for dried fruits usually ranges from 0.60 to 0.65 (Troller and Christian, 1978). Vegetables dried to a water activity of 0.1 - 0.35 rarely spoil unless extensive rehydration occurs in storage after drying (Troller and Christian, 1978).

When food materials are dried in a dehydrator, heated air is supplied continuously to the dehydrator to remove excess water. Simultaneous heat and mass transfer occur in the process of drying (Okos et al., 1992). Heat energy supplied from the surrounding environment is used to raise the temperature, activate the movement of water in the food, and evaporate moisture from the surface of the food. Transfer of heat from the environment to the food may be accomplished by convection, conduction, radiation, or a combination of these methods (Menon and Mujumdar, 1987). The energy efficiency in the drying operation depends heavily on the temperature and humidity of the air, the air flow rate, and the exposed area of food materials (Okos et al., 1992).

Several physical and chemical changes may occur in the dehydration of fruits. The most significant physical changes include changes in texture, shape, and color (Van Arsdel and Copley, 1964). With the removal of water from fruits, the cell wall of plant tissues is under gradually increased stress, which may lead to deformation of the cells. Shrinkage of whole or cut fruits become almost an inevitable physical change accompanying the dehydration of fruits in all kinds of dehydration operations. The texture of dried fruits is usually more rigid than the original. Depending on the conditions of drying and the amount of water removed, the rigidity of dried fruits will vary. The rigidity also is affected by severe drying conditions such as high temperature, rapid air flow.

Case hardening, a very complex phenomenon in the dehydration of all kinds of food, is a result of both physical and chemical changes (Zapsalis and Beck, 1985). Some chemical reactions related to case hardening include protein denaturation, gelatinization of starch, and increased sugar concentration on the surface of drying fruits. These chemical reactions in drying fruits may lead to the formation of a physical boundary that is impervious to moisture and retards the process of drying. Drying under mild environmental conditions may help alleviate case hardening (Van Arsdel and Copley, 1964).

Energy Aspects in Drying

Drying, an intermediate or final unit operation widely used in many areas of engineering, is an energy-intensive unit operation. Drying consumes up to 70% of the total energy in the manufacture of most wood products. In the manufacture of finished textile fabrics, fifty percent of the total energy consumption is used in drying operations. Over 70% of the total energy needed for on-farm corn production is supplied to remove excess water (Strumillo and Kudra, 1986).

Energy consumed in drying comprises more than 12% of the total energy used in food and agriculture in the United Kingdom (Table 2). For the United States, Richardson and Jenson (1976) reported that the estimated total energy consumed in drying was about 1600×10^9 MJ/year. This estimate of almost 20 years ago is probably low for the 1990's. Since 1950, overall energy use for crop drying has increased tremendously in the United States (Gunasekaran, 1986). Twelve to twenty percent of the total U.S. energy consumption is associated with the food system (Myers et al., 1979). Of this amount, almost 50% is consumed in food processing. According to 1974 energy consumption data, fifty-nine percent of the total energy used in the U.S. food processing industry was thermal energy (Combes and Boykin, 1981). Natural gas, propane and other fossil fuels, as well as electricity, have been major energy sources to remove water in the artificial dehydration of fruits and vegetables.

For most convective dryers, the majority of energy input is consumed in the evaporation of water from the drying materials and exhausted to the atmosphere in the

Table 2. Comparison of the annual drying energy (MJ) to the energy required for total processing of selected product groups in the United Kingdom

Subsector	Drying	Total	% due to drying
Food and agriculture	350	2860	12
Chemicals	230	3900	6
Textiles	70	1280	5
Paper	450	1370	33
Ceramic and building materials	140	1270	11
Timber	40	350	11
Total	1280	11030	12

(Source: Reay and Baker, 1982)

drying airstream. Results of a thermal energy analysis for a concurrent flow tunnel dehydrator for prunes (Thompson, 1981) showed that 58% of the total energy was required to evaporate moisture and 16% was discharged to the atmosphere through the exhaust air streams (Table 3).

Drying with Air Recirculation

The 1970's "energy crisis" substantially changed the way people think about energy. Energy is no longer considered to be cheap and endless. Increasing energy costs have forced food processors to reevaluate how energy is consumed. More and more attention has been directed to improving the efficiency of energy utilization. In the late 1970's, various projects were proposed to investigate the energy conservation in the food and agricultural industries (Myers et al. 1979).

Cruess and Christice (1921) studied the energy efficiency of tunnel fruit dehydrators for air-drying of prunes and recommended that 75% or more air be recirculated to save energy. Wiegand (1923) found that drying with air recirculation could improve the energy efficiency, decrease the drying time, and increase product quality. Although drying with air recirculation was studied as early as the 1920's, the major emphasis on recirculation was primarily in preventing case hardening.

Since the 1970's, the emphasis on air recirculation has been changed to improving the energy utilization efficiency. Groh (1978) indicated that up to 40% of total energy could be saved by increased air recirculation and use of a heat recovery exchanger.

Table 3. Energy audit of a concrete, concurrent flow tunnel dehydrator for prunes

Thermal energy loss/utilization	Percent of total thermal energy input
Moisture evaporation	58
Exhaust air	16
Burner and other losses	12
Air leaks (door, fan belt opening)	8
Walls and ceiling	3
Fruit and trays	3
Total	100

(Source: Thompson, et al., 1981)

Thompson et al. (1981) found that increased air recirculation could lead to at least 15% fuel savings in fruit drying using tunnel dehydrators. Harner et al. (1981) reported that air recirculation in combination with solar energy was a practical way to reduce energy consumption in peanut curing. Young (1984) concluded 26% energy savings and 15% reduction in drying time in recirculating type dryers in air-drying of peanuts. Improved product quality for recirculated air-dried peanuts was found. Kulasiri et al. (1986) also reported energy savings in peanut drying by air recirculation. Forty percent of energy savings in peanut drying was attributed to air recirculation (28%) and to solar energy collection (12%) (Young et al., 1988). However, air recirculation cannot be applied if the ambient air is very humid. Chung et al. (1987) concluded that air recirculation without dehumidification actually increased drying energy consumption and drying time in the humid seasons.

Automatic Control in Drying

Since the 1950's, over 75% of the United States corn crop has been dried artificially (Gunasekaran, 1986). With the need to artificially dry this huge quantity of grain, extensive efforts have made to automatically control the grain drying process.

There are many advantages of automatic control over human control. McFarlane and Bruce (1991) stated that a good control system requires accuracy, quick reaction, stability, and tolerance of condition changes. Human operators can achieve such good control only if they are skillful, accurate, alert, predictive, patient, and present near the drying facilities the whole time drying is in progress. With the complexity and continuing change in operating conditions, it is very difficult for human operators to maintain good control consistently. Automatic control becomes almost a necessity in drying operations in modern food and agricultural industries. For drying operations, improving dryer performance by proper control strategy under microprocessor control can result in energy savings of 5-30% of energy compared with a conventional non-automatic control system (Bakker-Arkema, 1982).

The controls applied to drying operations include dryer performance (drying temperature and time, mass flow rate, supply of drying air) and quality of final products such as final moisture content, breakage, etc. A good control over dryer performance is essential to the final quality of food products. For drying operations, control of the final moisture content to an appropriate level is the goal, while maintaining good performance of dryers is the means. Control of drying temperature, mass flow rate and air flow rate can be achieved through traditional control methods, such as on-off control, proportional-plus-integral-plus-differential (PID) control, etc., while control of product quality is a more complicated matter, both theoretically and technologically. Overdrying reduces the sale weight and consumes unnecessary energy, time and labor. Underdrying, on the other hand, will result in spoilage of products.

Matthews (1963, 1964) introduced a manually tuned PID controller to control a grain dryer. Zachariah and Isaacs (1966) conducted a theoretical investigation of moisture control for grain dryers with a PID controller, a PID-plus-forward controller, and an on-off controller. Ageness and Isaac (1967) developed a control system for a continuous-flow grain dryer based upon exhaust air temperature sensing. They found that monitoring the exhaust air temperature from a heated air dryer can provide a satisfactory signal for automatic moisture content control. The relationship between exhaust air temperature and the final moisture depended on the drying temperature, flow rate, initial moisture content, and drying time. Both on-off and proportional controllers were used and performed equally well with proper selection of system parameters. Frequent manual adjustment of errors due to changes in ambient condition and initial moisture content was needed for the control system. Holtman and Zachariah (1969) designed optimal controls for a continuous-flow dryer to prevent overdrying or underdrying. No commercial controllers were available in the 1960's due to the lack of advanced computing technology (McFarlane and Bruce, 1992).

The advent of microcomputers in the late 1970's made it possible for the commercial development of practical controllers for grain dryers. Stone and Kranzler (1981) developed a microprocessor (Motorola Exorterm 200) controlled thin-layer dryer in which a microprocessor-based computer was used for logic control and data acquisition. Relative humidity of drying air entering the dryer was controlled through proper mixing of recirculated exhaust and ambient air. The recirculation valve position was set by the computer system, which actuated a servo positioner using solid-state relays. A potentiometer was used to provide feedback information on the valve position. Drying temperature was maintained within ±2°C. Relative humidity was maintained within

±5%. Bunn et al. (1983) developed an 8080 microprocessor single-board computer that could be used as both a data logger and a dryer controller for in-bin drying of corn, wheat, or soybeans. The computer system was used to monitor the ambient dry bulb temperature and relative humidity and calculate the amount of heat that could be added to the air stream if the ambient air was too humid. A computer-based process control was developed by Faust et al. (1988) for automated drying of hardwood lumber. Loadcell transducers were used to measure weight changes. The amount of moisture removed and the end point of drying process were determined based upon the measured weight. The system performed well in the control of final moisture content. Hansmann and Noort (1992) developed a computerized counter- and parallel-flow fruit dehydration system with the wet bulb temperature of the drying air regulated through the control of air recirculation in junction with steam humidification. A personal computer was operated as the system controller. Loadcells also were used for sample weight measurement. Termination of drying was based upon an approximate average moisture ratio calculated from measured sample weight and the initial moisture content.

CHAPTER III

DEVELOPMENT OF CONTROL SYSTEM

Overview

This study was conducted in two phases: (1) development of an automatic control system for the exhaust air recirculation, and (2) dehydration of cut fruit samples using the developed exhaust air recirculation control system. In the first phase, the measurement system for temperature, air humidity ratio, and mass measurements was established and calibrated. Also, the automatic control mechanism for the exhaust air recirculation was designed, constructed, and evaluated. In the second phase, the dehydration of selected cut fruit samples was performed with the exhaust air controlled automatically based upon information collected from the dehydration system.

The Air Recirculation Dehydrator

Air drying of fruits with exhaust air recirculation has been extensively studied at the University of Tennessee, Knoxville (Walker, 1992; Liu, 1993). This study represents a continuation of their work. Four fruit dehydrators were modified to study the energy savings by air recirculation (Walker, 1992). Figure 1 shows a schematic diagram of a modified dehydrator. During the drying operation, the fruit samples were placed in an

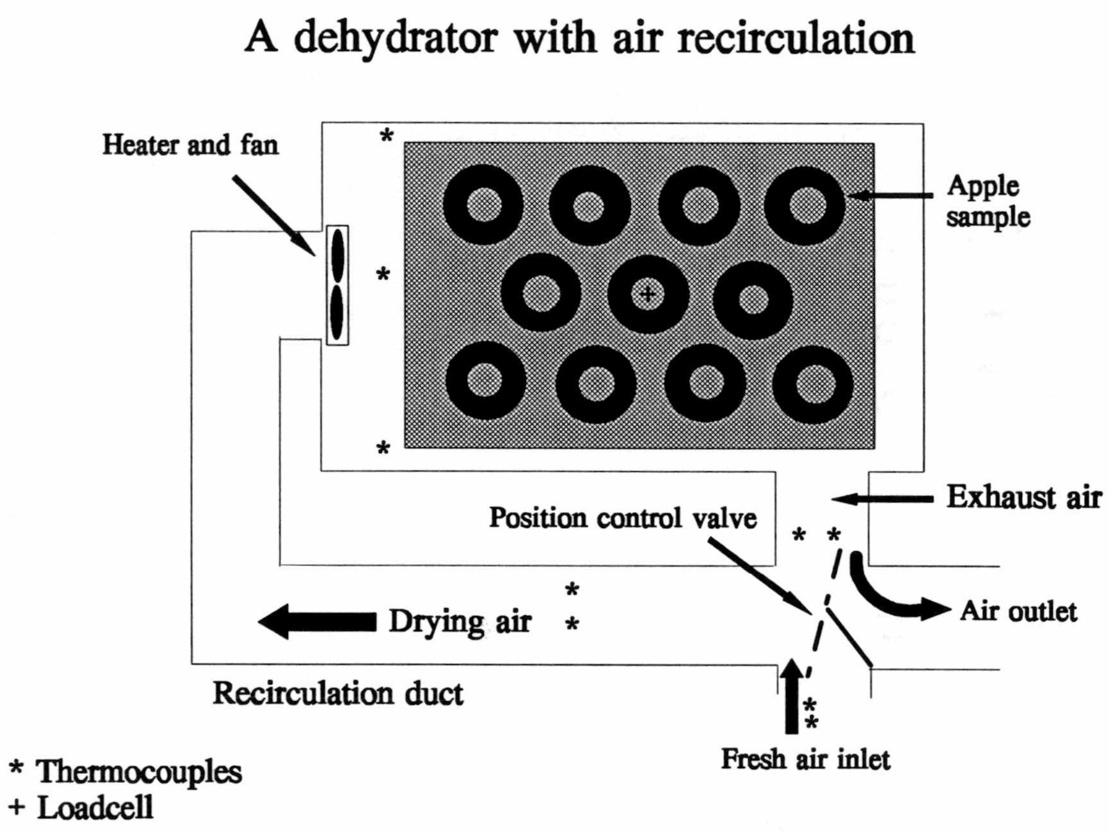

Figure 1. A fruit dehydrator with air recirculation.

enclosed environment. Fresh air entering and heated exhaust air leaving the dehydrator were regulated through a single valve. A portion of the air exiting the dehydrator was reused by recirculating it to conserve energy. The amount of air recirculated was controlled by the valve position. This system had many advantages. At the early stage of drying, some exhaust air recirculation could make use of the heat energy in the exhaust air and improve the energy utilization efficiency of the drying operation. As drying progressed to the falling rate stage, higher percentages of exhaust air could be recirculated to maintain the humidity ratio of the drying air and thus provide a milder drying medium to reduce physical damages of the drying materials, such as cracking, breakage, and case hardening. A microcomputer-based automatic control system appeared to be an appropriate method to monitor and control the exhaust air recirculation by adjusting the valve positions based upon real-time information gathered from the drying system.

Calculation of Air Recirculation Ratios

By conducting energy and mass balance analysis, the air recirculation ratios could be calculated. The system boundary shown in Figure 2 surrounded in the region where the position control valve was located. The amount of heat energy entering the system was equal to the amount of heat energy leaving the system. Also, the amount of air entering the system was the same as the amount of air leaving the system. It is assumed that heat loss across this boundary and air leakage from this system are insignificant. Governing equations for mass and energy balance may be developed.

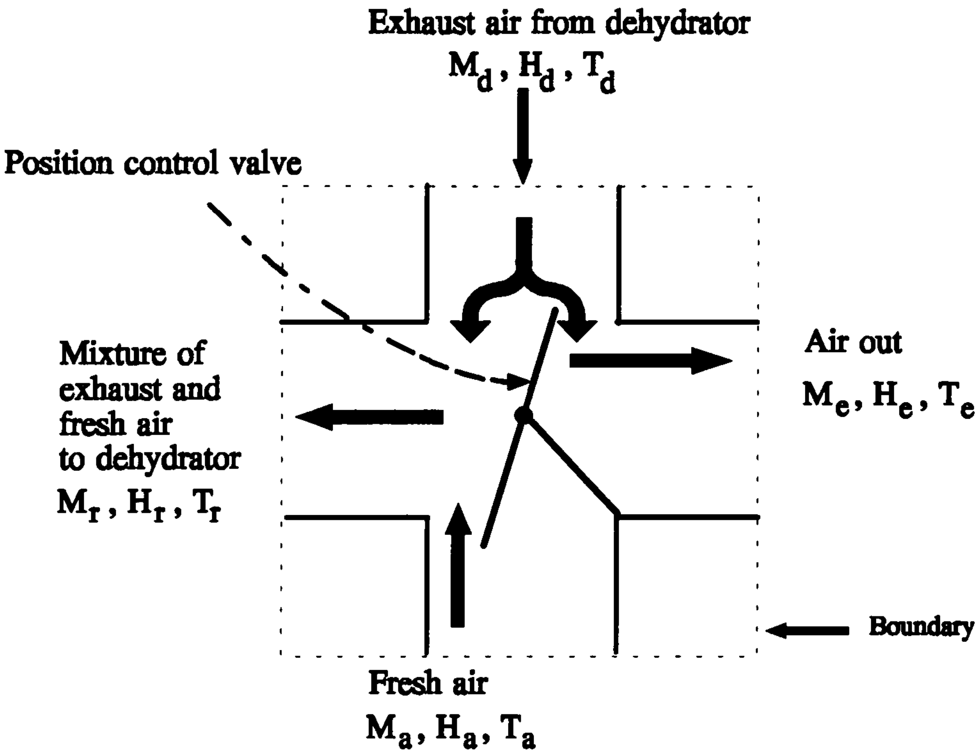

Figure 2. Boundary for heat and mass balance analysis for the calculation of the exhaust air recirculation ratio.

$$\textbf{Mass of air}_{in} = \textbf{Mass of air}_{out} \tag{1}$$

$$\textbf{Heat energy of air}_{in} = \textbf{Heat energy of air}_{out} \tag{2}$$

Therefore,

$$M_a + M_d = M_r + M_e \tag{3}$$

$$h_a + h_d = h_r + h_e \tag{4}$$

Where:

M = mass flow rate (kg dry air/s);

h = enthalpy (kJ/kg dry air);

subscripts:

a = ambient air;

r = mixture of ambient and exhaust air;

d = exhaust air from dehydrator;

e = exhaust air leaving the system.

The enthalpy (kJ/kg dry air) of the air may be determined by the moisture content and temperature of air (ASHRAE, 1989),

$$h = (1 + 1.805W)T + 2501W, \tag{5}$$

where W is the humidity ratio (kg water/kg dry air) and T is the dry bulb temperature of the air. The thermal energy H (kW) of air with a mass flow rate of M (kg/s) becomes

$$H = ((1 + 1.805W)T + 2501W)M. \tag{6}$$

Defining the recirculation ratio of exhaust air as

$$R = \frac{M_{recirculated}}{M_d} = \frac{M_d - M_e}{M_d} \tag{7}$$

and performing an energy balance using the equations developed above, it may be found that the recirculation ratio is a function of the psychrometric properties of the air as shown by Equation 8 (a detailed derivation of which is given in Appendix A).

$$R = \frac{2501(W_r - W_a) + (1 + 1.805W_r)T_r - (1 + 1.805W_a)T_a}{(1 + 1.805W_e)T_e - (1 + 1.805W_a)T_a + 2501(W_e - W_a)} \tag{8}$$

Where:

W_r= humidity ratio of mixed air (kg water/kg dry air);

W_a= humidity ratio of ambient air (kg water/kg dry air);

W_e= humidity ratio of exhaust air (kg water/kg dry air);

T_r= temperature of mixed air (°C);

T_a= temperature of ambient air (°C);

T_e= temperature of exhaust air (°C).

Equation 8 indicated that the air recirculation is a function of humidity ratios and temperatures of ambient air, exhaust air, and the mixture of the ambient and exhaust air in the recirculation duct at a given position.

Equation 8 may be further simplified if there are no drying materials in the dehydrator, i.e., if the humidity ratios of air entering and leaving the dehydrator were equal (Equation 9).

$$\mathbf{R} = \frac{T_r - T_a}{T_e - T_a} \tag{9}$$

For any fixed control valve position, there was a corresponding recirculation ratio. By measuring the three temperatures shown in Figure 2 at different control valve positions, the recirculation could be calculated using Equation 9. Walker (1992) used Equation 9 to calibrate the system and to identify the relationship between the recirculation ratio and the physical position of the control valve.

Using the calibration method developed by Walker (1992), the recirculation ratios at different valve positions could be measured. The correlation between the control valve position and the air recirculation ratio could then be determined. Calibration data based upon Equation 9 and temperature measurements in the recirculation system (Appendix B) were used to establish an empirical equation relating recirculation ratio to valve position (Equation 10).

$$R = 0.877\sin^2\theta + 0.125 \qquad (0.15 < R < 0.90) \qquad (10)$$

Where:

θ was the angular position (degrees) from zero position of the valve (0% recirculation).

This empirical equation depicts the relationship between R and θ quite well (R^2=0.9998, Figure 3) except where the recirculation was lower than 15% or higher than 90% - rates outside the recirculation ranges to be considered in this study.

System Instrumentation and Control Devices

System instrumentation

The dehydrators used by Walker (1992) were used with minor modifications in this study. The dry and wet bulb temperatures of the ambient, exhaust, and the recirculated air were measured simultaneously by a datalogger (CR-7X, Campbell Scientific, Inc., Logon, UT). Type-T thermocouples were used as temperature sensors. The temperature of heated air immediately downstream of the heater also was recorded. This temperature was an average of five temperature sensors distributed along a plane in the rear of the dehydrator. The signal from these thermocouples was used as an input to

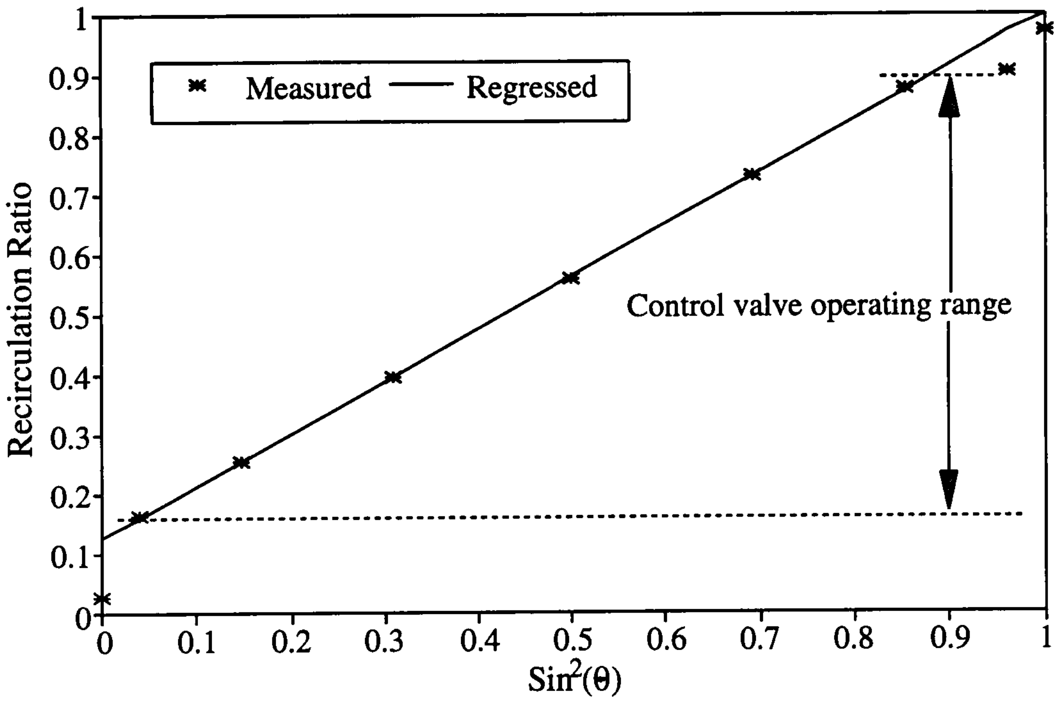

Figure 3. Relationship between air recirculation ratio and recirculation control valve position (angular distance) in the microcomputer control of a fruit dehydrator.

a PID controller which maintained the drying air temperature at 60±1°C throughout the drying process. Since the datalogger was not appropriate for the control purpose of this study, a multifunction analog and digital I/O board (CIO-AD08-PGH, ComputerBoards, Inc., Mansfield, MA) was used to accomplish the control of the humidity ratio. Temperature measurement by the multifunction board using thermocouples usually requires an ice bath. To avoid using the ice bath, the dry and wet bulb temperatures of the drying air in the recirculation duct measured by the datalogger were converted to linear output voltage signals and sent as input signals to the continuous output channels of the datalogger. The multifunction board measured the voltage signals from the datalogger, and converted them to the dry and wet bulb temperatures of the drying air in the recirculation duct. These dry and wet bulb temperatures were then used to calculate the humidity ratio of the drying air in the recirculation duct, and this humidity ratio was used as an input parameter for recirculation ratio control.

The cut fruit samples were placed on perforated plastic trays. Each plastic tray was 40 cm by 30 cm in width with a thickness of 0.4 cm. The plastic fruit trays were placed on aluminum metal frames (40 cm x 30 cm x 23 cm). Each metal frame could hold four trays. The trays were separated vertically by about 5 cm. The metal frame was tied to an aluminum plate (5 cm x 8 cm x 0.5 cm) by four steel cables. A hook, used to hang the frame to a loadcell, was mounted to the aluminum plate (Figure 4). A 11.35 kg loadcell (Model 10025, S. Himmelstein & Co.) mounted on top of the dehydrator was used to weigh the frame and the sample. Weight of the fruit sample was recorded by the

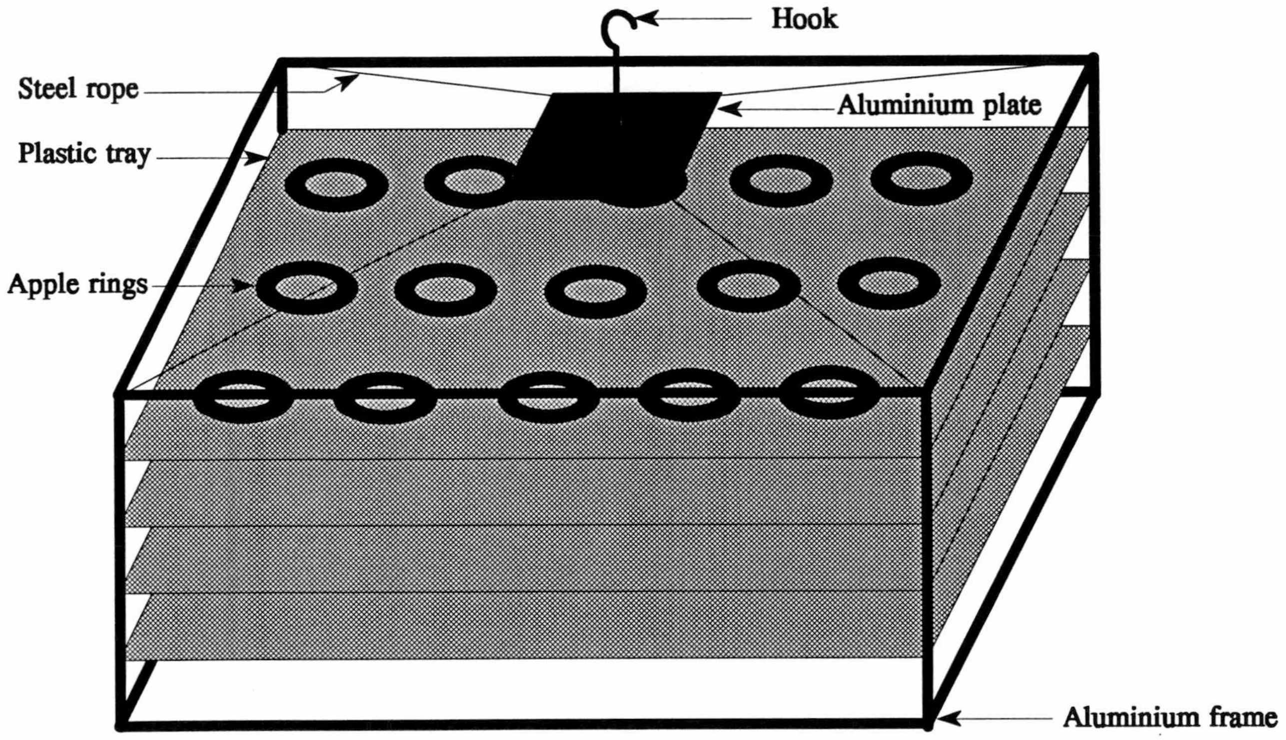

Figure 4. Diagram of the aluminum frame with four trays of apple rings.

multifunction board mounted inside an IBM® PC XT. The weight measured by the multifunction board was used to determine the amount of moisture removed and as an input parameter for control.

Automatic control devices

The devices used in the automatic control of exhaust air recirculation included a stepping motor, a stepping motor driver, two timing pulleys, and a timing belt. The stepping motor driver (American Precision Industry, Model CMD-40) drove the stepping motor (SLO-SYN®, model MO61, Superior Electric Co., Bristol, CT) to control the position of the recirculation control valve. A timing pulley (BERG®, model 20TP4-28, W.M. Berg, Inc., New York, NY) mounted on the axle of the stepping motor transmitted the angular movement from the stepping motor through the timing belt (BERG®, model 20TB-120, W.M. Berg, Inc., New York, NY) to a larger pulley (BERG®, model 20TP6-48, W.M. Berg, Inc., New York, NY) installed on top of mounting shaft of the recirculation control valve. The centers of the two pulleys were 15.24 cm apart. The gear ratio of the smaller pulley to the larger pulley was 28/48. There were 400 steps per revolution of the stepping motor with 0.9° angular movement at each step. For every angular movement of the stepping motor, the valve moved 0.525° angularly in the same direction. Two microswitches were installed in the system to detect the upper and lower limits of the valve movement and prevent attempts to force the valve beyond the physical limits (Figure 5). An overall view of the installed control system is shown in Figure 6.

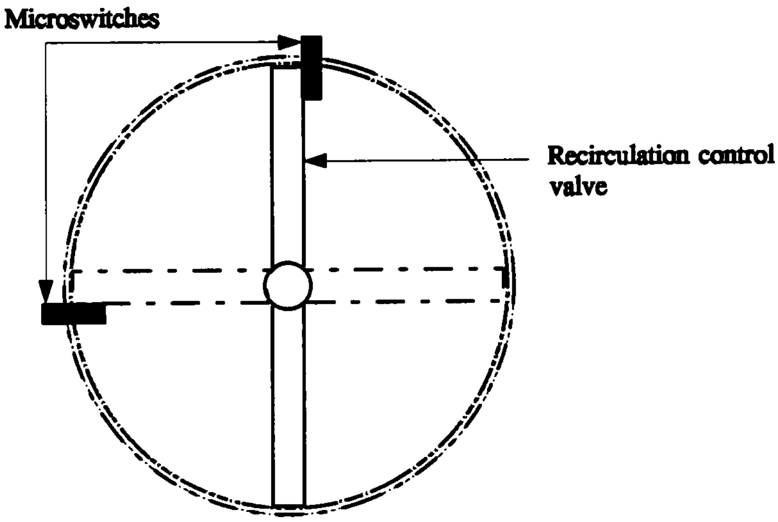

Figure 5. Locations of microswitches installed to prevent the recirculation control valve from moving beyond its physical limits.

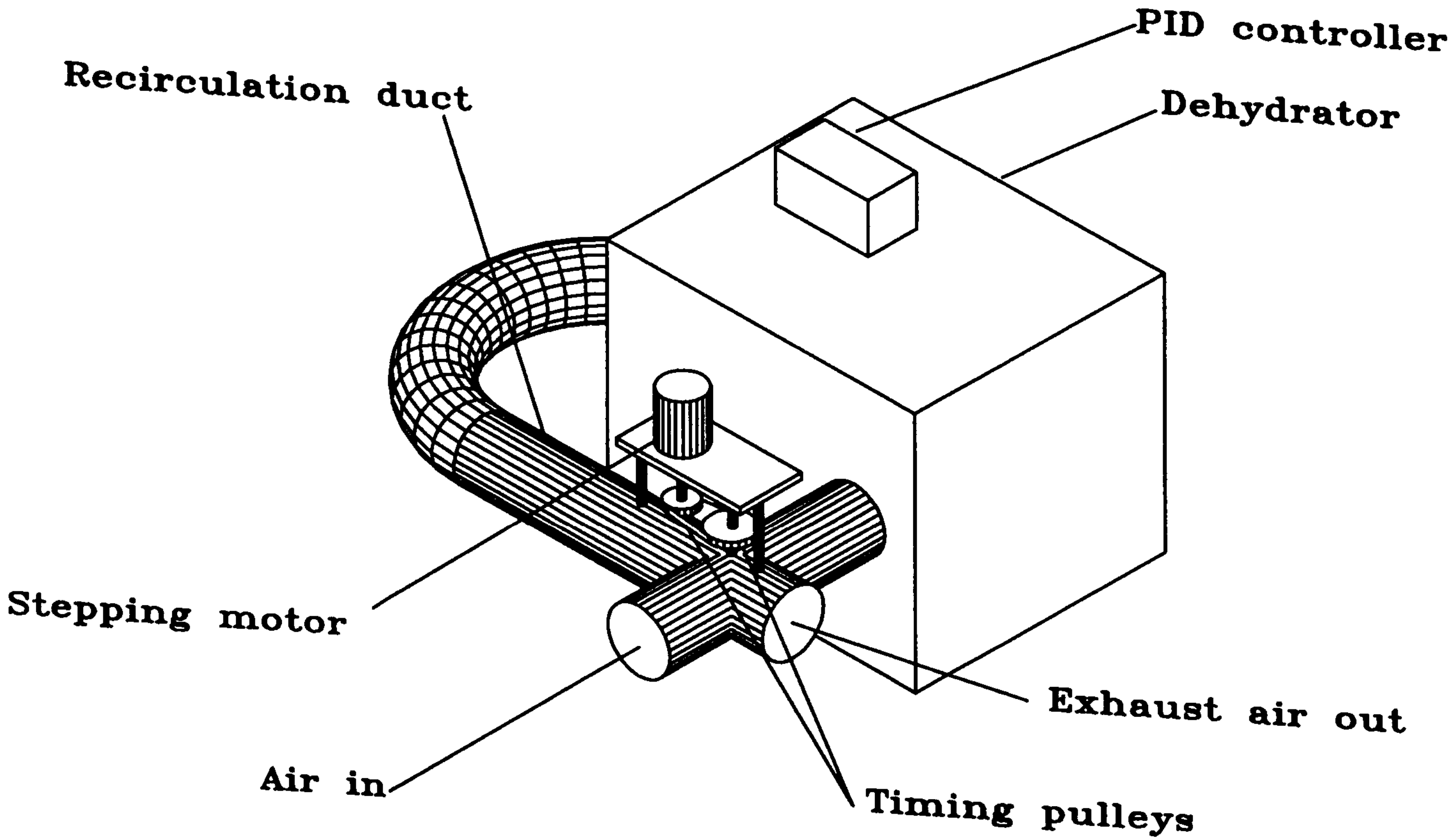

Figure 6. A fruit dehydrator with exhaust air recirculation controlled automatically.

The IBM® personal computer (PC) was used as the basic controller for the entire control system. It interfaced with the multifunction board, which gathered information such as the drying air temperatures and the sample weight from the dehydrator. Based upon the information collected from the system, the PC determined the position of the recirculation valve, and calculated the number of the steps and the direction of movement for the stepping motor. The signals were sent from the multifunction board to the stepping motor driver. These digital signals included a direction signal and a step signal. The stepping motor moved clockwise or counterclockwise based upon the direction signal. The step signal controlled the number of steps for the stepping motor to move. Figure 7 shows the flow of data and control signals for the system.

Control Strategies and Algorithm

Overview of system control concept

Control of the dehydration process involved automatic control of the exhaust air recirculation and manual termination of the dehydration process. When dehydration was started, the control system directed the recirculation control valve to a given initial position. As the dehydration progressed, the position control valve was adjusted to control the drying air humidity ratio within a specified range until the weight of the drying sample dropped below a preset level. By limiting the drying air humidity ratio to this range, the dehydration would occur under moderate temperature and humidity conditions to minimize possible physical damage to the food. Once the weight of the

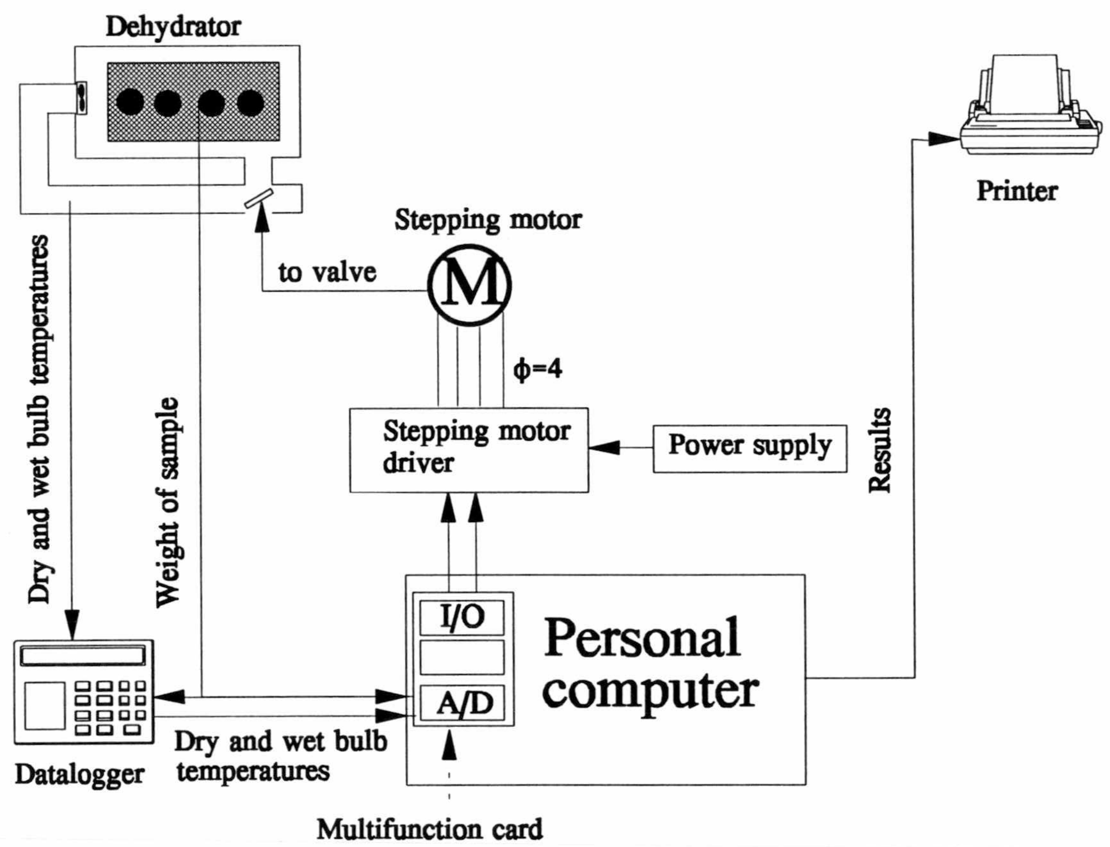

Figure 7. Flow of data and control signals for the system.

sample dropped below the preset value, i.e., after a specified percentage of weight was removed, the control system adjusted to a new control range for the humidity ratio of the drying air. With the removal of moisture from the sample, the recirculation control valve would be moved closer and closer to the 100% recirculation position to maintain the humidity ratio of the drying air within the preset range. Thus, a maximum recirculation ratio was imposed to prevent 100% recirculation of the exhaust air. Once the moisture content of the fruit reached a predetermined value, the collection of information from the drying system was terminated automatically and all recorded information was saved into an ASCII data file. The dehydration process was terminated manually.

General description of process control

In a typical dehydration operation with the microcomputer-based control system, drying would occur with an initial air recirculation R_0, depending upon the variety of fruit, ambient conditions, and the amount of fruit being dehydrated.

Under control of the microcomputer, the stepping motor would automatically move the position control valve to a specified initial operating position. Under normal ambient conditions, the air recirculation would be kept unchanged until the mass of the fruit sample in the dehydrator reached a mass corresponding to a specified percentage of the initial mass WT_c (critical weight ratio). During this drying period, if the drying air exceeded a specified maximum humidity ratio (HR_{max}) or dropped below a specified minimum humidity ratio (HR_{min}), the recirculation would be adjusted automatically to keep the air humidity ratio within those limits.

During the drying process, the system would monitor the mass changes of the fruit sample continuously as the moisture was removed. After the mass of the fruit sample dropped below the specified (WT_c), the system would periodically adjust the recirculation ratio to maintain the humidity ratio of drying air at a specified constant value (HRC). (In practice, the air humidity ratio value (HR) would be allowed to vary within a very narrow range.) This stage of control operation would provide a more humid drying air than that in the dehydrator without exhaust air recirculation.

With the progress of dehydration, less and less moisture is available for evaporation. The humidity ratio of the exhaust air thus becomes lower and lower. To maintain a constant humidity ratio of the drying air, more and more exhaust air must be recirculated. However, exhaust air should never be completely recirculated since this could negatively affect drying rate and food quality. Therefore, as previously noted, an upper limit of exhaust air recirculation should be imposed on to the system.

The termination of dehydration is based upon the amount of moisture removed from the food material. When the food material is dried to a predefined final moisture content, the dehydration process is terminated manually, and the collection of data is terminated automatically by the computer. Figure 8 depicts the process control logic.

Control strategies and specific control criteria

Several control strategies were involved in the dehydration of cut fruit with

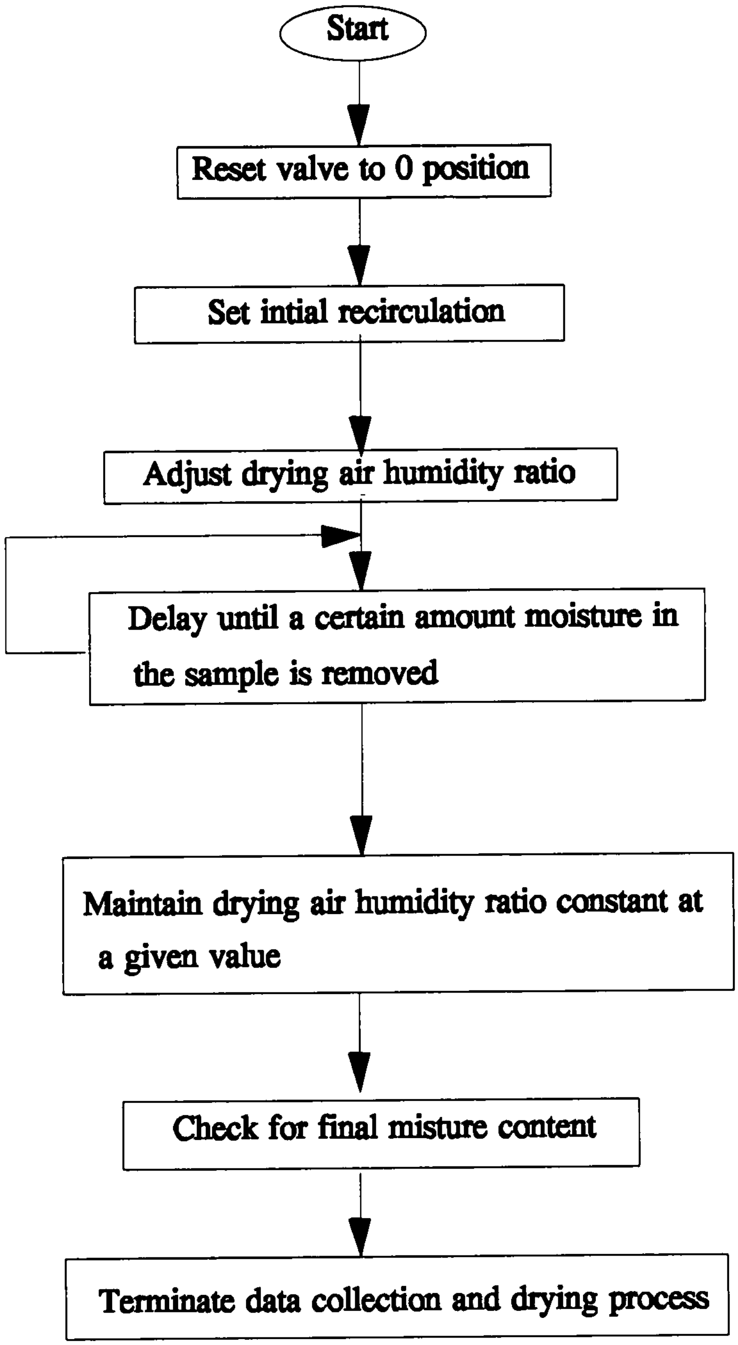

Figure 8. Overview of system control logic.

automatically controlled exhaust air recirculation. These control strategies were developed to fulfil the requirements mentioned above.

The first control strategy was to set the initial recirculation ratio. When the dehydration was started, the recirculation control valve was reset automatically to the 0% recirculation position (Zero position). An open-loop control was then employed to move the recirculation control valve from the Zero position to a specified initial operating position of 70% recirculation.

Immediately after the recirculation control valve was set at the initial operating position, the second control strategy was initiated to adjust the drying air humidity ratio periodically within a specified range between a maximum and a minimum ratios (HR_{max}= 0.029 and HR_{min}= 0.021). The operating range of humidity ratio between HR_{min} and HR_{max} is called the "deadband" (Figure 9). The stepping motor remained static if the humidity ratio of the drying air was within the deadband. The width of deadband might vary, depending upon specified limits. At the initial stage of dehydration, the deadband could be broad to allow rapid evaporation of water from the food material. After the mass of the fruit sample dropped below WT_c= 0.70, this control strategy was used to maintain the humidity ratio of the drying air within a much narrower deadband. The valve was automatically moved to a more open or closed position to adjust the humidity ratio of the drying air within this narrow deadband. Depending upon the ambient humidity conditions and initial moisture content of the sample, the humidity ratio of the drying air still might remain relatively humid when the mass of the sample was below

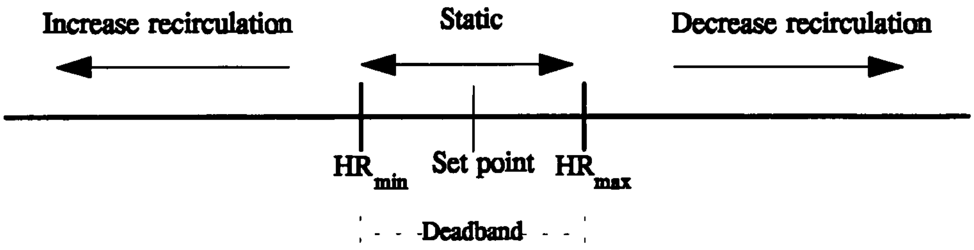

Figure 9. Sketch showing the second control strategy.

WT_c. If this occurred, no action was taken to close the valve until the humidity ratio dropped below 0.028.

The third control strategy was to limit the maximum air recirculation after the above conditions were met. With the progress of drying, less and less moisture was available for evaporation, particularly near the end of falling-rate stage of drying. To maintain a constant humidity ratio of 0.025±0.001, more and more exhaust air should be recirculated. The position control valve would be pulled closer and closer towards the maximum recirculation direction until the preset maximum recirculation was reached. If, during this stage of control, the humidity ratio of the drying air exceeded HR_{max}= 0.026, the recirculation control valve would be turned towards the Zero position to let more fresh air enter the dehydrator.

The last control strategy was to determine the final moisture content of the drying fruit sample. After the final moisture content of the fruit sample dropped below the predefined final moisture content, the collection of data from the dehydration system was terminated automatically and the collected data was saved to an ASCII text file.

Based upon the above description, the specific system control criteria for this study are summarized as follow:

1) The air recirculation first was adjusted automatically to an initial operating recirculation ratio of 70%.

2) The recirculation ratio was initially maintained in the range of 0.021 - 0.029 kg water/kg dry air. The maximum and minimum humidity ratios (HR_{max}

and HR_{min}) at this stage were 0.029 and 0.021, respectively. If the drying air humidity ratio exceeded 0.029 or dropped below 0.021, the recirculation was adjusted automatically to keep the air within those limits.

3) After the mass of the cut fruit samples dropped below 70% of the original weight, the recirculation ratio was adjusted to maintain the drying air humidity ratio constant at 0.025 with a tolerance of ±0.001. The maximum and minimum ratios (HR_{max} and HR_{min}) at this stage were 0.024 and 0.026. If, however, the mass was less than 70% of the original weight, but the drying air humidity ratio was 0.028 or greater, then more water should be removed before the system started to increase the recirculation ratio of the exhaust air. The actuation of the motor to adjust recirculation was thus delayed until the humidity ratio dropped below 0.028.

4) The maximum recirculation should not exceed 90% at any time.

5) When the fruit sample was dried to the predetermined final moisture content (20% wet basis), the dehydration process was terminated.

6) The system must be stable and require no manual adjustment after the dehydration was initiated.

Methods of humidity ratio and air recirculation control

The initial recirculation ratio control (first strategy) was accomplished using Equation 10 to convert the recirculation ratio to the valve position. The number of steps and the direction for the stepping motor movement were sent from the digital I/O port on the multifunction board. A series of digital pulses and a digital direction signal were received by the stepping motor driver. Under control of the stepping motor driver, the motor could, through the timing pulleys and the timing belt, drive the recirculation control valve to any position within the range of movement. The holding torque of the stepping motor was strong enough to counter the torque on the valve created by the forces of air entering and leaving the dehydrator.

Dry and wet bulb temperatures of the drying air in the recirculation duct were used to calculate the air humidity ratio. The calculated humidity ratio value was compared to the set point. The difference in the measured and set point humidity ratios, called error, was used to adjust the recirculation control valve. A closed-loop humidity ratio control system was employed to maintain the humidity ratio of the drying air at different preset levels (Figure 10). The number of pulses N, which was also the number of steps, was determined by the error and a proportional coefficient K (Equation 11).

$$N = K\epsilon = K(HR - HRC) \qquad (11)$$

Where:

N = number of pulses,

K = proportional coefficient,

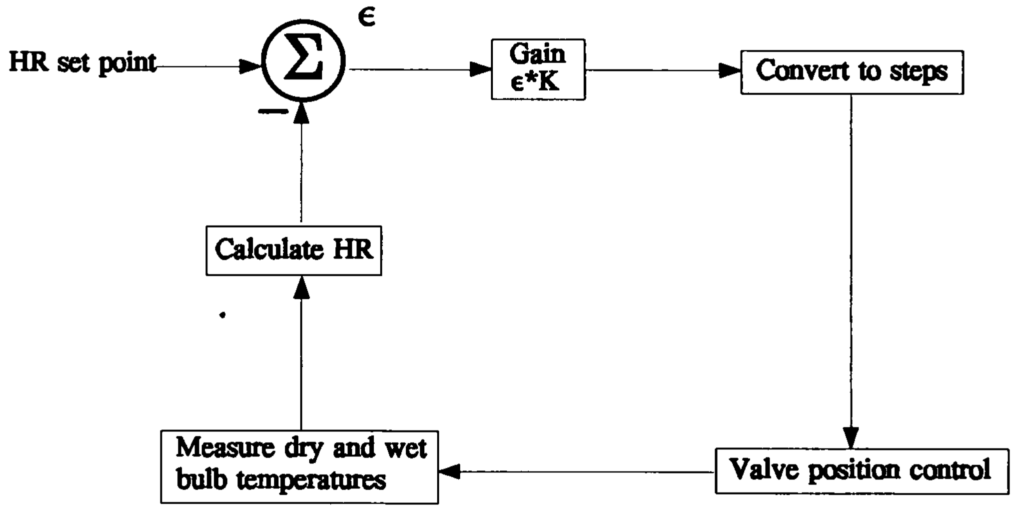

Figure 10. Block diagram of the control of drying air humidity ratio in the recirculation duct.

ε = error,

HR = measured humidity ratio of the drying air, and

HRC = humidity ratio set point for the third control strategy.

To move the control valve from the Zero position to the 100% recirculation position, 162 steps were needed. By recording the total number of steps from the Zero position, the position of the control valve could be determined.

The direction of the stepping motor was determined by the "sign" of the error. If the error was positive, which means that the humidity ratio was higher than the set point, then the valve would move in the 0% recirculation direction, allowing more air into the dehydrator. With the negative value of the error, the valve would move towards the maximum recirculation direction, reducing the supply of the fresh air.

For the second strategy, the movement of the stepping motor was determined by the magnitude of error, if outside the deadband of $|H_{min} - H_{max}|$. If the error was outside the upper limit of the deadband, which meant that the humidity ratio of the drying air was too high, the recirculation valve would be driven towards the Zero position. In contrast, if the error was outside the lower limit of the deadband, more air would be recirculated (Figure 9). By controlling the width of the deadband, the humidity ratio of the drying air might be set within different ranges. At the beginning of the dehydration, the deadband of the humidity ratio was be very broad. After the control system was initiated to maintain a constant humidity ratio, it was impossible to maintain of the dry air humidity ratio absolutely constant. In practice, the deadband of the humidity ratio control became very narrow. The error was allowed to vary within a very narrow range (±0.001 kg water/kg dry air). Applying a tolerance limit helps improve the stability of humidity ratio control. Since the humidity ratio was controlled at a tolerance of ±0.001, if the absolute value of error was greater than 0.001, this value became the control criterion. If the error value was within this range, the stepping motor remained idle. If this value was greater than 0.001, the stepping motor was actuated. According to Equation 11, the absolute value of the product of the gain and error must be greater than 1 to actuate the motor. During the control operation of maintaining a constant humidity ratio of the drying air with a tolerance of ±0.001, the minimum value of the proportional gain must be 1000. Selection of a proportional gain lower than 1000 will lead to a very slow response of the control. There should also be a maximum value of the gain. If the gain is selected higher than this value, the control of the system becomes unstable. This maximum value varies with the system, the ambient conditions, and the properties of the food (such as moisture content, etc.).

For any adjustment in the valve position, the drying air humidity ratio in the recirculation duct did not change immediately. If the absolute value of the error was large, great adjustment of the position control valve was needed. If the number of the steps sent out from the PC at each position adjustment was too large, control of humidity ratio was difficult to stabilize. To maintain smoother control of the recirculation control valve and prevent it from moving too rapidly, a maximum step number for each adjustment in the valve position was imposed on to the system.

Methods of critical weight ratio and final moisture content control

The critical weight ratio (WT_c) control was quite straightforward. The loadcell measured the mass of the sample, and the signal was sent to the multifunction board. The percentage of mass (WTR), defined as the ratio of the real-time mass of sample to the initial mass of the sample, was then obtained. This value was compared with the critical weight percentage value (WTRC). As soon as WTR became less than WTRC, the second control strategy (maintaining humidity ratio) was initiated. This strategy involved adjusting the valve position to maintain a constant humidity ratio of drying air as previously discussed.

The final moisture content was found using the same method used to determine WT_c. With the known initial moisture content and the measured weight of the sample, the real-time moisture content was calculated. As soon as the moisture content of the drying fruit sample dropped below the final moisture content set point, the data collection was terminated automatically. The collected data were then saved as an ASCII text format.

Control Program

A control program was developed in BASIC (Appendix C). The program used BASIC CALL routines provided by ComputerBoards, Inc. The final program contained one main program and five subroutines. This program originally was designed for normal ambient conditions and the termination of data collection initially was based upon the drying time. During the development and testing of this control program, the weather conditions varied. Functions of the control program were gradually expanded to accomplish the process control criteria under additional ambient condition parameters. Figure 11 shows the flow chart of the process control.

Main program

In the main program, the multifunction board was first initiated and the position control valve was reset to Zero position. The control-related parameters, such as initial sample weight, initial moisture content, final moisture content control point, initial recirculation ratio, and stepping motor control proportional coefficient were input into the computer by the operator. All the criteria of control strategy were placed in the main program. Data collected and a record of control actions recorded were sent to a printer during the dehydration process.

Subroutines

The control program contained five subroutines. These subroutines included the initial recirculation setting subroutine, weight and temperature measurement subroutine, stepping motor forward subroutine, stepping motor backward subroutine, and real-time air recirculation ratio tracking subroutine.

The initial recirculation setting subroutine calculated the valve position based on the initial recirculation ratio value and turned the valve to that initial position.

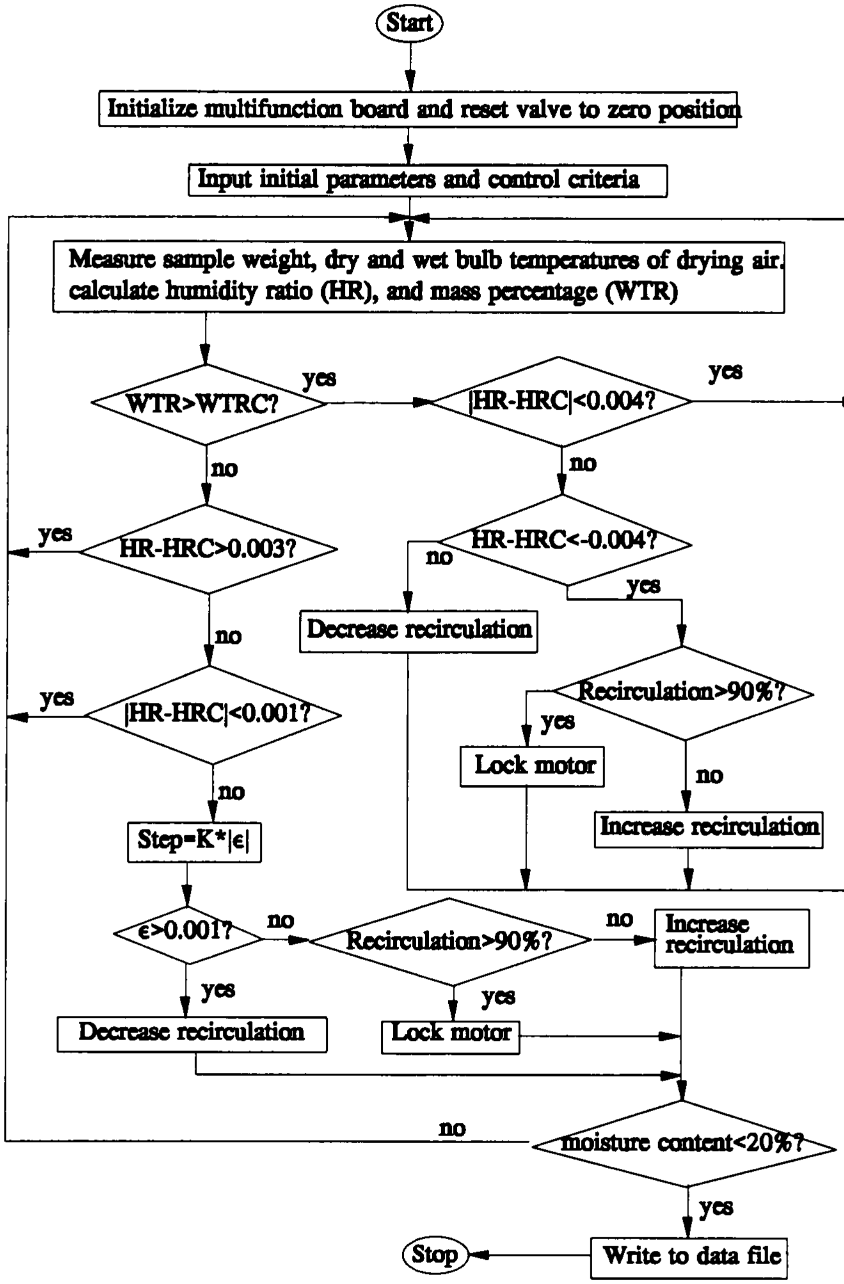

Figure 11. Flow chart of the microcomputer-based control of air recirculation in a batch-type fruit dehydrator.

The measurement subroutine measured the real-time sample mass and, dry and wet bulb temperatures of the drying air in the recirculation duct. The values of mass and temperatures measured by the multifunction board were the average of 100 scans over 3 seconds. The humidity ratio of the air mixture was calculated based upon measured dry and wet bulb temperatures.

Forward and backward subroutines sent digital signals from the digital output ports of the multifunction board. The digital signals were received by the stepping motor driver. The latter turned the valve clockwise or counterclockwise.

The recirculation ratio tracking subroutine recorded the position of the valve and calculated the real-time air recirculation ratio value.

Evaluation of the Control System

Evaluation of humidity ratio control system

The humidity ratio control system initially was tested under simulated drying conditions. The key attributes for evaluation included stability, response to a step change in the set point of the humidity ratio in the recirculation duct, the effect of sampling rate, and the effect of changes in the proportional coefficient. If the measured humidity ratio of the drying air was within ±0.001 around the set point, the control system was considered to be stabilized.

In the evaluation of the system, approximately 1 kg of water was put in a plastic pan (10.16 cm x 15.24 cm x 5.08 cm), which was placed in the center of the dehydrator.

The temperature of air exiting the heater section was kept at 60°C using a PID temperature controller. The initial recirculation ratio was set at zero. The humidity ratio control set point was set at 0.025 kg water/kg dry air for the first one hour in the start-up period. The set point was then changed to 0.020 for another hour period. The dry and wet bulb temperatures and the humidity ratio of the air mixture were recorded. Three proportional coefficients (1000, 2500 and 4000) were evaluated using this procedure. Three sampling periods were used: every 38, 60, and 120 seconds. The dehydrator was operated for at least 30 minutes before water was put into the dehydrator. All tests were triplicated.

Parameters evaluated were the time required for the humidity ratio to stabilize, the variation of humidity ratio after the humidity ratio stabilized, and time for the humidity ratio to stabilize again after a step change in the set point was imposed. The maximum rate of change in the humidity ratios (kg water/kg dry air per second) during warming up and cooling down periods was defined by Equation 12.

$$\textbf{Maximum rate of change in humidity ratio} = \max\left|\frac{\Delta HR}{\Delta t}\right| \quad (12)$$

The statistical analysis included standard deviation of the humidity ratio after stabilization, GLM (General Linear Model) for analysis of the effect of different proportional coefficients, and sampling periods on humidity ratio control. Statistical comparisons used Least-squared Means (LSMEANS) with the PDIFF option (SAS, 1985). All the statistical analysis was conducted using SAS on UTCC VAX mainframe.

Control system performance under actual drying conditions

After the humidity ratio control system was developed and tested, actual drying tests were conducted to evaluate the control system. Apple rings were dehydrated in the dehydrator with the automatic control system and in a second dehydrator without automatic control and air recirculation. The tests were triplicated.

Approximately 1000 grams of apple rings, evenly distributed on four plastic trays, were used for the tests in each of the two dehydrators. The plastic trays were placed in an aluminum frame supported by the loadcell to measure the mass changes. Apples were hand-peeled, cored, and then sliced to 7.62 mm thickness using an adjustable slicer. The moisture of apple samples was measured using the AOAC vacuum oven method 14.003 (AOAC, 1990). Fresh apples were smaller than those used in Walker's tests (Walker, 1992). The moisture content of the fresh apples was 85.4% (wet basis). The cumulative energy consumption in the two dehydrators was compared.

In Test I, a sample of apple rings weighing 1062 grams was placed in the dehydrator with an automatic control system. Another 1032 grams of apples were place in another dehydrator without an automatic control system and air recirculation.

In Test II, apple ring samples of 1070 and 1067 grams were place in the dehydrators with and without an automatic control system, respectively.

In the third test, 1068 and 1070 grams of apple ring samples were place in the two dehydrators with and without an automatic control system, respectively.

CHAPTER IV

RESULTS AND DISCUSSION

Evaluation of Humidity Ratio Control System

Effect of proportional coefficients

Since the control system imposed a tolerance for humidity ratio control, there must be a minimum value of proportional coefficient, depending on the value of the imposed tolerance. The maximum tolerance used in this control system was ±0.001 (kg water/kg dry air). The minimum value of error was thus ±0.001. Since the number of steps sent out by the control system, was proportional to the error (Equation 11), the minimum proportional coefficient in this study was 1000. Any proportional coefficient lower than 1000 would result in a value less than one step. Thus, no pulse would be sent from the control system.

<u>Overall performance</u>

For proportional coefficients of 1000, 2500, and 4000, responses of the control system to the start-up and step change in the set point are shown in Figures 12, 13, and 14. The sample interval for these tests was 60 seconds. No overshoot in the humidity ratio was found for the tests using a proportional coefficient of 1000. Overshoot was observed when using proportional gains of 2500 and 4000, with the latter showing the

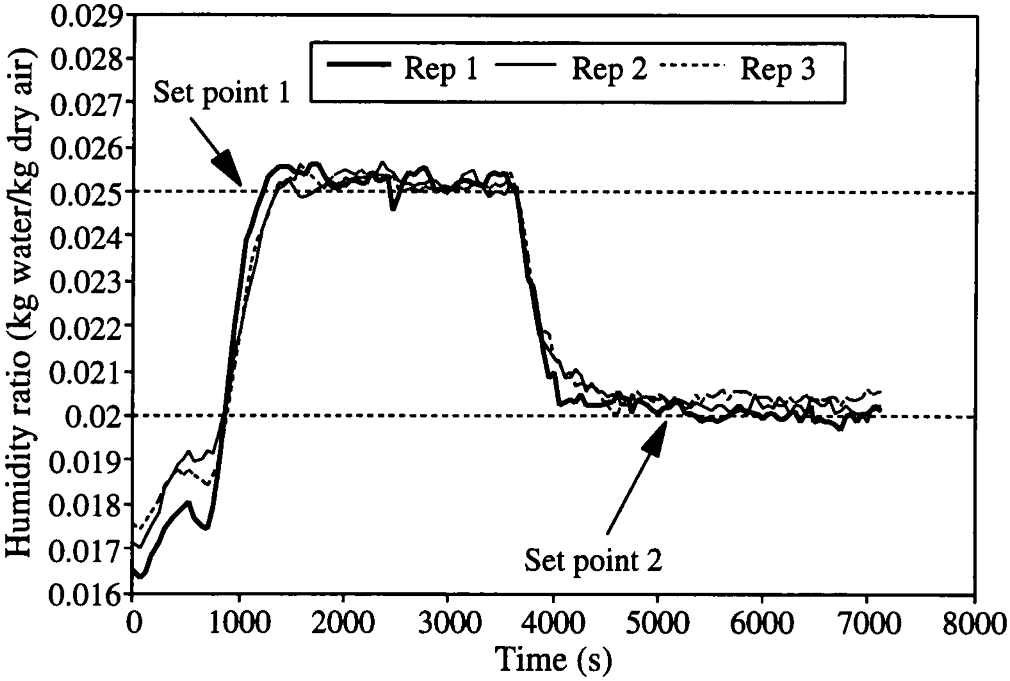

Figure 12. Humidity ratio changes with respect to time in the dehydrator performance test using a proportional coefficient of 1000.

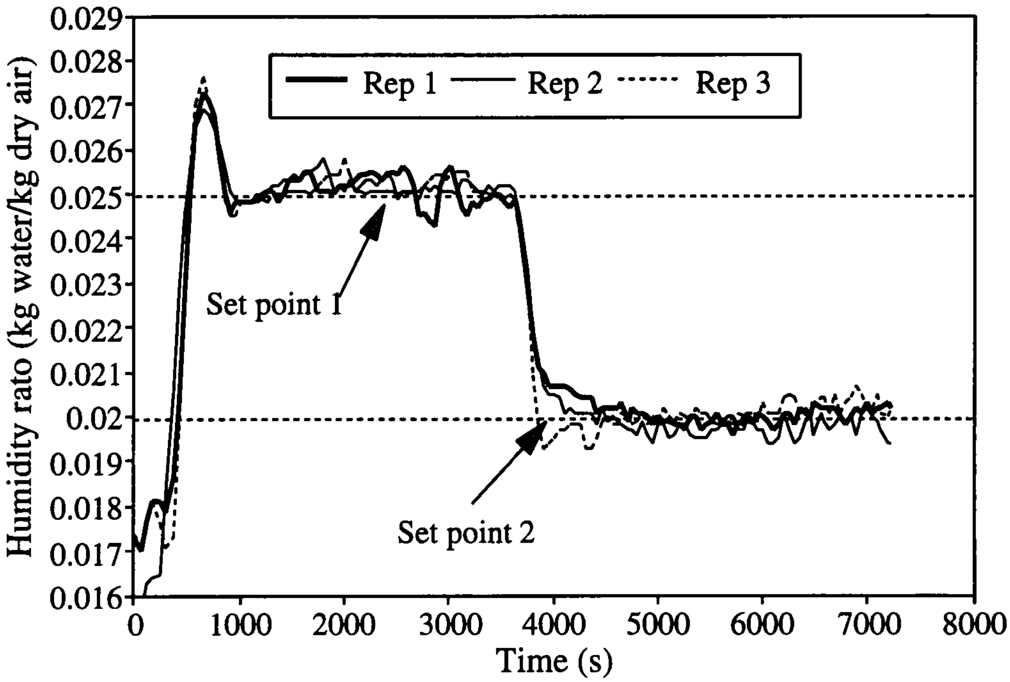

Figure 13. Humidity ratio changes with respect to time in the dehydrator performance test using a proportional coefficient of 2500.

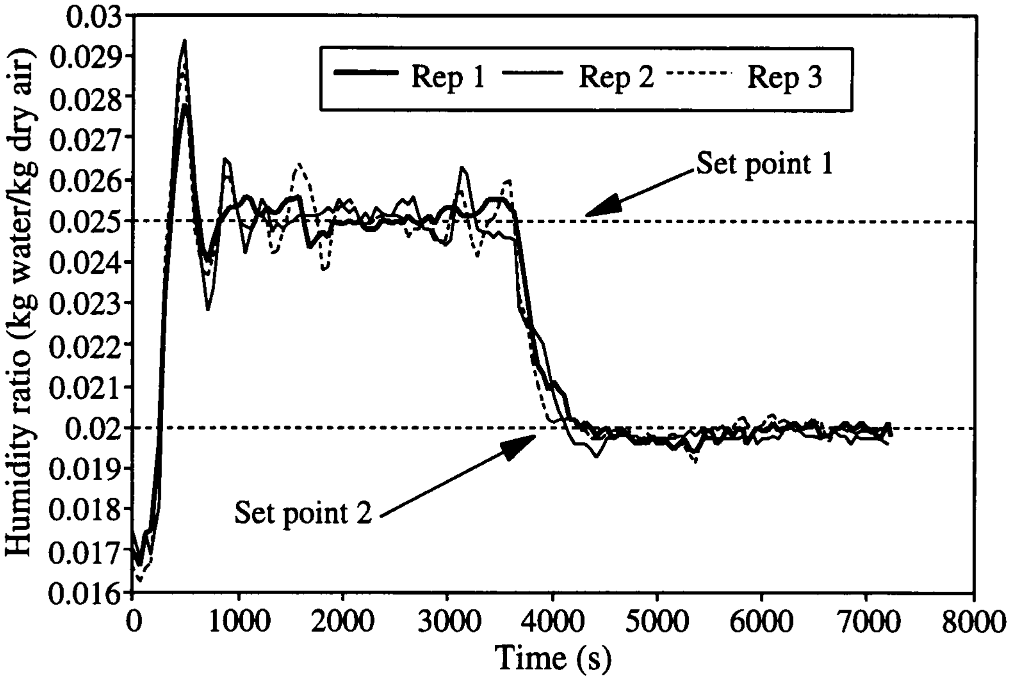

Figure 14. Humidity ratio changes with respect to time in the dehydrator performance test using a proportional coefficient of 4000.

greatest overshoot.

Different times were needed for the system to stabilize during the start-up period and after a step change in the set point of humidity ratio of the air mixture in the recirculation duct. As shown in Figure 15, the average time required for the system to stabilize was shortest for a proportional coefficient of 2500 during both the start-up period and after a step change in the set point. The average times required for the system to stabilize were 1221, 819, and 970 seconds, respectively, for the proportional coefficients of 1000, 2500, and 4000. Shorter times were needed for the system to stabilize after a step change in the set point compared to those needed during start-up. After a step change in the set point, the average times required for the system to stabilize again were 419, 248, and 358 seconds. Increasing or decreasing proportional coefficients caused an increase in the average time required for the system to stabilize.

The rate of humidity ratio changes during start-up to the set point of 0.025 and stepping down to 0.02, as measured by the maximum rate of humidity ratio change with respect to time (Equation 12), is shown in Figure 16. The average maximum rate of humidity ratio change increased almost linearly with the proportional coefficients.

It can be seen that an increase in the proportional coefficient results in a higher rate of humidity ratio change and an increase in overshoot during start-up. This may be explained by the following hypothesis:

> For the same error value, smaller proportional coefficients result in smaller steps, while larger proportional coefficients result in larger steps.

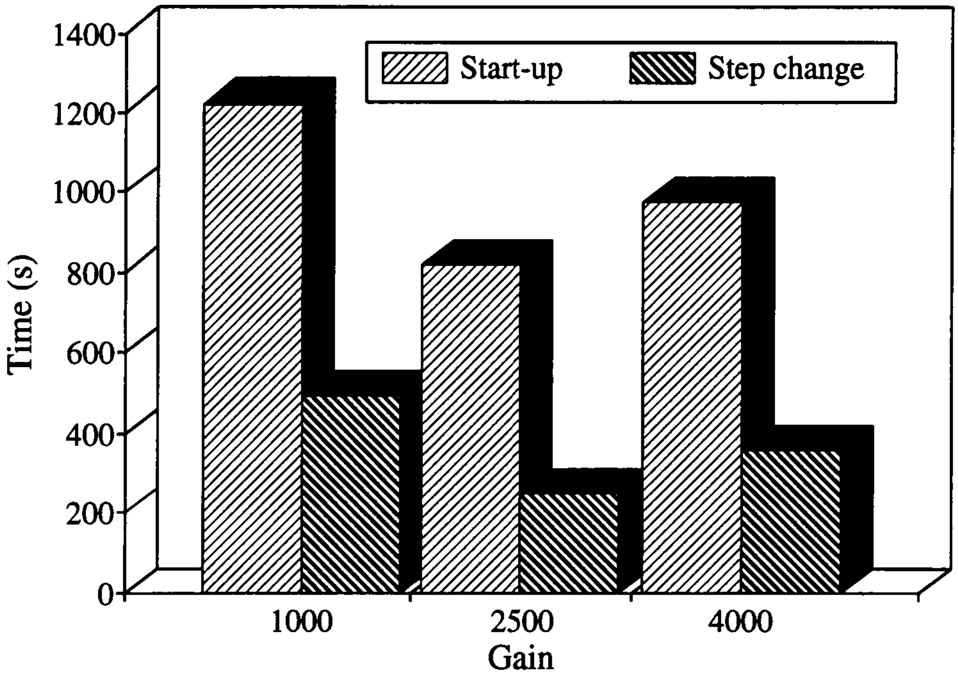

Figure 15. Average time required for the system to stabilize for the humidity ratio control during start-up period and after a step change in the set point using different proportional coefficients.

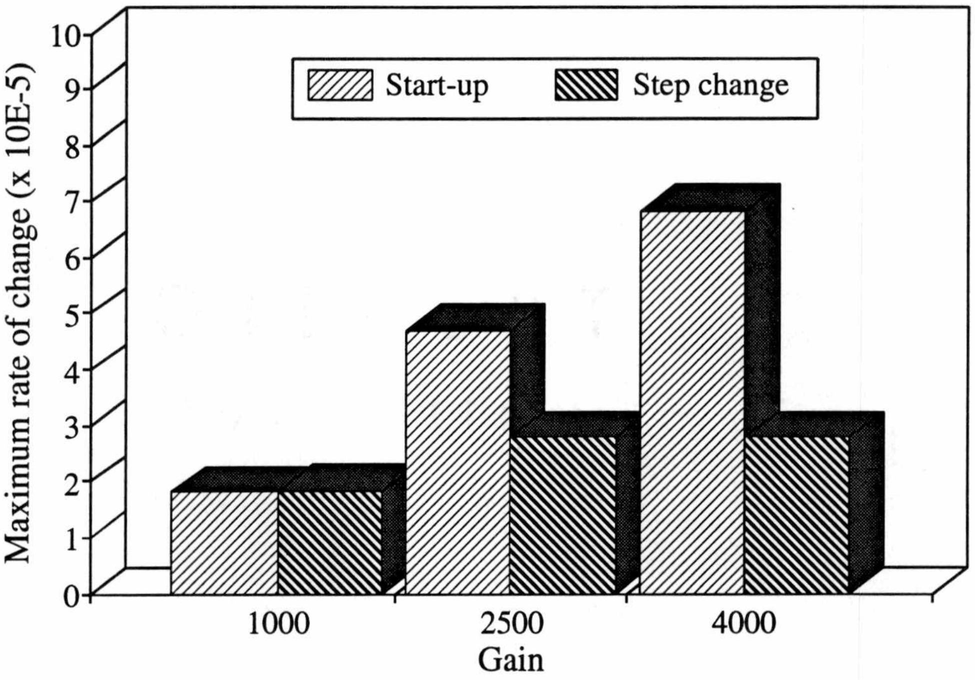

Figure 16. The maximum rate of change in the humidity ratio (kg water/kg dry air per second) during start-up period and after a step change in the set point of humidity ratio for different proportional coefficients.

The smaller steps result in smaller corrective actions, and the longer time is needed for humidity ratio to stabilize after a step change. Larger steps result in greater corrective action. As a result, overshoot may occur. With greater overshoot, longer time is necessary to stabilize the control system. Extremely high values of the proportional coefficient would lead to oscillation in the humidity ratio control.

Effect of proportional coefficient on humidity ratio control

After the system was stabilized, the humidity ratio of the drying air varied around the set point. The variation was affected by proportional coefficients. The variation of the humidity ratio was analyzed by analysis of variance (ANOVA).

For the set point of 0.025, after the system was stabilized, it was found that the variation of humidity ratio in the tests using the proportional coefficient of 1000 was significantly different from that using the proportional coefficient of 4000 (Pr=0.0016, Table 4). The control of humidity ratio using a proportional coefficient of 1000 appeared to be more stable than when using a proportional coefficient of 4000 (Figure 12 and Figure 14). No statistically significant difference in the variation of humidity ratio was found between the proportional coefficients of 2500 and 4000 (Pr=0.1666). The difference in variation of air humidity ratio using a proportional coefficient of 1000 and that using a proportional coefficient of 2500 was marginally significant (Pr=0.0684). It also appeared that the control of air humidity ratio using a proportional coefficient of

Table 4. Effect of proportional coefficients on humidity ratio control: Analysis of difference in the least squared means of the humidity ratio of the drying air in the recirculation duct after the control was stabilized at the set point of 0.025 kg water/kg dry air (Pr>|T| |H_o|: LSMEANS(i)=LSMEANS(j))

i/j	1000	2500	4000
1000	.	0.0684	0.0016
2500	0.0684	.	0.1660
4000	0.0016	0.1660	.

1000 was more stable than that using a proportional coefficient of 2500. The mean moisture contents of the drying air and their standard deviations were almost the same for all three proportional coefficients (Table 5). Since the control tolerance was set at 0.001, control using proportional coefficients of 1000 and 2500 could be considered to be successful and stable at the set point of 0.025, with all the measured humidity ratio values falling within the range of 0.024 and 0.026. Control using a proportional coefficient of 4000 could not be considered stable since some humidity ratio values fell outside the range of 0.024 and 0.026, with a minimum humidity ratio value of 0.0238 and a maximum humidity ratio value of 0.0264. It could be deduced from this observation that further increasing the proportional coefficient would lead to greater fluctuation of the humidity ratio and thus a more unstable system.

After a step change in the set point, the humidity ratio of drying air was again stabilized at the new set point of 0.020. The difference in humidity ratio control was statistically significant among all levels of proportional coefficients (Pr=0.0001, Table 6). The mean humidity ratio values were very close to the set point of 0.020 kg water/kg dry air. All humidity ratio values fell within the control range of 0.019 and 0.021 (Table 7).

Effect of sampling periods

Adjustment of the position control valve was based upon periodical measurement of the dry and wet bulb temperatures of the air mixture in the recirculation duct as well as the weight of sample in the dehydrator. Therefore, the sampling period should have

Table 5. Effect of proportional coefficients on humidity ratio control: Mean humidity ratio (kg water/kg dry air) of the drying air in the recirculation duct after the control was stabilized at the set point of 0.025 kg water/kg dry air

Prop. coeff.[a]	Mean humidity ratio	Standard deviation	Minimum	Maximum
1000	0.0252	0.0003	0.0241	0.0257
2500	0.0251	0.0003	0.0243	0.0258
4000	0.0251	0.0004	0.0238	0.0264

[a] Proportional coefficient.

Table 6. Effect of proportional coefficients on humidity ratio control: Analysis of difference in the least squared means of the humidity ratio of the drying air in the recirculation duct after the control was stabilized at the set point of 0.020 kg water/kg dry air (Pr>|T| $|H_o|$: LSMEANS(i)=LSMEANS(j))

i/j	1000	2500	4000
1000	.	0.0001	0.0001
2500	0.0001	.	0.0001
4000	0.0001	0.0001	.

Table 7. Effect of proportional coefficients on humidity ratio control: Mean humidity ratio (kg water/kg dry air) of the drying air in the recirculation duct after the control was stabilized at the set point of 0.020 kg water/kg dry air

Prop. coeff.[a]	Mean humidity ratio	Standard deviation	Minimum	Maximum
1000	0.0203	0.0002	0.0197	0.0210
2500	0.0200	0.0003	0.0193	0.0210
4000	0.0199	0.0003	0.0191	0.0201

[a] Proportional coefficient.

a significant effect upon stability of the humidity ratio control in this study. To test the effect of the sampling period, the proportional coefficient of the control was set at 2500 and the system was tested with sampling periods of 38, 60, and 120 seconds. If the measured humidity ratio of the drying air was within ±0.001 around the set point, then the control system was considered to be stabilized. Figures. 17, 18 and 19 show the effects of sampling period upon the control system.

Overall performance

The most severe overshoot and oscillation in the humidity ratio of the drying air during start-up was observed in the tests of using a sampling period of 38 seconds. The overshoot and oscillation became less severe with longer sampling periods (Figs. 17, 18, and 19). The average times required for the system to stabilize were 1091, 819, and 1109 seconds, respectively, for the sampling periods of 38, 60, and 120 seconds. After a step change in the set point, the average times required for the system to stabilize again were 401, 248, and 453 seconds, respectively, for the sampling periods of 38, 60, and 120 seconds. Increasing or decreasing the sampling period from 60 seconds increased the time required for the system to stabilize (Figure 20). The times required for the system to stabilize after a step change in the set point were less than those in start-up (Figure 20). The maximum rates of change in the humidity ratio decreased with the sampling periods (Figure 21). The maximum rates of change were greater during start-up than those immediately following a step change.

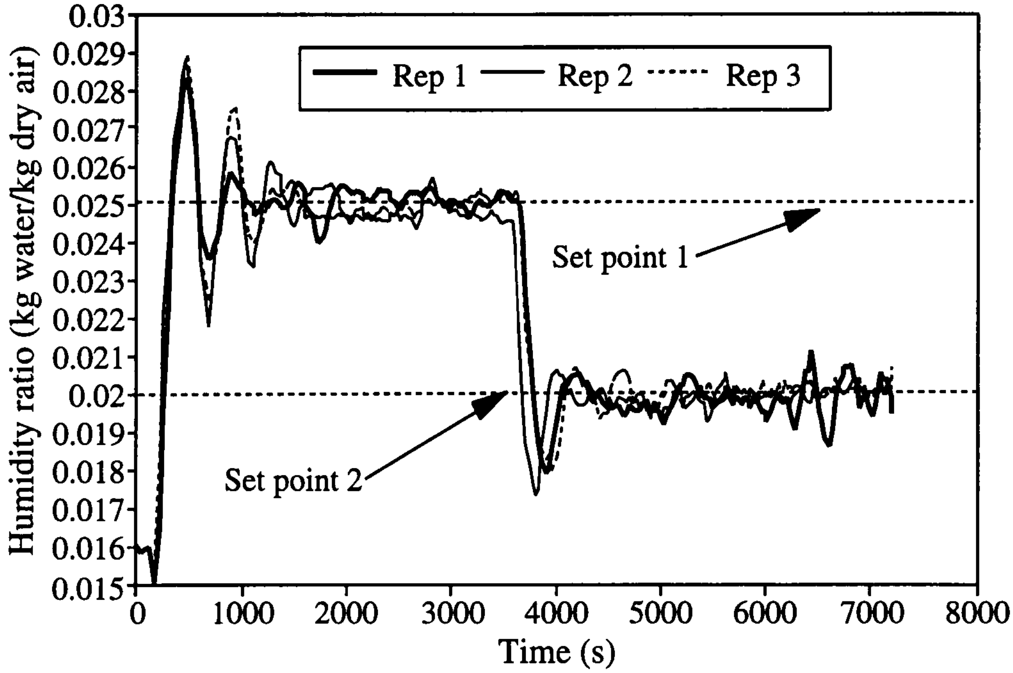

Figure 17. Humidity ratio changes with respect to drying time in the dehydrator performance tests using a sampling period of 38 seconds.

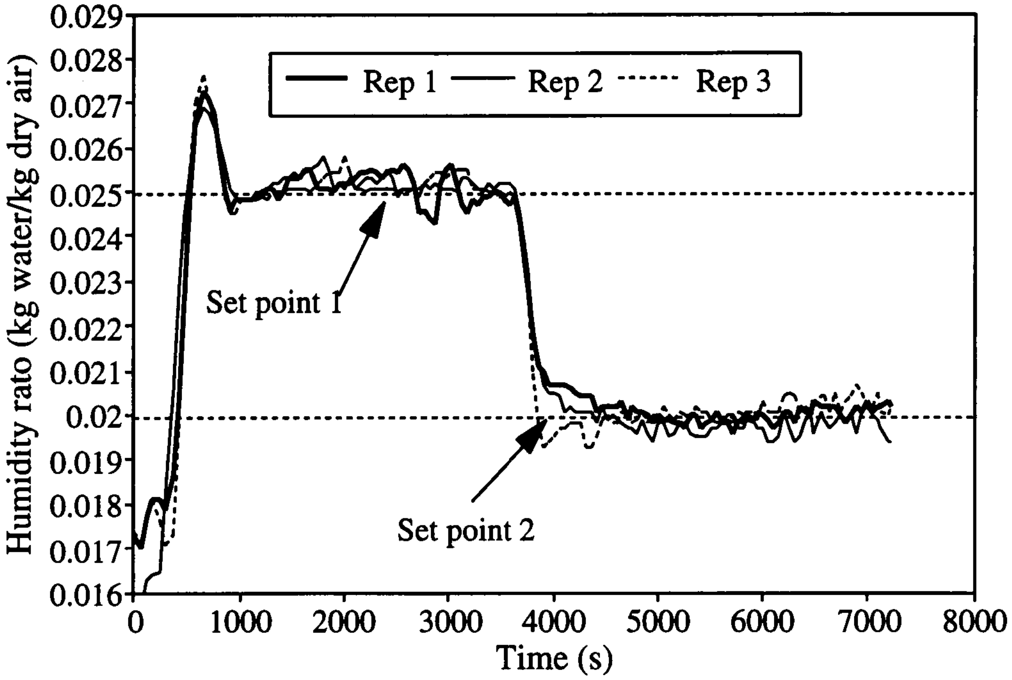

Figure 18. Humidity ratio changes with respect to drying time in the dehydrator performance tests using a sampling period of 60 seconds.

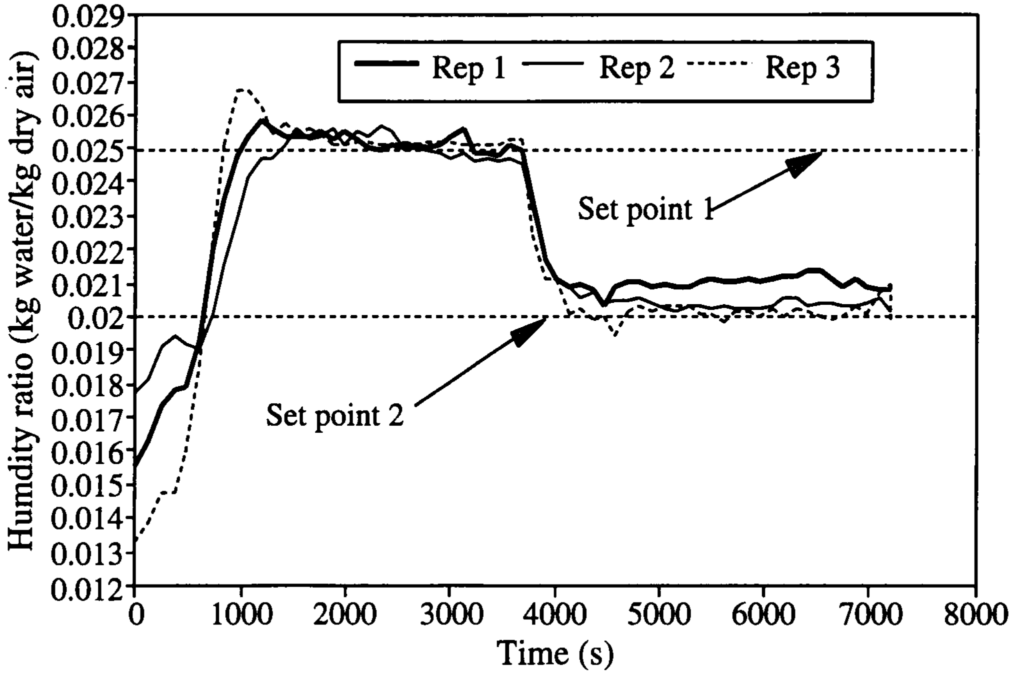

Figure 19. Humidity ratio changes with respect to drying time in the dehydrator performance tests using a sampling period of 120 seconds.

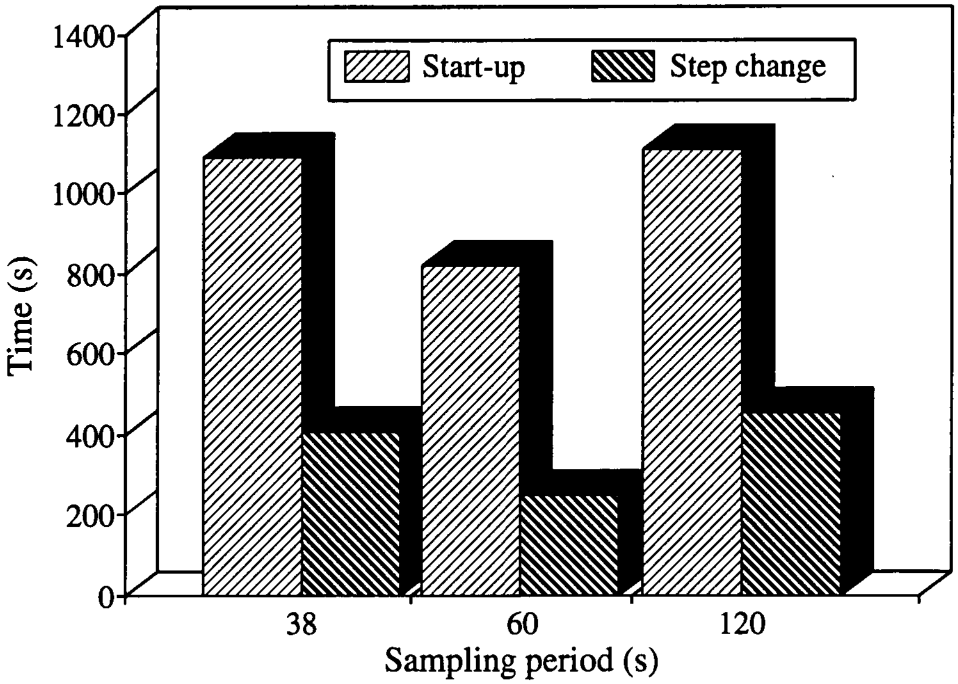

Figure 20. Average time for the system to stabilize in the control of humidity ratio using different sampling periods during start-up and after a step change in the set point.

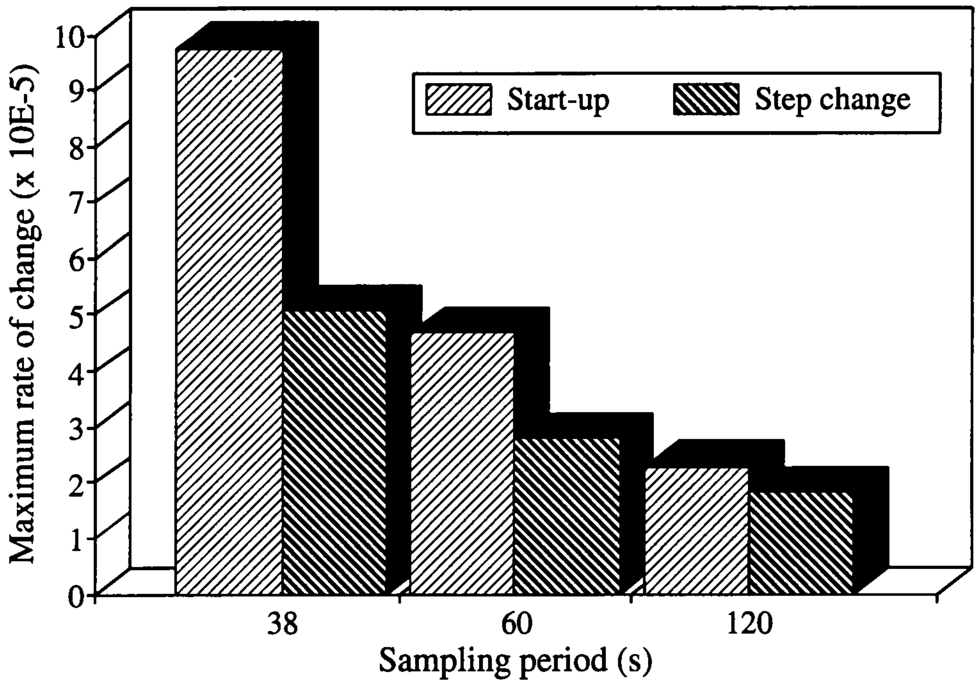

Figure 21. The average maximum rate of change in humidity ratio (kg water/kg dry air per second) during start-up and a step change in the set point using different sampling periods.

Overshoots and oscillation at low sampling periods may possibly be due to the frequent adjustment of the recirculation control valve. The system requires a response time to react to the adjustment. When the sampling period is too short, the system may not be able to react quickly enough after an initial adjustment and an additional adjustment is imposed. Over-adjustment may occur, leading to overshoot. Long sampling periods, on the other hand, lead to less frequent adjustments and slow response of the drying air humidity ratio control. Longer time is needed for the system to stabilize. Since control with a sampling period of 38 seconds led to overshoot and control with a sampling period of 120 seconds required a long time to stabilize, it appears that the sampling period for this system should not be greater than 120 seconds or less than 38 seconds.

Effect of sampling period on humidity ratio control

After the humidity ratio control stabilized at the set point of 0.025, the sampling period showed a significantly affected control of the air humidity ratio in the recirculation duct (Figure 17, 18, and 19). There was some indication that the control of humidity ratio after stabilization might behave differently among sampling periods (Pr>F ranged from 0.0638-0.0652, Table 8). It appeared that the control with a sampling period of 120 was the most stable (Figure 19). The mean of the humidity ratio was very close to 0.025, with the control of humidity ratio at a sampling period of 38 seconds showing the highest standard deviation. As for the reliability of control, the control of humidity ratio using the

Table 8. Effect of sampling periods on humidity ratio control: Analysis of difference in the least squared means of the humidity ratio of the drying air in the recirculation duct after the control was stabilized at the set point of 0.025 kg water/kg dry air (Pr>|T| $|H_o|$: LSMEANS(i)=LSMEANS(j))

i/j	1000	2500	4000
38	.	0.0638	0.0652
60	0.0638	.	0.06525
120	0.0652	0.06525	.

sampling periods of 60 and 120 performed very well, with all of the measured humidity ratio values falling within the control range (0.024-0.026). Unreliable control over the humidity ratio was observed with a sampling period of 38 seconds (Table 9).

For the humidity ratio control at the set point of 0.02, after stabilization, the control of the humidity ratio behaved differently for different sampling periods (Figure 17, 18, and 19). The control of the humidity ratio at the sampling period of 38 seconds was not significantly different from that at the sampling period of 60 seconds (Pr=0.5308, Table 10). The control of humidity ratio at the sampling period of 120 seconds was significantly different from those at the sampling periods of 60 and 38 seconds, with the former appearing to be the most stable (Figures 17, 18, and 19). The mean moisture contents of the drying air was close to the set point of 0.020 (Table 11). The standard deviation of humidity ratio values was also very close. Only the control at the sampling period of 60 was reliable since all the measured humidity ratio values fell within the control range (0.019-0.021). Controls at the sampling periods of 38 and 120 seconds were not reliable, with some measured humidity ratio values falling outside the control range of 0.019-0.021 (Table 11).

Control System Performance under Actual Drying Conditions

Test I

Figure 22 shows the humidity ratio change of the drying air in the recirculation duct versus drying time in the automatic control system for Test I. The recirculation ratio

Table 9. Effect of sampling periods on humidity ratio control: Mean humidity ratio (kg water/kg dry air) of the drying air in the recirculation duct after the control was stabilized at the set point of 0.025 kg water/kg dry air

Sampling period	Mean humidity ratio	Standard deviation	Minimum	Maximum
38	0.0250	0.0005	0.0234	0.0276
60	0.0251	0.0003	0.0243	0.0258
120	0.0251	0.0003	0.0241	0.0258

Table 10. Effect of sampling periods on humidity ratio control: Analysis of difference in the least squared means of the humidity ratio of the drying air in the recirculation duct after the control was stabilized at the set point of 0.020 kg water/kg dry air (Pr>|T| $|H_0|$: LSMEANS(i)=LSMEANS(j))

i/j	1000	2500	4000
38	.	0.5308	0.0001
60	0.5308	.	0.0001
120	0.0001	0.0001	.

Table 11. Effect of sampling periods on humidity ratio control: Mean humidity ratio (kg water/kg dry air) of the drying air in the recirculation duct after the control was stabilized at the set point of 0.020 kg water/kg dry air

Sampling period	Mean humidity ratio	Standard deviation	Minimum	Maximum
38	0.0200	0.0003	0.0187	0.0211
60	0.0200	0.0003	0.0193	0.0210
120	0.0205	0.0004	0.0194	0.0214

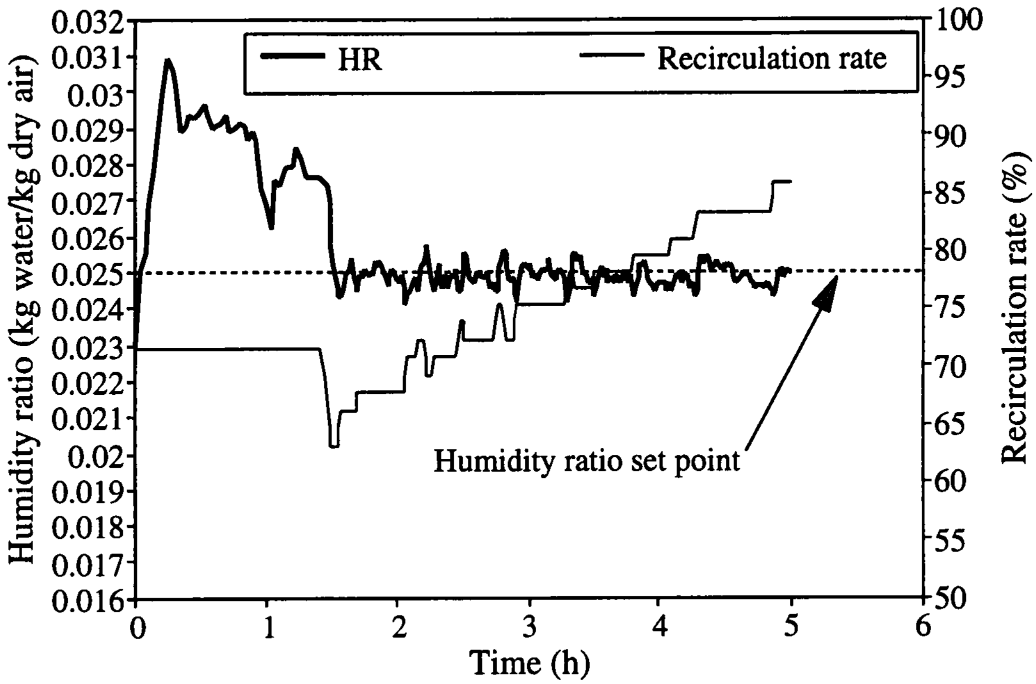

Figure 22. The humidity ratio change in the recirculation duct and the recirculation ratio with respect to the drying time in Test I.

(R), calculated from the number of the steps of motor movement using Equation 9 also is shown. The initial humidity ratio of the drying air in the recirculation duct was 0.023 kg water/kg dry air. It increased rapidly to a peak and started to fluctuate. The recirculation ratio was kept unchanged during the initial drying period (before the weight ratio, WTR, dropped below 0.7). The stepping motor did not react immediately after the weight ratio (WTR) dropped below 0.7 since the humidity ratio of the air mixture in the recirculation duct was still 0.003 higher than the set point of 0.025 (Figure 22 and Figure 23). During the initial drying period, the drying air humidity ratio was higher than the set point. When the control system began to maintain the humidity ratio of the drying air at the new set point, the recirculation first was reduced and then began to increase gradually. The recirculation ratio increased almost linearly with the drying time. It took approximately 5 minutes for the system to stabilize after the control system began to maintain the humidity ratio of the drying air at 0.025 kg water/kg dry air. The final recirculation rate was 86%. The humidity ratio was controlled within the control limits (0.024-0.025) in the later drying period.

Comparisons of the dehydrator performance, based upon changes in the weight ratio (WTR) are shown in Figure 24 for Test I. The final weight ratio of the drying sample with the automatic control system was slightly higher than that with no control and 0% recirculation. The final moisture content (20.6%, wet basis) of the apple rings dried with the automatic control system was slightly higher than that of no air recirculation system (17.9 %, wet basis). As shown in Figure 23, the removal of moisture

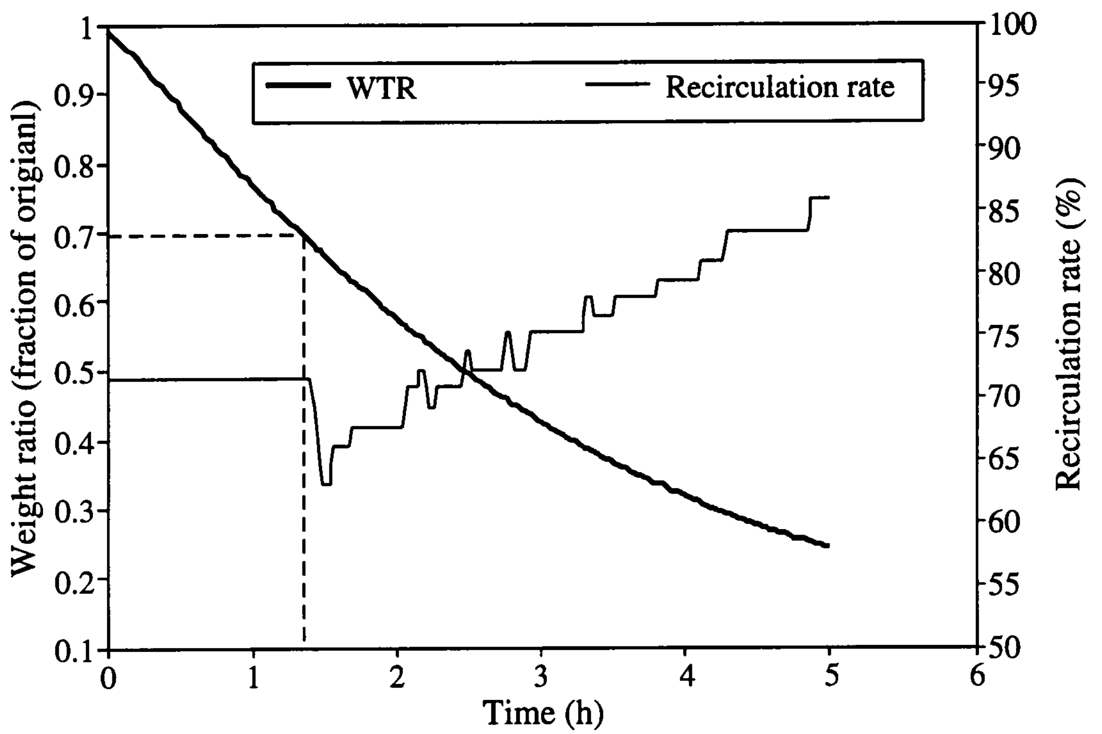

Figure 23. The weight changes in the automatically controlled dehydrator and the recirculation ratio with respect to the drying time in Test I.

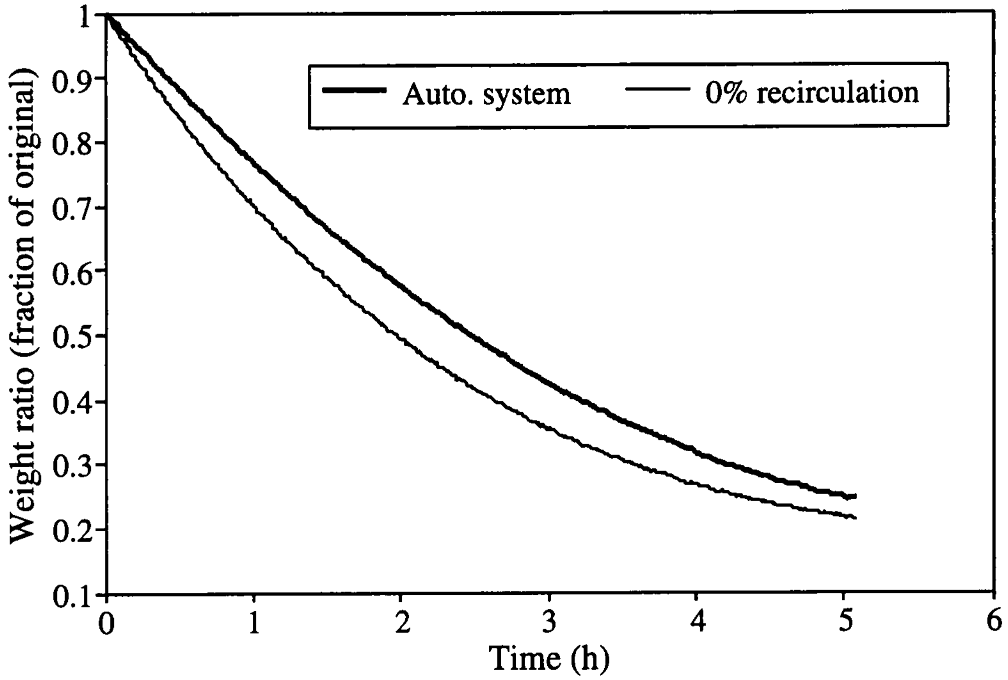

Figure 24. The comparison of the weight ratio changes in the dehydrators with and without automatic control system, respectively, with respect to the drying time in Test I.

from the apple samples in the dehydration using the automatic control system was not as fast as that without air recirculation. The possible reason may be the high moisture content in the drying air since the initial moisture content of the drying air was very close to the set point of 0.025 kg water/kg dry air. Dehydration with high moisture content in the drying air would be expected to retard the moisture removal. Decreasing the recirculation rate under these conditions may improve the removal of moisture from the drying samples.

Energy consumption for the two dehydrators in this test was not recorded because of a technical error in the datalogger program.

Test II

Figure 25 shows the changes of the humidity ratio of the drying air in the recirculation duct and the recirculation ratio versus drying time in the automatic control system. The initial humidity ratio of the air mixture in the recirculation duct was 0.0198 kg water/kg dry air. The drying air humidity ratio increased rapidly to a peak and then varied around 0.025 kg water/kg dry air. The recirculation ratio of the air recirculation was kept unchanged in the initial drying period. During the period from start-up to the point at which the weight ratio (WTR) dropped below 0.7, the moisture content of the drying air was generally lower than that in Test I. A probable reason is the lower initial moisture content of the drying air (0.0198 kg water/kg air, compared to 0.023 kg water/kg dry air in Test I). After the weight ratio dropped below 0.7, the recirculation ratio

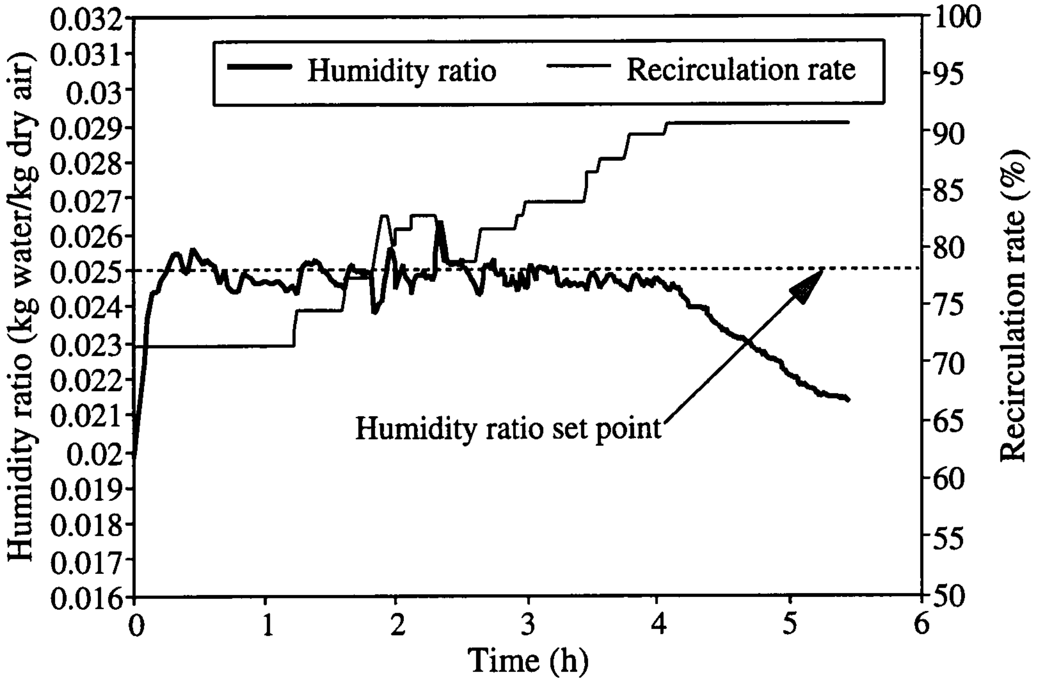

Figure 25. The humidity ratio change in the recirculation duct and the recirculation ratio with respect to the drying time for the automatic control system of Test II.

increased gradually to a point where the air recirculation reached 90% (Figure 26). It took only 2 minutes for the system to stabilize after the control system began to maintain the humidity ratio of the drying air in the recirculation duct. This stabilization time was less than that in Test I. The probable reason is that the humidity ratio of the drying air was very close to the set point when the system was initiated to maintain the humidity ratio. The motor was locked after the recirculation ratio reached the maximum set limit (90%). Maintaining a minimum set point for the humidity ratio was not possible after the motor was locked. Less and less moisture was available for evaporation. Therefore, the humidity ratio of the drying air in the recirculation duct decreased after the air recirculation reached 90%.

The moisture loss of apple samples in the two dehydrators was similar (Figure 27). The final moisture contents were almost the same, with 18.4% and 17.8% (wet basis) for the automatically controlled dehydrator and the unit without air recirculation, respectively. The cumulative energy consumption showed significant difference between the two dehydrators (Figure 28). The dehydrator without air recirculation consumed more energy. The energy savings for the automatically controlled system was 31.3%.

Test III

For this test, the dehydration started with an initial humidity ratio of 0.0206 in the recirculation duct. The humidity ratio of the drying air in the automatically controlled dehydrator increased rapidly to a peak and then began to decrease. When the weight ratio dropped below 0.7, i.e, the weight of the apple sample dropped to 70% of the original

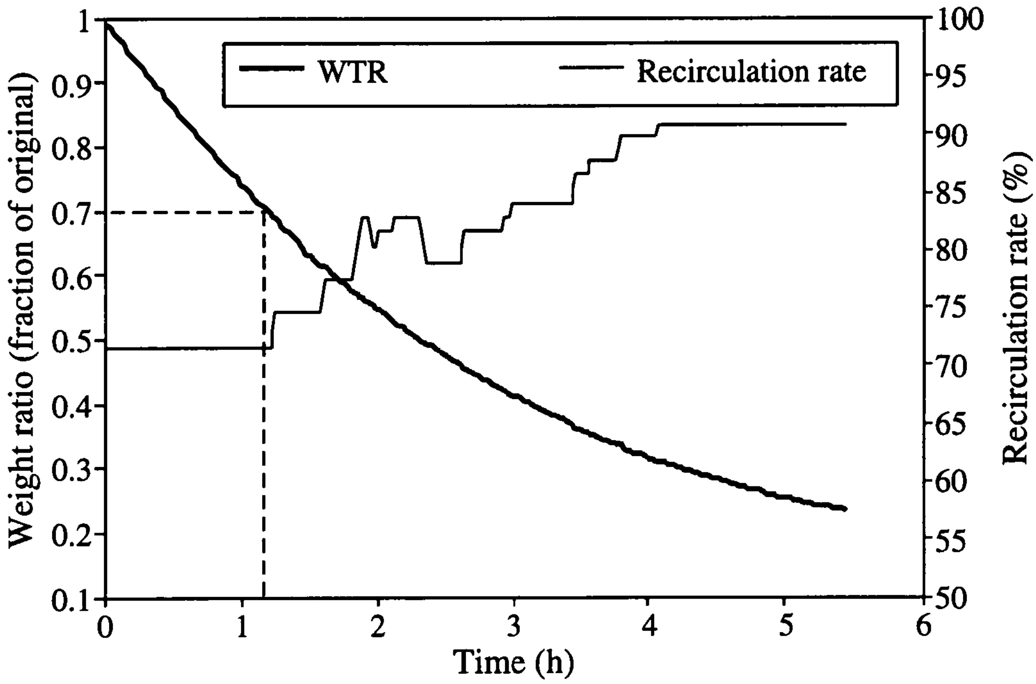

Figure 26. The weight change in the automatically controlled dehydrator and the recirculation ratio with respect to the drying time in Test II.

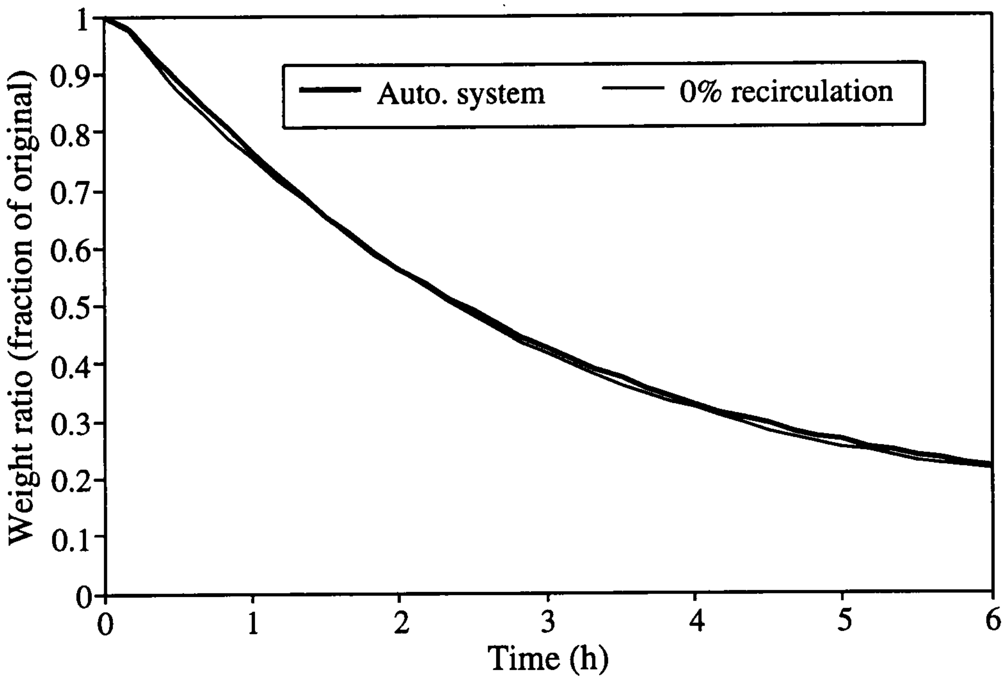

Figure 27. The comparison of the weight ratio changes in the dehydrators with and without the automatic control system, respectively, with respect to the drying time in Test II.

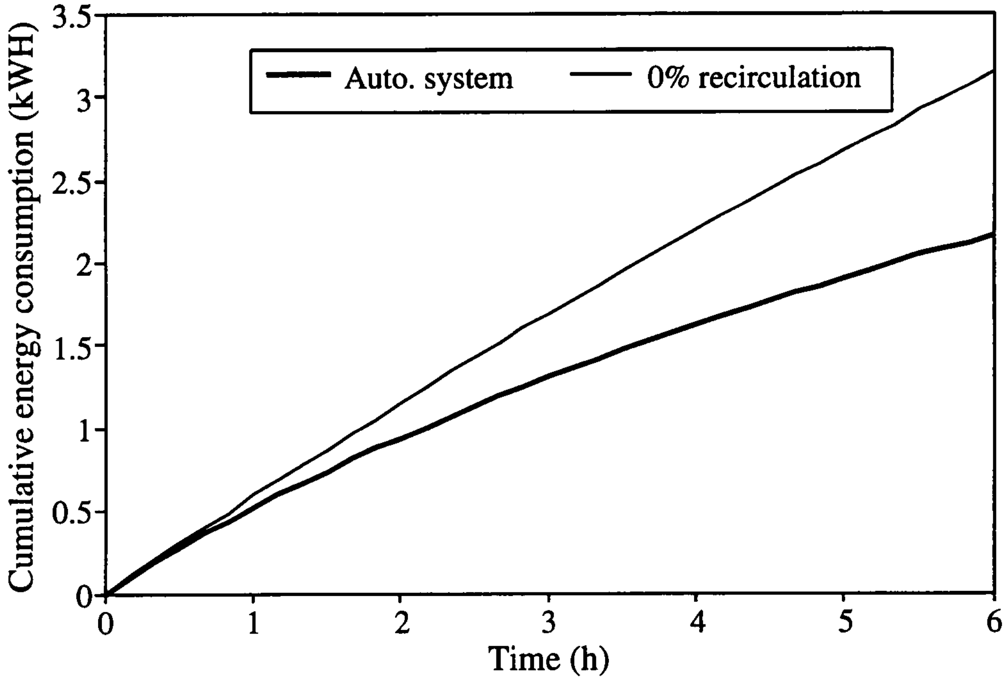

Figure 28. The comparison of cumulative energy consumption between the dehydrators with and without the automatic control system, respectively, with respect to the drying time in Test II.

weight, the humidity ratio of the drying air in the recirculation duct actually was below the set point. The control system immediately started to increase the recirculation of the exhaust air and drove the recirculation control valve towards the maximum recirculation (Figures 29 and 30). The system stabilized in about 5.2 minutes after the control system began to maintain the humidity ratio of the drying air in the recirculation duct. When the recirculation ratio reached 90%, the motor was locked and the dehydration continued with an air recirculation of 90%. The humidity ratio of the drying air dropped gradually after the maximum recirculation ratio was reached.

The rate of moisture removal from the apple samples was almost the same for the two dehydrators (Figure 31). The final moisture contents of the dried apple rings were 18.3% and 17.6% (wet basis) for the automatic control system and the system without air recirculation, respectively. The dehydration with the automatic control system showed a better energy efficiency over the dehydration without air recirculation (Figure 32). The overall energy savings were 31.4% for the automatic control system compared to the dehydration without air recirculation.

The energy required to remove 1 kg of water from the cut fruit samples for this automatic control system was about 16.7 kWH/kg water per kg dry solids. This value is slightly higher than Walker's results (15.9 kWH/kg water per kg dry solids).

The energy consumed to remove 1 kg of water from the cut fruit samples was around 23.3 kWH/kg water per kg dry solids for the dehydration without air recirculation in the study. This value is smaller than Walker's results (30.6 kWH/kg water per kg dry

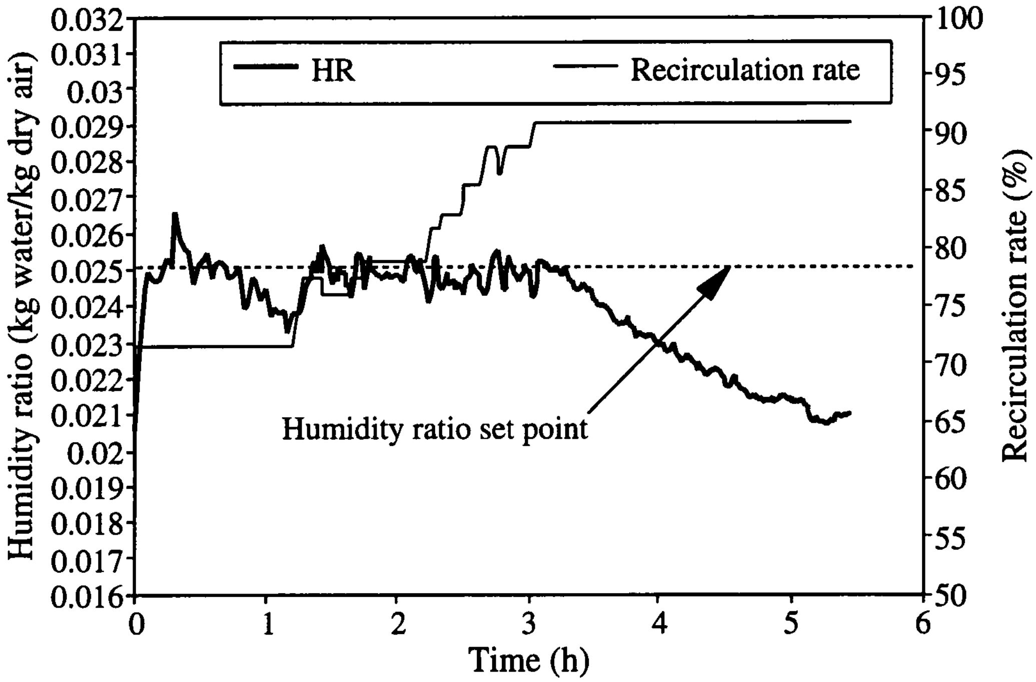

Figure 29. The humidity ratio change in the recirculation duct and the recirculation ratio with respect to the drying time in Test III.

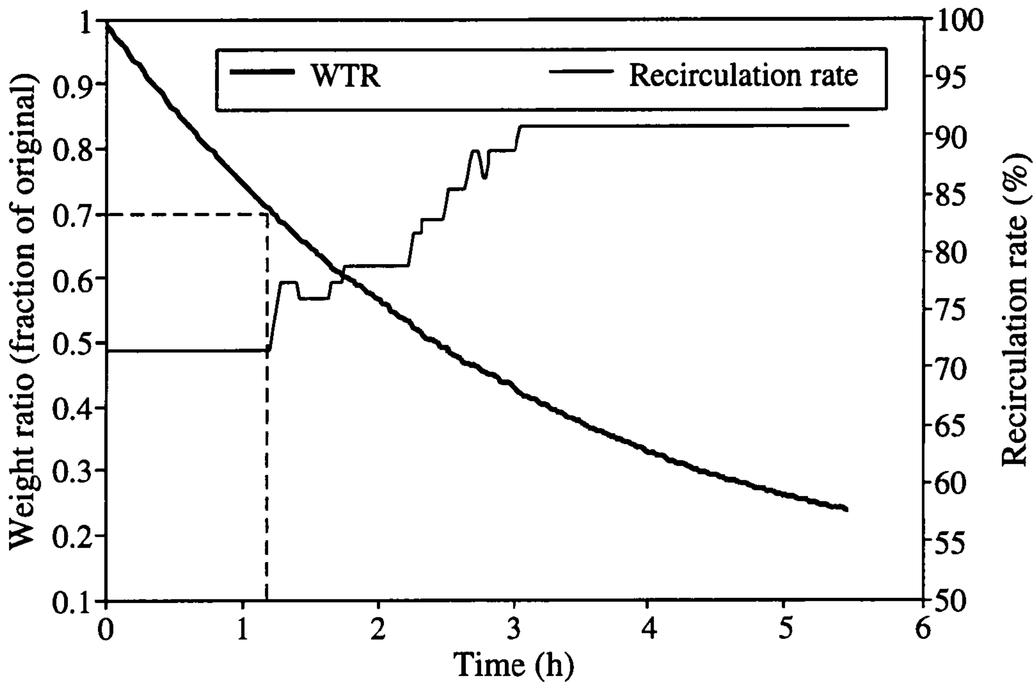

Figure 30. The weight changes in the automatically controlled dehydrator and the recirculation ratio with respect to the drying time in Test III.

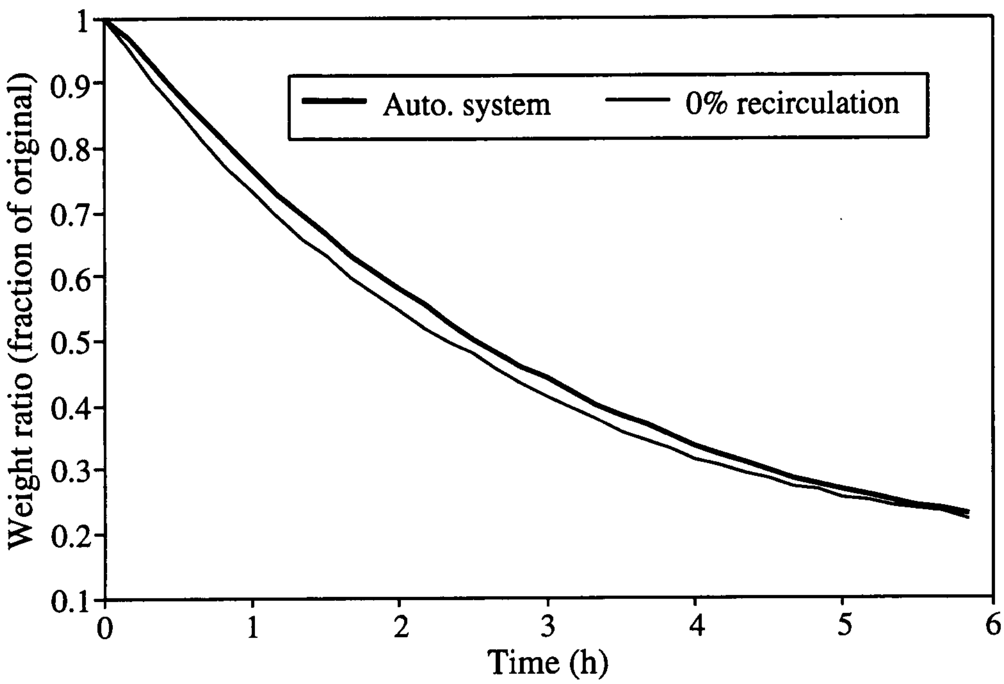

Figure 31. The comparison of the weight ratio changes in the dehydrators with and without the automatic control system, respectively, with respect to the drying time in Test III.

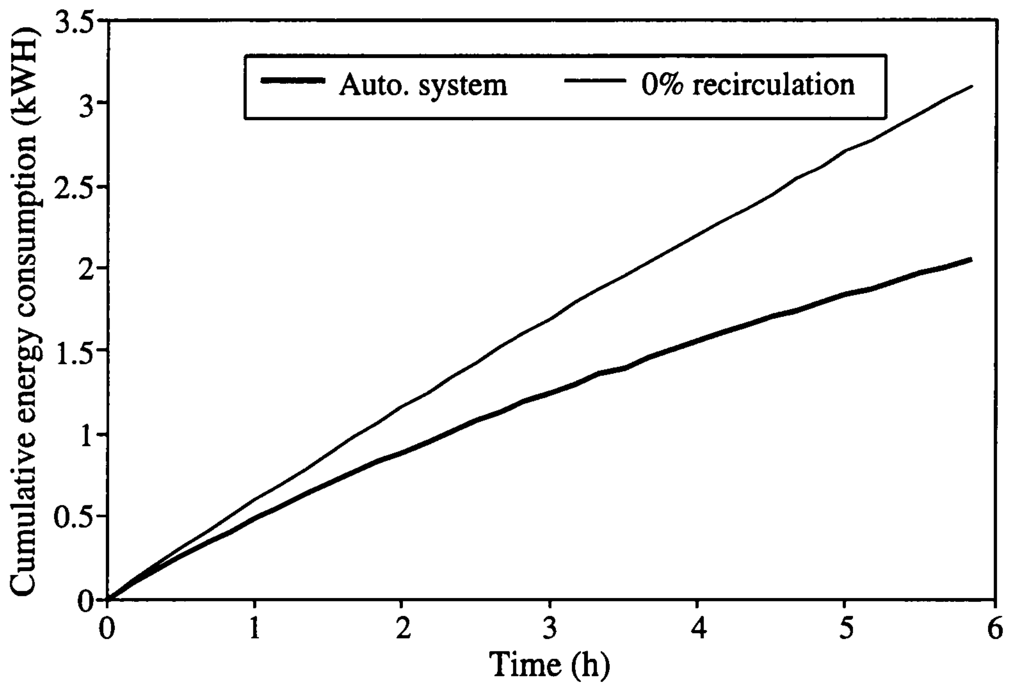

Figure 32. The comparison of cumulative energy consumption between the dehydrators with and without the automatic control system in Test III.

solids). The dehydration of apple rings was conducted in the summer season (August, 1993). Wakler conducted his study in the early part of October, 1991. The difference in the drying seasons may have attributed to the difference in the energy consumptions in the dehydration of apple rings without air recirculation between the two studies.

CHAPTER V

SUMMARY AND CONCLUSIONS

A microcomputer-based data acquisition and control system for exhaust air recirculation in a fruit dehydrator was developed and tested. A microcomputer was used as a digital feedback controller. The objectives of this study included: (1) development of the microcomputer-based control system for a fruit dehydrator to automatically control the recirculation of exhaust air in the drying operation, (2) testing the microcomputer-based control system under actual drying conditions, and (3) comparison of the performance of the dehydrator with microcomputer-based recirculation control with the performance of a similar dehydrator with no air recirculation.

A control program, written in BASIC, was developed to accomplish the air recirculation control. The control parameters for the batch-type dehydrator included the initial recirculation ratio, humidity ratio of the mixture of the recirculated and fresh air after a certain amount of moisture in the sample was removed, and the maximum recirculation ratio. A stepping motor was used to drive a recirculation control valve, which adjusted the amount of the exhaust air exiting and the fresh air entering the dehydrator.

A datalogger was used to measure the temperatures of the drying air, ambient air, exhaust air, and the mixture of the recirculated and fresh air in the recirculation duct.

Electrical signals representing the dry and wet bulb temperatures in the recirculation duct were amplified by the datalogger and sent to a multifunction board. The dry and wet bulb temperatures of the air mixture in the recirculation duct measured by the multifunction board were used to calculate the humidity ratio of the air.

In the control of the humidity ratio of the air mixture in the recirculation system, a negative proportional control was used. The measured humidity ratio value was compared with the humidity ratio set point. The difference between them was used as the input signal (error) to the stepping motor system, which moved the recirculation control valve to the appropriate position. The absolute value of the error was multiplied by a proportional coefficient to obtain the number of steps for the stepping motor movement. The direction of the stepping motor was determined by the sign of the error. The microcomputer calculated the magnitude and the sign of the error and sent digital signals from the multifunction board, which sent the control signals (the number of the steps and direction of the stepping motor movement) to a stepping motor driver. The stepping motor received the digital signals from the stepping motor driver and turned the recirculation control valve to an appropriate position.

The control system first was tested using water in a dehydrator. The effect of the proportional coefficient and the sampling period on the humidity ratio control was evaluated.

Tests were then conducted by drying apples in dehydrators. The performance the dehydrator with the automatic control system was compared with one without air recirculation. The energy consumption, water removal, and drying time were considered.

The tests of the system led to the following conclusions:

1. The proportional coefficient had a significant effect on the humidity ratio control. There seemed to be an optimum value of the proportional coefficient. Increasing or decreasing the proportional coefficient from the optimum value would increase the time required for the system to stabilize. Increasing the proportional coefficient would lead to an overshoot of the humidity ratio. The average maximum rate of change in the humidity ratio increased with the proportional coefficient. A high proportional coefficient was not recommended.

2. The sampling period also influenced the humidity ratio control significantly. Either increasing or decreasing the sampling period from the optimum sampling period would result in prolonged time for the system to stabilize after a step change in the set point. The maximum rate of change in the humidity ratio decreased with the sampling period. Overshoot was associated with high sampling periods.

3. The test of the dehydrator using apple samples under actual dehydrator conditions indicated that energy consumption for the automatically controlled dehydrator was less than that without air recirculation. The energy savings were about 31% over the dehydration without air recirculation.

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APPENDICES

APPENDIX A

APPENDIX A

Theoretical Calculation of Recirculation Ratio

For the air flow and boundary defined in Figure 2, the amount of air entering the system is equal to the amount of air leaving the system assuming no leakage. Also, the amount of energy entering the system is the same as the amount of air leaving the system, assuming that there is negligible heat loss from the system. Two equations governing conservation for mass and heat balance can be developed.

$$\text{Mass of air}_{in} = \text{Mass of air}_{out} \tag{1}$$

$$\text{Heat energy of air}_{in} = \text{Heat energy of air}_{out} \tag{2}$$

Therefore,

$$M_a + M_d = M_r + M_e \tag{3}$$

$$h_a + h_d = h_r + h_e \tag{4}$$

Where:

M and h = mass flow rate (kg dry air/s) and enthalpy (kJ/kg dry air), respectively of the air, and subscripts:

a= ambient air,

r= recirculated air,

d and e = exhaust air from dehydrator, and air leaving the system, respective.

Since the enthalpy of air can be determined by the humidity ratio and temperature (ASHRAE, 1989),

$$h = (1 + 1.805W)T + 2501W, \tag{5}$$

where W and T are the humidity ratio (kg water/kg dry air) and dry bulb temperature of the air, the heat energy H (kW) of air with a mass flow rate of M (kg/s) becomes

$$H = ((1 + 1.805W)T + 2501W)M. \tag{6}$$

Therefore, energy balance can be expressed by

$$\begin{aligned} &((1+1.805W_a) + 2501W_a)M_a + \\ &((1+1.805W_d) + 2501W_d)M_d = \\ &((1+1.805W_r) + 2501W_r)M_r + \\ &((1+1.805W_e) + 2501W_e)M_e. \end{aligned} \tag{7}$$

Assuming the humidity ratio and temperature of exhaust air from the dehydrator are equal to those leaving the dehydrator, then

$$W_d = W_e, \tag{8}$$

and

$$T_d = T_e. \tag{9}$$

Defining the recirculation ratio of air as

$$R = \frac{M_r}{M_d} = \frac{M_d - M_e}{M_d} = 1 - \frac{M_e}{M_d}, \tag{10}$$

and replacing M_e by

$$M_e = M_a + M_d - M_r. \tag{11}$$

By rearrangement, Equation 10 can be written as

$$R = \frac{2501(W_r - W_a) + (1 + 1.805W_r)T_r - (1 + 1.805W_a)T_a}{(1 + 1.805W_e)T_e - (1 + 1.805W_a)T_a + 2501(W_e - W_a)}. \tag{12}$$

APPENDIX B

APPENDIX B

Table B1. The relationship between the recirculation ratio and the angular position of recirculation control valve from 0% recirculation position

Angular position of recirculation control valve from 0% recirculation position	Recirculation ratio
0	0.030
11.25	0.162
22.50	0.253
33.75	0.396
45	0.556
56.25	0.732
67.50	0.877
78.75	0.905
90	0.968

APPENDIX C

APPENDIX C

Control Program

```
1 ' ***   BASIC PROGRAM FOR MICROCOMPUTER-BASED CONTROL ***
2 '***    OF EXHAUST AIR RECIRCULATION IN A FRUIT DEHYDRATOR ***
4 '***    BRIEF DISCRIPTIONS OF CONTROL PROGRAM:
6 '***    A MULTIFUNCTION BOARD (CIO-AD08-PGA, ComputerBoards, Inc.) IS USED IN
8 '***    DATA COLLECTION OF TEMPERATURES (TDRY, AND TWET) AND SAMPLE
10 '***   WEIGHT (WT). BASIC CALL, AN ASSEMBLY LANGUAGE PROVIDED BY
15 '***   ComputerBoards, Inc., IS USED TO PERFORM DATA ACQUISION.
20 '***   SEVERAL MODES (MD%(I)) IN 'BASIC CALL' WITH SPECIFIC FUNCTIONS ARE
          USED:
25 '***   MODE DECLARATION= MD%(I)
30 '***   MD%(0):  INITIATION OF A/D, MD%(1):   DECLARE LOWER AND
          UPPER SCAN LIMITS;
35 '***   MD%(4):  PERFORM A/D CONVERSION
40 '***   MD%(13):  READ DIGITAL SIGNALS,  MD%(14):  WRITE DIGITAL
          SIGNALS
50  DIM WTR(1600) : DIM TDRY(1600) : DIM TWET(1600) : DIM HR(1600)
60  DIM T(1600) :  DIM P(1600) : DIM RATIO(1600)
195 '**************************************************************************
200   'INITIALIZATION OF MULTIFUNCTION BOARD
300   DEF SEG = &H6000              'DECLARE CODE SEGMENT
600   BLOAD "CIO8.BIN", 0    'LOAD ASSEMBLY LANGUAGE
700   DIM D%(8)
800   SCREEN 0, 0, 0
900   CLS
905   LPRINT : LPRINT TIME$ : LPRINT    'PRINT REAL TIME
1000    KEY OFF
1200    D%(0) = &H300               'SET BASE ADDRESS
1300    MD% = 0                     'SET MODE=0
1400    F% = 0
1500    CALL CIO8(MD%, D%(0), F%)
1600    IF F% <> 0 THEN PRINT "MODE 0 ERROR #"; F% :  STOP
1700    OUT &H303, 0           'SET OUTPUT BASE ADDRESS
1800    MD% = 1                     'SET MODE=1
1900    D%(0) = 3                   'SET LOWER CHANNEL LIMIT
2000    D%(1) = 5                   'SET UPPER CHANNEL LIMIT
2100    CALL CIO8(MD%, D%(0), F%)
2200    IF F% <> 0 THEN PRINT "ERROR IN SETTING CHANNEL LIMITS #";
        F% :  STOP
2300    'INITIALIZATION OF MULTIFUNCTION BOARD STOPS HERE
2305 '*************************************************************************
2400    'RESET VALVE TO ZERO POSITION
2500    'MICROSWITCH LOWER LIMIT DETECTION
2600    MD% = 13                    'SET MODE=13, READ DIGITAL SIGNAL
2700    CALL CIO8(MD%, D%(0), F%)
```

```
2800    IF F% <> 0 THEN PRINT "MODE 13 ERROR #";  F% :   STOP
2900    IF D%(0) = 5 THEN 4300      'VALVE IS IN UPPER LIMIT POSITION
3000    IF D%(0) = 6 THEN 4400      'VALVE IS IN LOWER LIMIT POSITION
3100    MD% = 14      'SET MODE=14,  WRITE DIGITAL SIGNAL
3200    D%(0) = 2      'SET DIGITAL OUTPUT #2 HIGH AND TURN VALVE BACKWARD
3300    CALL CIO8(MD%,  D%(0),  F%)
3400    PRINT  :   PRINT                    'SET PULSE DURATION
3500    IF F% <> 0 THEN PRINT "MODE 14 ERROR #";  F% :   STOP
3600    MD% = 14
3700    D%(0) = 0                           'SET ALL DIGITAL OUTPUTS LOW
3800    CALL CIO8(MD%,  D%(0),  F%)
3900    PRINT  :   PRINT
4000    PRINT "BACKWARD......"
4100    GOTO 2600
4200    CLS
4300    LOCATE 2,  4 :   PRINT "VALVE IS IN UPPER LIMIT POSITION!" :   GOTO
        3100
4400    LOCATE 4,  4 :   PRINT "VALVE IS IN ZERO POSITION NOW!"
4500    FOR I = 0 TO 1              'MOVE MOTOR TWO STEPS FORWARD TO
4600    MD%=14                      'RELEASE VALVE FROM LOWER LIMIT POSITION
4700    D%(0)=3
4800    CALL CIO8(MD%, D%(0), F%)
4900    IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
5000    CLS
5100    MD% = 14
5200    D%(0) = 0      'RESET ALL DIGITAL OUTPUTS LOW, LOCK MOTOR
5300    CALL CIO8(MD%,  D%(0),  F%)
5310    IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
5320    NEXT I
5330    CLS
5332 '*****************************************************************************
5335    'MAIN PROGRAM
5340    LOCATE 2, 4 :   INPUT "INITIAL WEIGHT OF FRUIT SAMPLE (g) ="; WTI
5345    LOCATE 3, 4 :  INPUT "INITIAL MOISTURE CONTENT OF SAMPLE (0-100%,  WET
        BASIS)="; MOINI
5346    MOINI=MOINI/100        'MOINI=INITIAL MOISTURE CONTENT (0-100%,  WET BASIS)
5347    WTDRYB=WTI-WTI*MOINI
5350    LOCATE 5, 4 :   INPUT "CRITICAL WEIGHT RATIO = "; WTRC
5400    LOCATE 6,  4 :   INPUT "HUMIDITY RATIO SET POINT = ";  HRC
5405    IF HRC>.05 THEN 5400 'HRC CANNOT BE >0.05
5410    LPRINT "INITIAL SAMPLE WEIGHT (g) ="; WTI
5415    LPRINT "INITIAL SAMPLE MOISTURE CONTENT ="; MOINI
5420    LPRINT "CRITICAL WEIGHT RATIO = "; WTRC
5500    LPRINT "HUMIDITY RATIO SET POINT =";  HRC
5600    LOCATE 8, 4 :  INPUT "INPUT PROPORTIONAL GAIN (MUST BE >= 1000)= "; X
5700    LPRINT "PROPORTIONAL GAIN (MUST BE >= 1000)="; X
5800    LOCATE 10, 4 :  INPUT "INITIAL RECIRCULATION RATIO (0 - 1) ="; AIRCIR
5806    LOCATE 12, 4 :  INPUT "DATA OUTPUT FILENAME (EXTENSION = PRN)"; N$
5807    LPRINT "INPUT PARAMETERS COMPLETED" :  LPRINT
5810    LPRINT :  LPRINT TIME$ :  LPRINT
5850    GOSUB 30000                 'INITIAL RECIRCULATION RATIO SETTING
```

```
6355  LPRINT : LPRINT TIME$ : LPRINT
6360  FOR I= 1 TO 500
6370  LOCATE 12, 4 : PRINT "VALVE IS IN THE INITIAL OPERATING POSITION"
6380  LOCATE 14, 4 : PRINT "PLEASE WAIT FOR SYSTEM TO STABILIZE....."
6381  PRINT I
6382  NEXT I
6383  CLS
6384  LPRINT : LPRINT "SYSTEM STABILIZED, MEASURMENT BEGINS  " : LPRINT
      TIME$ : LPRINT
6385  GOTO 6400                          'CALL MEASUREMENT SUBROUTINE
6386  IF HUMID>.005 THEN GOSUB 12000   'IF DRYING AIR IS TOO HUMID
6388  IF TOTAL>134 THEN 6390        'IF RECIRCULATION >90%, GO ON
                                    MEASURING
6389  IF HUMID<-.004 THEN GOSUB 16000  'IF DRYING AIR IS TOO DRY
6390  CLS
6396  FOR I= 1 TO 500
6397  LOCATE 10, 4 : PRINT "CRITICAL WEIGHT RATIO HAS NOT REACHED"
6398  LOCATE 12, 4 : PRINT "DELAY = "; I
6399  NEXT I
6400  GOSUB 7300
6401  LPRINT : LPRINT "ONE MEASUREMENT COMPLETES  " : LPRINT
      TIME$ : LPRINT
6402  HUMID = INT(1000*W+.5)/1000 - HRC     'CALCULATION OF ERROR
6410  IF WTR > WTRC THEN CLS : GOTO 6386      'DETECT IF WEIGHT
                                             RATIO IS BELOW SET POINT
6511  IF HUMID>.003 THEN 6390       'IF DRYING AIR IS STILL TOO HUMID
6580  IF J>1599 THEN 7210           'MAXIMUM DATA ARRAY=1600
6590  IF MOFINAL<.2 THEN 7210       'IF FINAL MOISTURE CONTENT IS
                                    BELOW SET POINT
6600  IF HUMID > .001 THEN GOSUB 12000 : GOTO 6800
6650  IF TOTAL>134 THEN 6800        'IF RECIRCULATION > 90%, GO ON
                                    MEASURING
6700  IF HUMID < -.001 THEN GOSUB 16000 : GOTO 6800
6800  FOR I = 0 TO 390              'ADJUST SAMPLING PERIOD
6900  PRINT "PLEASE WAIT......"; : PRINT I
7100  NEXT I
7200  GOTO 6400                     'CONTINUE MEASURING
7210  OPEN N$+".PRN" FOR OUTPUT AS #1  'WRITE DATA TO FILE
7214  FOR I=1 TO J
7215  WRITE #1, T(I), TDRY(I), TWET(I), HR(I), WTR(I), P(I), RATIO(I)
7219  NEXT I
7220  CLOSE #1
7225  LOCATE 25, 4 : PRINT "DRYING COMPLETED "
7230  END
7235 '****************************************************************************
7300  'SUBROUTINE FOR TEMPERATURE AND WEIGHT MEASUREMENTS
7400  CLS
7410  J=J+1            'COUNT TOTAL NUMBER OF  MEASUREMENTS
                       (= ARRAY NUMBER)
7500  COUNT = COUNT + 1  'COUNT EACH MEASUREMENT
7600  M = 0
```

```
7700    MD% = 4
7800    CALL CIO8(MD%, D%(0), F%)
7900    IF F% <> 0 THEN PRINT "ERROR IN WEIGHT MEASUREMENT #"; F% :   STOP
8000    M = M + 1
8100    IF M = 1 THEN 8210
8110    IF M=2 THEN 8300
8200    GOTO 8400
8210    SUMWT=SUMWT+D%(0) :  GOTO 7700         'MEASURE SAMPLE WEIGHT
8300    SUMDRY = SUMDRY + D%(0) : GOTO 7700    'MEASURE DRY BULB
                                               TEMPERATURE
8400    SUMWET = SUMWET + D%(0) 'WET BULB TEMPERATURE
8500    IF COUNT = 100 THEN 8700
8600    PRINT "MEASURING......"; COUNT :   GOTO 7500
8700    CLS
8710    WTAD=SUMWT/100          'AVERAGE OF 100 MEASUREMENTS
8715    WT=.977145*WTAD-1.06572
8716    MOFINAL=INT(100*(WT-WTDRYB)/WT+.5)/100
8720    WTR=WT/WTI
8800    TDRYAD = SUMDRY / 100
8900    TWETAD = SUMWET / 100
8910    'CALCULATION OF HUMIDITY RATIO
9000    TDRY = INT(((TDRYAD * .032569 + .031978) * 10000 + .5))/ 10000
9100    TWET = INT(((TWETAD * .032569 + .031978) * 10000 + .5))/ 10000
9300    TKDRY = TDRY + 273.15
9400    TKWET = TWET + 273.15
9500    TKWET2 = TKWET * TKWET :   TKWET3 = TKWET2 * TKWET :   TKWET4 =
        TKWET3 * TKWET
9600    TKDRY2 = TKDRY * TKDRY :   TKDRY3 = TKDRY2 * TKDRY :   TKDRY4 =
        TKDRY3 * TKDRY
9700    C1 = -7511.52 :   C2 = 89.63121 :   C3 = 2.399897E-02
9800    C4 = -.000011654551# :   C5 = -.000000012810336#
9900    C6 = 2.0998405D-11 :   C7 = -12.1507992#
10000   P = 101.325
10100   PWS=EXP(C1/TKWET+C2+C3*TKWET+C4*TKWET2+C5*TKWET3+C6*TKWET4
        +C7*LOG(TKWET))   'SATURATION VAPOR PRESSURE
10200   PWD=EXP(C1/TKDRY+C2+C3*TKDRY+C4*TKDRY2+C5*TKDRY3
        +C6*TKDRY4+C7*LOG(TKDRY))   'VAPOR PRESSURE AT DRY BULB TEMPERATURE
10300   WS = .61298 * PWS / (P - PWS)
10400   W =((2501-2.381*TWET)*WS-(TDRY-TWET))/(2501+1.805*TDRY-4.186*TWET)
10410   W=INT(100000!*W+.5)/100000!
10800   CLS
10805   'DETERMINE DRYING TIME
10810   X$=TIME$ :  Y$=LEFT$(X$, 2) :  W$=MID$(X$, 4, 2) :  Z$=RIGHT$(X$, 2)
10815   TH=VAL(Y$)*3600              'CONVERT HOUR TO SECONDS
10818   TM=VAL(W$)*60                'CONVERT MINUTE TO SECONDS
10820   TS=VAL(Z$)
10830   T(J)=TH+TM+TS                'TIME IN SECONDS
10835   TDRY(J)=TDRY
10840   TWET(J)=TWET
10845   WTR(J)=INT(1000*WTR+.5)/1000
10850   HR(J)=W
```

```
10860  TP=T(J)-T(1)
10862  IF TP<0 THEN TP=TP+86400!
10868  GOSUB 35000
10870  RATIO(J)=RATIO
10900  FOR I = 0 TO 19
10910  LOCATE 4, 4 :  PRINT "WEIGHT OF SAMPLE = "; WT
10915  LOCATE 5, 4 :  PRINT "MOISTURE CONTENT OF SAMPLE="; MOFINAL*100
10920  LOCATE 6, 4 :  PRINT "WEIGHT RATIO = "; WTR(J)
11000  LOCATE 10, 4 :  PRINT "DRY TEMP AT DUCT = ";  TDRY(J)
11100  LOCATE 12, 4 :   PRINT "WET TEMP AT DUCT = ";  TWET(J)
11200  LOCATE 14, 4 :   PRINT "HUMIDITY RATIO AT DUCT = ";  HR(J)
11210  LOCATE 15, 4 :  PRINT "RECIRCULATION RATIO ="; INT(100*RATIO+.5)
11220  LOCATE 16, 4 :  PRINT "TIME ELAPSED = "; TP      'DRYING TIME
11225  LOCATE 18, 4 :  PRINT "COMPUTER REAL TIME  = "; TIME$
11230  LOCATE 20, 4 :  PRINT "TIME (s) = "; T(J)
11300  NEXT I
11310  LPRINT :  LPRINT "WEIGHT OF SAMPLE = "; WT
11315  LPRINT "MOISTURE CONTENT = "; MOFINAL*100
11320  LPRINT "WEIGHT RATIO AT PRESENT ="; WTR(J)
11400  LPRINT "DRY TEMP = "; TDRY(J)
11500  LPRINT "WET TEMP = "; TWET(J)
11600  LPRINT "HUMIDITY RATIO (KG WATER/KG DRY AIR) = "; HR(J)
11605  LPRINT "REAL TIME = "; TIME$
11610  LPRINT "TIME NOW = "; T(J)
11620  LPRINT "TIME ELAPSED = "; TP
11700  COUNT = 0
11800  SUMDRY=0 :  SUMWET=0 :  SUMWT=0
11900  RETURN
11950  '***********************************************************************
12000  'HUMIDITY RATIO IS HIGHER THAN UPPER LIMIT
12050  'SUBROUTINE FOR MOVING VALVE BACKWARD
12100  CLS
12110  FOR I = 1 TO 20
12200  LOCATE 4,  4 :   PRINT "HUMIDITY RATIO IS TOO HIGH"
12300  NEXT I
12305  M=0
12310  LPRINT "HUMIDITY RATIO IS TOO HIGH,  VALVE WILL BE OPEN"
12320  LPRINT "BACKWARD BEGINS"
12400  LOCATE 8, 4 :   PRINT "VALVE WILL BE PULLED TOWARDS MAXIMUM
                                  RECIRCULATION DIRECTION"
12500  N = INT(X * HUMID)              'DETERMINE # OF STEPS
12550  IF N>=10 THEN N=N/3  'IF # OF STEPS IS TOO HIGH,  CUT BY 3
12600  'MICROSWITCH LOWER LIMIT DETECTION
12700  FOR I = 1 TO N
12800  MD% = 13
12900  CALL CIO8(MD%,  D%(0),  F%)
13000  IF F% <> 0 THEN PRINT "MODE 13 ERROR #";  F% :   STOP
13100  IF D%(0) = 5 THEN 14500       'VALVE IS IN UPPER LIMIT POSITION
13200  IF D%(0) = 6 THEN 14600       'VALVE IS IN LOWER LIMIT POSITION
13300  MD% = 14        'SET DIGITAL PULSE OUTPUT,  TURN VALVE BACKWARD
13400  D%(0) = 2       'SET DIGITAL OUTPUT #2 HIGH AND TURN VALVE BACKWARD
```

```
13500  CALL CIO8(MD%, D%(0), F%)
13600  PRINT : PRINT
13700  IF F% <> 0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
13800  MD% = 14
13900  D%(0) = 0        'SET ALL DIGITAL OUTPUTS LOW
14000  CALL CIO8(MD%, D%(0), F%)
14100  PRINT : PRINT
14200  M = M + 1 : PRINT "STEP = "; (-1)*M
14300  NEXT I
14305  LPRINT "BACKWARD STEPS ="; (-1)*M
14306  LPRINT "BACKWARD COMPLETES   " : LPRINT TIME$ : LPRINT
14400  TOTAL=TOTAL-M : P(J)=(-1)*M   TOTAL = POSITION OF VALVE, P(J)
       IS # OF STEPS IN EACH ADJUSTMENT
14410  GOTO 15500
14500  LOCATE 10, 4 : PRINT "VALVE TURND TO WRONG DIRECTION!" : K
       = 1 : GOTO 14700
14600  LOCATE 12, 4 : PRINT "VALVE IS IN LOWER LIMIT POSITION!" : K = 1
14700  FOR I= 0 TO 1
14800  MD%=14
14900  D%(0)=3
15000  CALL CIO8(MD%, D%(0), F%)
15010  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
15200  MD% = 14
15300  D%(0) = 0              'RESET ALL DIGITAL OUTPUTS LOW, LOCK MOTOR
15400  CALL CIO8(MD%, D%(0), F%)
15410  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
15420  NEXT I
15500  M=0
15550  IF K=1 THEN 15700
15600  GOTO 15900
15700  LOCATE 24, 4 : PRINT "UNABLE TO CONTROL, ADJUST PROPORTIONAL RATIO!"
15800  PRINT "TERMINATED DUE TO CONTROL FAILURE " : GOTO 7210
15900  RETURN
15950 '*************************************************************************
16000  'HUMIDITY RATIO IS OUTSIDE LOWER LIMIT
16001  'SUBROUTINE FOR MOVING MOTOR FORWARD
16002  LPRINT "FORWARD BEGINS   " : LPRINT TIME$ : LPRINT
16100  CLS
16110  FOR I = 1 TO 20
16200  LOCATE 8, 4 : PRINT "HUMIDITY RATIO IS TOO LOW"
16300  LOCATE 10, 4 : PRINT "VALVE WILL TURN TOWARDS ZERO POSITION"
16310  NEXT I
16315  M=0
16320  LPRINT "HUMIDITY RATIO IS TOO LOW"
16330  LPRINT "VALVE WILL TURN TOWARDS ZERO POSITION"
16400  N = INT(X * (-1) * HUMID) : PRINT "STEP = "; N
16500  IF N>=10 THEN N=N/3
16800  FOR I = 1 TO N
16900  MD% = 13
17000  CALL CIO8(MD%, D%(0), F%)
17100  IF F% <> 0 THEN PRINT "MODE 13 ERROR #"; F% : STOP
```

```
17200  IF D%(0) = 5 THEN 18700  'VALVE IS IN UPPER LIMIT POSITION
17300  IF D%(0) = 6 THEN 18800 'VALVE IS IN LOWER LIMIT POSITION
17400  MD% = 14         'SET DIGITAL PULSE OUTPUT, TURN VALVE FORWARD
17500  D%(0) = 3        'SET DIGITAL OUTPUT #2 HIGH AND TURN VALVE FORWARD
17600  CALL CIO8(MD%, D%(0), F%)
17700  PRINT : PRINT
17800  IF F% <> 0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
17900  MD% = 14
18000  D%(0) = 0        'SET ALL DIGITAL OUTPUTS LOW
18100  CALL CIO8(MD%, D%(0), F%)
18200  PRINT : PRINT
18300  M = M + 1
18400  PRINT "STEP = "; M
18450  LPRINT "STEP = "; M
18500  NEXT I
18501  LPRINT "FORWARD COMPLETES   " : LPRINT TIME$ : LPRINT
18550  P(J)=M : PRINT P(J) : TOTAL=TOTAL+M
18600  GOTO 19700
18700  LOCATE 4, 4 : PRINT "VALVE IS IN UPPER LIMIT POSITION!" : K = 1: GOTO 19700
18800  LOCATE 6, 4 : PRINT "VALVE TURND TO WRONG DIRECTION!" : K =1
18900  FOR I = 0 TO 1
19000  MD%=14
19100  D%(0)=2
19200  CALL CIO8(MD%, D%(0), F%)
19300  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
19400  MD% = 14
19500  D%(0) = 0        'RESET ALL DIGITAL OUTPUTS LOW, LOCK MOTOR
19600  CALL CIO8(MD%, D%(0), F%)
19610  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% : STOP
19620  NEXT I
19700  M=0
19710  IF K=1 THEN 19900
19800  GOTO 20100
19900  LOCATE 28, 4 : PRINT "UNABLE TO CONTROL, ADJUST PROPORTIONAL RATIO!"
20000  PRINT "TERMINATED DUE TO CONTROL FAILURE " : GOTO 7210
20100  RETURN
20900 '****************************************************************************
30000  'SETS INITIAL AIR RECIRCULATION RATIO
30100  IF AIRCIR=0 THEN 34300
30200  Y1=(AIRCIR-.124933)/.876968    'CONVERT RECIRCULATION RATIO
30300  Y2=1-Y1                        'TO ANGULAR POSITION OF VALVE
30400  Y3=SQR(Y1/Y2)
30500  ANGLE=ATN(Y3)*180/3.1415926#
30600  MSTEP0=ANGLE*(48/28)/.9        'CONVERT ANGULAR POSITION TO # OF STEPS
30700  INISTEP=INT(10*MSTEP0+.5)/10
31200  MSTEPH0=ANGLE*48/28/.9
31300  MSTEPH=INT(10*MSTEPH0+.5)/10
32400  FOR I=1 TO INISTEP
32500  MD%=13
32600  CALL CIO8(MD%, D%(0), F%)
32700  IF F%<>0 THEN PRINT "MODE 13 ERROR #"; F% : STOP
```

```
32800  IF D%(0)=5 THEN 34105       'VALVE IS IN UPPER LIMIT POSITION
32900  IF D%(0)=6 THEN 34106       'VALVE IS IN LOWER LIMIT POSITION
33000  MD%=14
33100  D%(0)=3
33200  CALL CIO8(MD%, D%(0), F%)
33300  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
33400  PRINT
33500  MD%=14
33600  D%(0)=0
33700  CALL CIO8(MD%, D%(0), F%)
33800  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
33900  PRINT
34000  K1=K1+1
34100  NEXT I
34104  GOTO 34200
34105  LOCATE 5, 4 :  PRINT "VALVE IS IN UPPER LIMIT POSITION" :  GOTO 34160
34106  LPRINT "VALVE IS IN UPPER LIMIT POSITION!" :  STOP
34150  LPRINT "INITIAL STEPS = "; K1 :  GOTO 34300
34160  FOR I=0 TO 2
34165  MD%=14
34168  D%(0)=2
34170  CALL CIO8(MD%, D%(0), F%)
34175  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
34180  MD%=14
34185  D%(0)=0
34187  CALL CIO8(MD%, D%(0), F%)
34188  IF F%<>0 THEN PRINT "MODE 14 ERROR #"; F% :  STOP
34190  NEXT I
34200  TOTAL=K1+2              TOTAL=TOTAL STEPS AT PRESENT,  POSITION POINTER
34205  LPRINT :  LPRINT "INITIAL STEPS IS = "; TOTAL
34300  RETURN
34350 '**************************************************************************
35000  'DETERMINE RECIRCULATION RATIO FROM ANGULAR POSITION OF VALVE
35110  'SUBROUTINE FOR CALCULATING REAL TIME RECIRCULATION RATIO
35100  ANGLE1=3.1415926#*TOTAL*(28*.9)/48/180
35200  RATIO=.877*(SIN(ANGLE1))^2+.125
35300  RETURN
```

APPENDIX D

APPENDIX D

List of Symbols

h	Enthalpy of air (kJ/kg dry air)
h_a	Enthalpy of ambient air (kJ/kg dry air)
h_d	Enthalpy of exhaust air from the dehydrator (kJ/kg dry air)
h_e	Enthalpy of exhaust air exiting the dehydrator (kJ/kg dry air)
h_r	Enthalpy of drying air in the recirculation duct (kJ/kg dry air)
H	Thermal energy of air (kW)
HR	Measured drying air humidity ratio in the recirculation duct, kg water/kg dry air
HR_{max}	Maximum humidity ratio in the control deadband, kg water/kg dry air
HR_{min}	Minimum humidity ratio in the control deadband, kg water/kg dry air
HRC	Humidity ratio set point in the recirculation duct, kg water/kg dry air
K	Proportional coefficient
M	Mass flow rate of air, kg dry air/s
M_a	Mass flow rate of ambient air entering the dehydrator, kg dry air/s
M_d	Mass flow rate of exhaust air from the dehydrator, kg dry air/s
M_e	Mass flow rate of exhaust air exiting the drying system, kg dry air/s
M_r	Mass flow rate of drying air in the recirculation duct, kg dry air/s
N	Number of steps
R	Recirculation ratio of exhaust air
R_0	Initial recirculation ratio of exhaust air

T Temperature of air, °C

T_a Temperature of ambient air entering the dehydrator, °C

T_d Temperature of exhaust air from the drying system, °C

T_e Temperature of exhaust air exiting the drying system, °C

T_r Temperature of drying air in the recirculation duct, °C

W Humidity ratio of air (kg water/kg dry air)

WT_c Critical weight ratio

WTR Measured weight ratio (fraction of original)

θ Angular position (degrees) of control valve from Zero (0% recirculation) position

ε Error = HR - HRC

VITA

Lihan Huang was born in Fuzhou, China on July 4, 1964. He graduated from The Affiliated High School to Fujian Normal University in July, 1981, and entered Fuzhou University in the Light Industry Department in September, 1981, and received a Bachelor of Engineering degree in Food Technology in July 1985. From August, 1985 to August 1987, he worked with Fuzhou University as an Assistant Instructor. Between September 1987 and December 1989, he studied in Fujian Agricultural College as a graduate student for his Master of Science degree. Before he graduated, he accepted a graduate research assistantship from Kansas State University in 1990 and then studied in the Agricultural Engineering Department at that University. In August 1991, he transferred to the University of Tennessee, Knoxville, where his wife was studying, and received a Master of Science degree in Agricultural Engineering in spring, 1994.

He is a member of the Chinese National Society of Nutrition, the Institute of Food Technologists, and the American Society of Agricultural Engineers. He is also a member of Phi Kappa Phi and Gamma Sigma Delta honor societies.