To the Graduate Council:

I am submitting herewith a dissertation written by Xia Liu entitled "Energy Conservation by Recirculation of Drying Air". I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Engineering.

Luther R. Wilhelm, Major Professor

We have read this dissertation and recommended its acceptance:

Accepted for the Council:

Associate Vice Chancellor and Dean of The Graduate School

ENERGY CONSERVATION BY RECIRCULATION OF DRYING AIR

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Xia Liu

May 1994

ACKNOWLEDGEMENTS

The author wishes to express true gratitude to her major professor, Dr. Luther R. Wilhelm, for valuable advise, helpful suggestions and encouragement given throughout her entire graduate program.

The author further wishes to express her appreciation to Dr. Fred D. Tompkins, head of the department and committee member, for his constructive criticism, invaluable assistance and encouragement throughout her entire graduate program.

Appreciation is also expressed to the committee members, Dr. Zachary A. Henry and Dr. Mary G. Leitnaker, for their assistance and valuable suggestions in the completion of this research.

The support of all the faculty of the Department of Agricultural Engineering has been extremely valuable to the completion of this research and is appreciated.

Appreciation is also to Dr. O. Glen Hall, Dean of the College of Agricultural Sciences and Natural Resources, for his friendship and encouragement.

Special thanks is expressed to Terry H. Walker, graduate research fellow, for his assistance in setting up the experiment.

ABSTRACT

An air recirculation system was used to reduce energy cost for batch food dehydration. The specific objectives of this study were: to test the effect of different air recirculation rates on energy consumption and drying time; and to identify the drying schedule that could maximize the energy savings without decreasing drying rate. In the study, apples and peaches were used as test materials. Fixed recirculation rates of 0, 70, 80, and 90% were applied to both apple and peach drying. Variable-rate recirculation was applied to apple material only. For both apple and peach drying tests, very significant differences in energy use were observed between no recirculation and the 70, 80, and 90% recirculation rates. Recirculation rates of 70, 80, and 90% were not significantly different in energy consumption. The 70% or higher recirculation rate produced an energy savings over no recirculation of approximately 50% for drying apples and 46% for drying peaches. Apple drying took approximately 5 hours, while peach drying took approximately 35 hours to reach the target moisture content (25% w.b.). For all tests of each product, the total drying times were nearly the same for all recirculation rates. The moisture diffusion models were successful in providing good prediction of drying rates for both apples and peaches. The model results also indicated that air recirculation rates did not significantly affect drying rates. Variable recirculation rate drying yielded the same energy consumption and drying time as fixed recirculation rate drying. Based upon these results, a fixed recirculation rate of 80% for apple ring and 70% for peach half drying were suggested.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURES **PAGE**

CHAPTER 1

INTRODUCTION

BACKGROUND

Food drying is an ancient art, necessary to preserve foods during seasons of abundance. This practice has been handed down to the present day. The major objectives in food drying are:

1. to reduce moisture content so that spoilage will not occur before foods are consumed (Brooker et al., 1974),
2. to save shipping and transportation costs, and
3. to concentrate the nutrition value.

Forced air convection drying is a common method used in drying agricultural products, such as fruits, vegetables, grains, etc. The drying of solids is usually taken to mean the removal of a liquid from a moist solid by evaporation (Berger and Pei, 1973). The heat required for evaporation has to be supplied to the material, therefore, heat and mass transfer occur simultaneously. Obviously, the process which uses air for heat conduction and transportation of water vapor are highly energy intensive because of the great amount of heat required. One method proposed for reducing the energy consumption is the recirculation of drying air to more fully utilize its potential (Young, 1984). In conventional dehydrators, the outside air is drawn into a dehydrator chamber where it is heated and blown through or over the product. The air removes moisture from the produce and is exhausted. The heat content of the exhausted air is much higher than that of the ambient air and so is its relative humidity. The heat content of this air is lost when it is exhausted. Recirculating a portion of the exhausted air back into the dehydrator is one way to recover the lost heat, but this approach is not without problems. The recirculation air increases the relative humidity of the drying air, and reduces its moisture absorbing capacity. A reduction in drying rate may result. Imperfect control of the recirculated air schedule during drying may seriously impair quality of product by causing undesirable changes in shape, structure, browning reaction, mold growth, etc. Thus, an accurate quantitative description of the moisture movement during drying is required to permit selection of the best recirculation schedule.

OBJECTIVES

The objective of this study is to find the optimum recirculation rate by evaluating fixed recirculation rates from 0 to 90 percent. A variable rate recirculation schedule can then be developed to optimize the drying process.

Specific objectives are as follows:

1. Perform theoretical analysis on moisture diffusion during drying and develop mathematical models to describe the process.
2. Evaluate the effect of fixed and variable rate recycled drying air on energy consumption. The evaluation will be based upon experimental and theoretical analysis.

3. Determine the best schedule of recycling rates to optimize the drying process in terms of energy consumed and drying time.

CHAPTER 2

LITERATURE REVIEW

MECHANISMS OF DRYING POROUS SOLIDS

A drying process generally undergoes two stages (Brooker et al, 1974): a constant rate and a falling rate period. During the constant drying rate period, diffusion of liquid from the interior of the solid is sufficiently rapid to keep the surface completely wet. This constant rate period continues only as long as the water is supplied to the surface as fast as it is evaporated (Geankoplis, 1978). The second stage is characterized by a continuously decreasing liquid concentration at the surface. The rate of evaporation at any instant is solely a function of the relation between the surface and interior of the drying medium (Newman, 1931).

Moisture transfer in biological materials may involve several mechanism such as liquid diffusion (Crank, 1975, Van Arsdel et al, 1973a, Berger and Pei, 1972), vapor diffusion (Babbit, 1950, Wang and Hall 1961, Berger and Pei, 1972), and capillary forces (Van Arsdel et al, 1973a). The importance of each mechanism is limited to a particular range of drying (Husain, 1972). Van Arsdel et al (1973a) described two major moisture transfer mechanisms for fruit and vegetable drying: capillary flow and moisture diffusion.

Capillary Flow

Van Arsdel et al (1973a), Reeve (1959a), Crafts (1944) and Charley (1970) noted that the original cellular tissues, in their living state, exhibited the property of turgor, meaning that each cell was distended by its liquid contents and consequently had taken on a structural stiffness. Water kept the wet body distended, but its interior was under compression because of the surface forces.

As drying progresses, the physical unbalance of forces at an interface between a liquid and a gas or vapor produces the effect of a suction on the liquid, familiar in the rise of a liquid in a capillary tube or wick dipping beneath its surface (Van Arsdel et al, 1973a). Water at all levels within the layer moves through the gradually narrowing channels between solid structures at velocities dependent on the forces producing the flow and the viscous resistance to this motion. When the solid structure begins to strongly resist further distortion, water in the surface layer of material will begin to be drawn down into the interstices, exerting stronger and stronger suction as the curvature of liquid surfaces becomes sharper. Eventually air will be drawn all the way to the bottom of the layer, and capillary suction can then no longer be a force producing flow of the remaining water (Van Arsdel et al, 1973a).

Moisture Diffusion

Van Arsdel et al (1973a) pointed out that whether or not the early phases of the drying of a wet body were considered to be governed by capillary flow phenomena, the late phases were indisputably governed by diffusional phenomena.

The water molecules make their way through a region of higher water vapor pressure toward the nearest region of lower vapor pressure. This takes place within the solid fine structure, the capillaries, pores, and small voids of a product. The moisture diffuses outward until it reaches the open end of a capillary and is carried away in a rapidly moving air stream (Van Arsdel et al, 1973a).

EFFECTS OF DRYING

Migration of Soluble Constituents

As water evaporates from the surface, moisture moves from the interior of the product to points nearer its surface. Some dissolved substances also change their location (Van Arsdel et al, 1973a). As the solution nears the surface, pure water evaporates from it, leaving behind an increasingly concentrated solution in the outer layers. As drying progresses, this solution becomes highly concentrated making outward moisture movement more difficult.

Shrinkage

Van Arsdel et al (1973a) noted that as water evaporates from a wet surface the diameter of superficial water-filled pores and capillaries diminishes and solid structural elements pull closer together under the influence of surface tension. This effect spreads into deeper layers of tissue and eventually all the way to the center. When the tissue starts to dry, the cells lose turgor, and the walls become more or less flaccid. Some cells collapse and much air is entrapped in intercellular spaces (Crafts, 1944). Thus, unequal shrinkage in different parts of a single material often produces a grotesquely warped and distorted dry product.

Controlled Drying Conditions

The major factors that affect the rate of moisture movement out of the product are drying air temperature, air velocity, and relative humidity. Carefully controlled drying conditions can avoid formation of a hard layer on the surface (case hardening) and unequal shrinkage of the product. It is desirable to dry with moist air so that unequal shrinkage or case hardening can be reduced. This can be accomplished by controlled partial recirculation of exhausted air. Recirculating exhausted air also saves large amounts of drying energy, thus reducing drying cost.

RECIRCULATING DRYING AIR

Air is the usual medium employed in the drying process. It has two principal functions in the drying of fruits or other foods. It conveys heat from a heating device to the product and thereby causes the water in the product to vaporize. Air also serves as a vehicle for the transfer of moisture from the product to the outside atmosphere (Cruess, 1958). As air is exhausted from the dryer, a large amount of heat is lost. Recirculating a portion of this exhausted air from the dryer can significantly reduce heat loss. Major advantages for recirculating exhausted air include:

1. Significant energy savings,

2. Preventing case hardening due to rapid surface evaporation.

Harner et al (1981) reported improved efficiency of energy utilization in recirculation of peanut curing air. The roof of the peanut drying facility was retrofitted to incorporate a bare plate solar collector. Two-thirds of the total airflow required by the fans was drawn through the bare plate collector. The remaining air required was drawn through a portable collector attached to the drying facility. Due to natural convection, the exhaust air from the drying trailers was directed toward the inlets of the bare plate collector, thus some recirculation of exhaust air was achieved. Ten batches (six trailers each) of peanuts were cured using the system. Energy savings due to recirculation amounted to 3.48 kL of liquified petroleum gas for the ten cures.

Sokhansanj and Sosulaki (1981) investigated the effects of recirculating high humidity air on the drying rate and changes in grain quality for wide ranges of drying air humidities and temperatures. They found that a reduction in drying rate with an increase in the exhaust recycling ratio. They also pointed out that using a higher recycling ratio at an early stage of drying would not save energy. Thus, they suggested that a higher recycling ratio should be supplied during the final stage of drying to save more energy without decreasing drying rate.

Rumsey et al (1981) reported on the development of a grain drying model for fixed bed walnut drying which incorporated recirculation. English walnuts were dried from a field moisture ranging from 10 to 30 percent to a final moisture content of 8 percent. Energy savings of up to 30 percent were obtained by recirculating 60 percent of the air.

Cook et al (1982) reported the development of simulation procedures to predict the performance of recirculating dryers for peanut curing. They found that some recirculation strategies were successful in providing up to 20 percent energy savings without increasing drying time.

Noyes (1977) reported the performance of a commercial grain dryer with partial exhaust air recirculation. He also reported favorable energy conservation.

Converse (1972) reported on a modified laboratory crossflow dryer that consisted of three separate compartments. Two compartments were used for drying and one was used for cooling. The exhaust air from the cooler and the middle section were mixed and heated to 143°C. The heated air then was divided into two streams; one to the first stage dryer and the other to the second stage. Lerew et al (1972) simulated the same dryer and reported 50% percent reduction in energy consumption.

Chung et al (1991) developed a gas-modulating control system with air recirculation for use in the rice drying. They evaluated the effect of air recirculation rates on drying energy consumption. They reported that for rice drying, water removal rate decreased due to the high humidity of the recirculation air. Therefore, they suggested the use of dehumidified recirculation air to conserve the energy.

Thompson et al (1981) studied energy saving methods for tunnel dehydrators. They investigated the thermal losses associated with tunnel dehydrators and found that 42% of energy was lost due to exhausted air, burner inefficiency, air leakage, and others. They utilized the energy conservation techniques such as increasing air recirculation, minimizing air leakage, etc to prevent heat losses. Thompson et al (1981) then concluded that these improved dehydrators could operate 50% more efficiently to remove water than before.

Young (1984) performed drying tests for peanuts over a three-year period to compare the energy consumption, drying rate, and market values of peanuts from conventional and recirculating dryers. He reported that the recirculating type dryers averaged 26% lower energy requirements, 15.1% lower drying times, and 1.3% higher market values.

Walker (1992) modified existing home-type dehydrators with a recirculation damper, and used the modified units to dry apple rings and peach halves. He evaluated the effects of air recirculation rates of 0, 25, 50, and 75% on energy consumption and drying time. Approximately 53% savings for drying peaches and 46% savings for drying apples was observed for the 75% recirculation rate. He also found that drying times for each fruit were the same for all recirculation rates.

MATHEMATICAL MODELS FOR MOISTURE TRANSFER

A considerable amount of work for modeling of product drying has been reported in the literature. The general purpose of incorporating factors into a model is to describe the process so that the best prediction can be achieved.

Brooker et al (1974) summarized the physical mechanisms for the transfer of moisture in capillary porous materials such as cereal grains as followings:

1. liquid movement due to surface forces (capillary flow);
2. liquid movement due to moisture concentration differences (liquid diffusion);
3. liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion);
4. vapor movement due to moisture concentration differences (vapor diffusion);
5. vapor movement due to temperature differences (thermal diffusion);
6. water and vapor movement due to total pressure differences (hydrodynamic flow).

Luikov (1966) and his co-workers in the Soviet Union developed a mathematical model for describing the drying of capillary porous products based on the physical mechanisms listed above. The model equations are a system of partial differential equations of the following form:

$$\frac{\partial M}{\partial t} = \nabla^2 D_{11} M + \nabla^2 D_{12} T + \nabla^2 D_{13} P \tag{2.1}$$

$$\frac{\partial T}{\partial t} = \nabla^2 D_{21} M + \nabla^2 D_{22} T + \nabla^2 D_{23} P \tag{2.2}$$

$$\frac{\partial P}{\partial t} = \nabla^2 D_{31} M + \nabla^2 D_{32} T + \nabla^2 D_{33} P \tag{2.3}$$

where D_{11}, D_{22}, and D_{33} are the phenomenological coefficients, while the other D-values represent the coupling coefficients. The coupling results from the combined effects of the moisture, temperature, and total pressure gradients on the moisture, energy and total mass transfer. Due to lack of the phenomenological transfer coefficients for cereal grains (Brooker et al, 1974), Luikov's system of Equations 2.1, 2.2, and 2.3 have not yet been applied to grain.

Since the pressure gradient is not significant during grain drying (Brooker et al, 1974) , the above system is reduced as:

$$\frac{\partial M}{\partial t} = \nabla^2 D_{11} M + \nabla^2 D_{12} T \tag{2.4}$$

$$\frac{\partial T}{\partial t} = \nabla^2 D_{21} M + \nabla^2 D_{22} T \tag{2.5}$$

Equations 2.4 and 2.5 have been applied to a number of products including corn (Husain et al, 1972). It was concluded that consideration of the coupling effects of temperature and moisture in the analysis of cereal-grain drying is required in a very limited number of cereal grains. Therefore, the phenomenological equations become:

$$\frac{\partial M}{\partial t} = \nabla^2 D_{11} M \tag{2.6}$$

$$\frac{\partial T}{\partial t} = \nabla^2 D_{22} T \tag{2.7}$$

Equations 2.6 and 2.7 describe the drying and thermal behavior of cereal grains very well (Brooker et al, 1974). However, in practical analyses of cereal-grain drying the temperature gradients do not have to be considered. Neglecting the temperature gradients in a cereal-grain-kernel during drying leads to the ultimate simplification of Luikov's equations:

$$\frac{\partial M}{\partial t} = \nabla^2 D_{11} M \tag{2.8}$$

In Equation 2.8, the transfer coefficient D_{11} is D, the diffusion coefficient. Researchers have used a number of solutions to Equation 2.8 for predicting the drying behavior of cereal grains (Brooker et al, 1974).

Crank (1956) solved Equation 2.8 analytically for regular shaped bodies such as an infinite plane, an infinite cylinder, and a sphere as follows:

For an infinite plane:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-\left(\frac{\pi(2n+1)}{2L}\right)^2 Dt} \tag{2.9}$$

For an infinite cylinder,

$$MR = \frac{4}{r^2} \sum_{n=1}^{\infty} \frac{1}{\lambda_n^2} e^{-\lambda_n^2 Dt} \tag{2.10}$$

For a sphere,

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\left(\frac{n\pi}{r}\right)^2 Dt} \tag{2.11}$$

where

L is the plate half-thickness, m

r is the radius, m

λ_n is the roots of Bessel function of order zero.

In the above equations the average moisture content is expressed as a dimensionless quantity, MR, the moisture ratio:

$$MR = \frac{M - M_e}{M_o - M_e} \tag{2.12}$$

where

M_e is the equilibrium moisture content, d.b., and

M_0 is the initial moisture content, d.b.

Whitaker and Young (1972) utilized theoretical equations 2.9, 2.10, and 2.11 in simulating moisture movement in peanut kernels. Since the peanut kernel does not have a perfect geometric shape, the best geometric representation was determined by comparing equations 2.9, 2.10, and 2.11 to the drying data of peanut kernels. They reported that the cylindrical model predicted the experimental drying rate with the greatest accuracy and the diffusion coefficient D in the equation was a function of temperature. Equations 2.9, 2.10, and 2.11 have also been used for wheat (Becker, 1959), and corn drying (Chittenden and Hustrulid, 1966, and Hamdy and Barre, 1969).

The solutions in Equations 2.9, 2.10, and 2.11 involve the calculation of an infinite number of terms. Typically only the first term is needed to provide a good estimate of the drying rate. Using this simplification, the following expression results, for an infinite plate, infinite cylinder, and sphere, respectively:

$$MR = \frac{8}{\pi^2} e^{-\left(\frac{\pi}{2L}\right)^2 Dt} \qquad (plate) \tag{2.13}$$

$$MR = \frac{4}{\lambda^2 r^2} e^{-\lambda^2 Dt} \qquad (cylinder) \tag{2.14}$$

$$MR = \frac{6}{\pi^2} e^{-\left(\frac{\pi}{r}\right)^2 Dt} \qquad (sphere) \tag{2.15}$$

For fixed values of L and r, the general form of Equations 2.13, 2.14, and 2.15 is:

$$MR = \frac{M - M_e}{M_0 - M_e} = C\, e^{-kt} \tag{2.16}$$

where

C is a coefficient,

k is a constant, s^{-1}.

Brooker et al (1974) noted that Equation 2.16 has frequently been used to predict the drying of grain. Colson and Young (1990) pointed out that Equation 2.16 described whole pod drying with reasonable accuracy. Henderson and Pabis (1961) utilized Equation 2.16 to model shelled maize drying at different temperatures. They found a good correlation between model and experimental data. They reported that the constant k in Equation 2.16 was a function of temperature.

Several purely empirical drying equations have also been developed for cereal grains. Thompson (1967) proposed the following equation for calculating drying of shelled corn in the temperature range between 60 and 149°C:

$$t = A \ln MR + B(\ln MR)^2 \qquad (2.17)$$

where

$$A = 1.86178 + 0.00488\, T, \qquad B = 427.3640\, e^{-0.033017T} \qquad (2.18)$$

T is product temperature, °C.

t is time, minutes.

Becker (1959) determined the drying rate data for wheat and proposed the following equations:

for $(Dt)^{0.5} < 0.034$,

$$\frac{M - M_e}{M_0 - M_e} = 1 - 24.82(Dt)^{0.5} + 142.29Dt \qquad (2.19)$$

for $(Dt)^{0.5} \geq 0.034$,

$$\frac{M - M_e}{M_0 - M_e} = 0.509\, e^{-629.68Dt} \qquad (2.20)$$

where

$$D = 76.8\, e^{-\frac{11080}{T_{abs}}} \qquad (2.21)$$

T_{abs} is product temperature, °K,

t is time, minutes.

Brooker et al (1974) reported that empirical drying equations often gave the best results in predicting drying behavior of cereal grains. The equations could be employed with confidence within the temperature, relative humidity, airflow velocity and moisture content range for which they were derived.

Other major types of drying models include Page's equation (Page, 1949):

$$MR = e^{-kt^n} \tag{2.22}$$

and the diffusion model (Troeger and Hukill, 1971, Troeger and Butler, 1979, and Muhidong et al, 1992):

$$MR = u\ e^{-kt} \tag{2.23}$$

where k, n, and u are drying constants.

Osborn et al (1991) evaluated Equations 2.11, 2.22 and other drying models for their soybean thin-layer moisture adsorption experiments. They concluded that Page's equation provided the best fit to the experimental data. The drying constant k was a function of both air temperature and relative humidity, while n was not significant.

Muhidong et al (1992) examined Equations 2.16, 2.17, 2.22, and 2.23 during thin-layer drying of kenaf. They found that Page's equation was the appropriate model to describe thin-layer drying of bast and corn fibers of kenaf. The drying constants k and n were affected by air temperature and air flow.

Troeger and Hukill (1971) used Equation 2.23 for a single layer drying of corns. They divided whole drying process into three stages. The model fitted the experimental data satisfactorily. Troeger and Butler (1979) applied the same model to simulate solar drying of peanuts. They reported that the simulation gave reasonable estimates of energy use and of drying time.

Based upon previous studies on Equation 2.23, Cook et al (1982) successfully adapted that model for use with recirculation of air during peanut drying. They recommended using their modified model with a recirculation strategy to obtain energy savings without a significant increase in drying time.

CHAPTER 3

THEORETICAL ANALYSIS

DIFFUSION IN ONE DIRECTION

The mathematical theory of diffusion in homogeneous media is based on the hypothesis that the rate of transfer of a diffusing substance through a unit area of a section is proportional to the concentration gradient measured normal to the section (Crank, 1957). The moisture transfer process thus can be derived based upon Fick's law of molecular transfer:

$$F = -D\frac{\partial M}{\partial x} \tag{3.1}$$

where

F	is the rate of moisture transfer, m/s
M	is moisture content, % d.b.
x	is the space coordinate measured normal to the section, m
D	is the diffusion coefficient, m^2/s.

Drying porous solids, such as apples and peaches, is an unsteady state mass transfer process. Partial differential equations of diffusion for such a process can be derived from Equation 3.1 as shown in the following paragraph.

Figure 3.1 is an element of volume with Δx, Δy, and Δz dimensions. Suppose the mass flow is in the x direction. A mass balance based upon the element

(Geankoplis, 1978) can be thus written as:

$$rate\ of\ input = rate\ of\ output + rate\ of\ accumulation \tag{3.2}$$

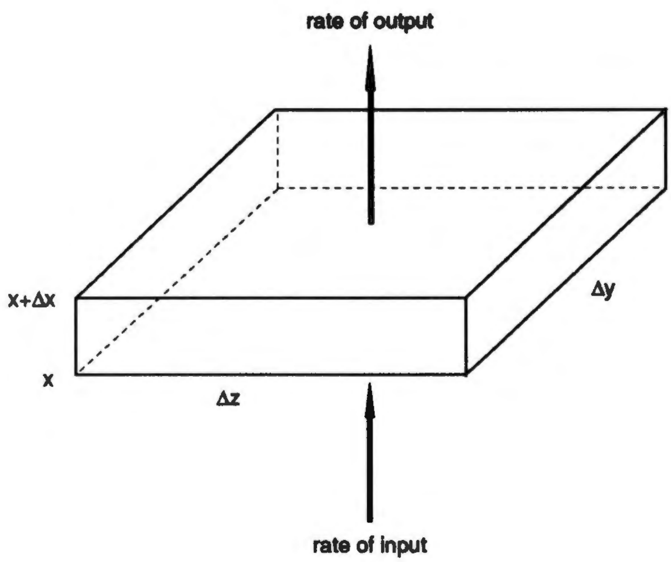


Figure 3.1 Unsteady-state diffusion in one direction

$$rate\ of\ input = -D\frac{\partial M}{\partial x}|_x \tag{3.3}$$

$$rate\ of\ output = -D\frac{\partial M}{\partial x}|_{x+\Delta x} \tag{3.4}$$

$$rate\ of\ accumulation = (\Delta x \Delta y \Delta z)\frac{\partial M}{\partial t} \tag{3.5}$$

Substituting Equations 3.3, 3.4, and 3.5 into Equation 3.2 and dividing by Δx Δy Δz,

$$-D\frac{\left.\frac{\partial M}{\partial x}\right|_{x} - \left.\frac{\partial M}{\partial x}\right|_{x+\Delta x}}{\Delta x} = \frac{\partial M}{\partial t} \tag{3.6}$$

letting Δx approach zero, yield diffusion in x direction:

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \tag{3.7}$$

For diffusion in all three directions a similar derivation gives:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + \frac{\partial^2 M}{\partial z^2}\right) \tag{3.8}$$

The Solution to Equation 3.7 can be obtained by separation of variables (Crank, 1975). That solution is written as:

$$M = X(x)T(t) \tag{3.9}$$

where X and T are functions of x and t respectively. Substitution into Equation 3.7 yields:

$$X\frac{dT}{dt} = DT\frac{d^2X}{dx^2} \tag{3.10}$$

which may be rewritten:

$$\frac{1}{T}\frac{dT}{dt} = \frac{D}{X}\frac{d^2X}{dx^2} \tag{3.11}$$

On the left-hand side is an expression depending on t only, while the right-hand side depends on x only. Both sides therefore must be equal to the same constant which is commonly taken as $-\lambda^2D$. Therefore, two ordinary differential equations are yielded:

$$\frac{1}{T}\frac{dT}{dt} = -\lambda^2 D \tag{3.12}$$

and

$$\frac{1}{X}\frac{d^2X}{dx^2} = -\lambda^2 \tag{3.13}$$

with solutions:

$$T = e^{-\lambda^2 Dt} \tag{3.14}$$

and

$$X = A \sin\lambda x + B \cos\lambda x \tag{3.15}$$

Thus, a solution of Equation 3.7 has the form:

$$M = (A \sin\lambda x + B \cos\lambda x)\, e^{-\lambda^2 Dt} \tag{3.16}$$

where A and B are constants of integration. Since Equation 3.7 is a linear equation, the most general solution is obtained by summing solutions of Equation 3.16, giving:

$$M = \sum_{m=1}^{\infty} (A_m \sin\lambda x + B_m \cos\lambda x)\, e^{-\lambda_m^2 Dt} \tag{3.17}$$

where A_m, B_m, and λ_m are determined by the initial and boundary conditions for any particular problem. If we are interested in diffusion out of a plane sheet with a thickness q, through which the diffusing substance is initial uniformly distributed and the surfaces of which are kept at zero concentration, the conditions are:

$$M = M_0, \qquad 0 < x < q, \qquad t = 0 \tag{3.18}$$

$$M = 0, \qquad x = 0, \qquad x = q, \qquad t > 0 \tag{3.19}$$

The boundary conditions (3.19) are:

$$B_m = 0, \quad \lambda_m = \frac{m\pi}{q} \tag{3.20}$$

and hence the initial condition (3.18) becomes:

$$M_0 = \sum_1^{\infty} A_m \sin\frac{m\pi}{q}, \qquad 0 < x < q \tag{3.21}$$

By multiplying both sides of Equation 3.21 by sin(pπx/q) and integrating from 0 to q using the relationship:

$$M_0 \int_0^q \sin\frac{p\pi}{q} dx = \sum_1^{\infty} \int_0^q A_m \sin\frac{p\pi x}{q} \sin\frac{m\pi}{q} dx \tag{3.22}$$

The terms for which m is even vanish, giving:

$$A_m = \frac{4M_0}{m\pi}, \qquad m = 1, 3, 5, \ldots \tag{3.23}$$

The solution to Equation 3.17 is therefore:

$$M = \frac{4M_0}{\pi} \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin\frac{(2n+1)\pi x}{q} e^{-\frac{(2n+1)^2\pi^2 Dt}{q^2}} \tag{3.24}$$

where 2n+1 has been substituted for m for convenience so that n takes values 0, 1, 2, 3 ... .

Integrating Equation 3.24 yields diffusion in all x direction:

$$M = \frac{8qM_0}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{-\frac{(2n+1)^2\pi^2}{q^2}Dt} \tag{3.25}$$

Instead of an infinite number of terms in Equation 3.25, only the first term of the equation is necessary for many solutions. Thus, Equation 3.25 becomes:

$$M = \frac{8qM_0}{\pi^2} e^{-\left(\frac{\pi}{q}\right)^2 Dt} \tag{3.26}$$

DIFFUSION IN TWO DIRECTIONS

For diffusion in two directions:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \tag{3.27}$$

The solution to Equation 3.27 can be obtained by the method of separation of variables (Crank, 1975) and following the same procedure as in the previous solution for diffusion in one direction. Thus, we find a solution to Equation 3.27 by setting:

$$M = X(x)Y(y)T(t) \tag{3.28}$$

where X, Y, and T are functions of x, y, and t respectively. Substitution in Equation 3.27 yields:

$$XY\frac{dT}{dt} = DT\left(Y\frac{d^2X}{dx^2} + X\frac{d^2Y}{dy^2}\right) \tag{3.29}$$

which may be rewritten:

$$\frac{1}{T}\frac{dT}{dt} = D\left(\frac{1}{X}\frac{d^2X}{dx^2} + \frac{1}{Y}\frac{d^2Y}{dy^2}\right) \tag{3.30}$$

On the left-hand side is an expression depending on t only, while the right-hand side depends on x and y. Both sides therefore must be equal to the same constant which is conveniently taken as $-\lambda^2D$. Therefore, two ordinary differential equations are yielded:

$$\frac{1}{T}\frac{dT}{dt} = -\lambda^2 D \tag{3.31}$$

and

$$\frac{1}{X}\frac{d^2X}{dx^2} + \frac{1}{Y}\frac{d^2Y}{dy^2} = -\lambda^2 \tag{3.32}$$

solutions are:

$$T = e^{-\lambda^2 Dt} \tag{3.33}$$

and

$$X = A \sin\lambda_1 x + B \cos\lambda_1 x \tag{3.34}$$

$$Y = C \sin\lambda_2 y + D \cos\lambda_2 y \tag{3.35}$$

Thus, a solution of Equation 3.27 has the form:

$$M = (A \sin\lambda_1 x + B \cos\lambda_1 x)(C \sin\lambda_2 y + D \cos\lambda_2 y)\, e^{-\lambda^2 Dt} \tag{3.36}$$

where A, B, C, and D are constants of integration. Since Equation 3.27 is a linear equation, the most general solution is obtained by summing solutions of Equation 3.36, giving:

$$M = \sum_{m=1}^{\infty} (A_{1m} \sin\lambda_{1m} x + B_{1m} \cos\lambda_{1m} x)\,(A_{2m} \sin\lambda_{2m} y + B_{2m} \cos\lambda_{2m} y)\, e^{-\lambda_m^2 Dt} \tag{3.37}$$

where

$$\lambda_m^2 = \lambda_{1m}^2 + \lambda_{2m}^2 \tag{3.38}$$

where A_m, B_m, C_m, D_m and λ_m are determined by the initial and boundary conditions for any particular problem. If we assume that an apple ring is a plane sheet with thickness q and length l, the boundary conditions are:

$$M = M_0 \quad at \quad 0 < x < q, \quad 0 < y < l, \quad t = 0 \tag{3.39}$$

$$M = 0 \quad at \quad x = 0, \quad y = 0, \quad x = q, \quad y = l, \quad t > 0 \tag{3.40}$$

The boundary conditions (3.40) demand that

$$B_m = 0, \quad D_m = 0, \quad \lambda_{1m} = \frac{m\pi}{q}, \quad \lambda_{2m} = \frac{m\pi}{l} \tag{3.41}$$

and hence the initial condition (3.39) becomes:

$$M_0 = \sum_1^{\infty} \left(A_m \sin\frac{m\pi x}{q}\right)\left(C_m \sin\frac{m\pi y}{l}\right) \tag{3.42}$$

$$0 < x < q, \quad 0 < y < l \tag{3.43}$$

By multiplying both sides of (3.42) by sin(pπx/q)sin(rπy/l) and integrating from 0 to q and 0 to l using the relationships:

$$\begin{aligned} &M_0 \int_0^q \sin\frac{p\pi x}{q}dx \int_0^l \sin\frac{r\pi y}{l}dy = \\ &\sum_1^{\infty} \int_0^q A_m \sin\frac{m\pi x}{q}\sin\frac{p\pi x}{q}dx \int_0^l C_m \sin\frac{m\pi y}{l}\sin\frac{r\pi y}{l}dy \end{aligned} \tag{3.44}$$

Equation 3.44 becomes:

$$\frac{4lqM_0}{m^2\pi^2} = A_m C_m \frac{lq}{4} \tag{3.45}$$

The terms for which m is even vanish, giving:

$$A_m C_m = \frac{16M_0}{m^2\pi^2}, \quad m = 1, 3, 5, \ldots \tag{3.46}$$

Substituting Equation 3.41 and 3.46 into 3.37, the solution of Equation 3.37 is therefore:

$$\begin{aligned} M = &\frac{16M_0}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \sin\frac{(2n+1)\pi x}{q} \\ &\sin\frac{(2n+1)\pi y}{l} \; e^{-\left(\frac{(2n+1)^2\pi^2}{q^2} + \frac{(2n+1)^2\pi^2}{l^2}\right)Dt} \end{aligned} \tag{3.47}$$

Integrating Equation 3.47 yields diffusion in x and y directions:

$$M = \frac{64M_0}{\pi^2} \sum_{n=0}^{\infty} \frac{lq}{(2n+1)^4\pi^2} e^{-\left(\frac{(2n+1)^2\pi^2}{q^2} + \frac{(2n+1)^2\pi^2}{l^2}\right)Dt} \tag{3.48}$$

For many applications, only the first term of the series is necessary to adequately describe the drying process. That common approach will be followed in this analysis. Thus, the Equation 3.48 becomes:

$$M = \frac{64M_0 lq}{\pi^4} e^{-\left(\frac{1}{q^2} + \frac{1}{l^2}\right)\pi^2 Dt} \tag{3.49}$$

Equation 3.49 is a moisture diffusion model for a plane sheet. This equation will be the initial model used to fit apple and peach drying data.

CHAPTER 4

MATERIALS AND METHODS

TEST MATERIALS

The peaches used in this study were Red Haven and Sun High varieties harvested from a Dandridge Tennessee orchard. The peaches were transported to the Agricultural Engineering Department at The University of Tennessee immediately after harvesting. They were washed, halved, and pitted prior to drying.

Apple drying tests were made using a Golden Delicious apple variety obtained from Crossville, Tennessee. Apples were mechanically peeled, cored, and sliced into 5 mm thick rings prior to drying.

EQUIPMENT AND INSTRUMENTATION

Walker (1992) modified four batch dehydrators purchased from Nutriflow Co. (Portland, Oregon) with air recirculation ducts for drying tests using peaches and apples. The same system was used for the peach drying portion of this research. All dehydrators had similar design (length: 45 cm x width: 37 cm x height: 33 cm). Each dehydrator was capable of holding ten plastic trays (length:41.3 cm x width: 36.5 cm). However, the peaches were sufficiently large that only four trays could be used. A fan, installed near the rear of the dehydrator, forced air through the unit at a constant flow rate. An electrical resistance element (1500 Watt), located in front of the fan provided heat for the system. A PID temperature controller was used to maintain the drying temperature (65°C). Power to the dehydrator fans bypassed the temperature controller unit to permit continuous operation of the fans.

Five thermocouples were attached to a wire screen mounted in a plane just in front of the heating element to measure the heated air temperature at the top, bottom, middle, right, and left positions. These thermocouples were connected in parallel to the temperature controller input so that the average of these five inputs was used as the input control parameter (Walker, 1992).

All dehydrator energy use was measured by kilowatt-hour meters (Sangamo Electric Co., Springfield, Illinois) individually connected to each dehydrator. The kilowatt-hour meters were modified by painting a thin black band around the reflective underside of each meter's rotating disk. Photoelectric sensors were mounted within each meter. A small reflective break left in the band allowed a photoelectric sensor to generate a pulse as the break passed over the sensor. Thus, each rotation of the meter disk produced a pulse. During tests, one kilowatt-hour meter was found to generate two pulses for each disk revolution. Therefore, pulses from this unit were divided by two during data analysis to obtain actual revolution disk counts.

The original instrumentation was modified for apple drying to permit automatic weight measurement. A specially constructed stainless steel support rack was suspended from a SHC load cell (Model 10025, S Himmelstein & Co.) mounted near the center of the dehydrator top. A small hole drilled through the top of the unit allowed the support rack to be suspended from a single support hook. Four dehydrator trays were trimmed to 41.3 cm x 31.5 cm such that they would fit within the support rack. Clearance between the support rack and the dehydrator walls was approximately 2 cm. Four small teflon rods mounted on the rack provided a low friction surface in the event of contact with the dehydrator side walls. The signal from the load cell was sent to a strain gage conditioner (model 2160, Measurements Group, Instruments Division, Raleigh, North Carolina). Figure 4.1 provides an overview of the installation.

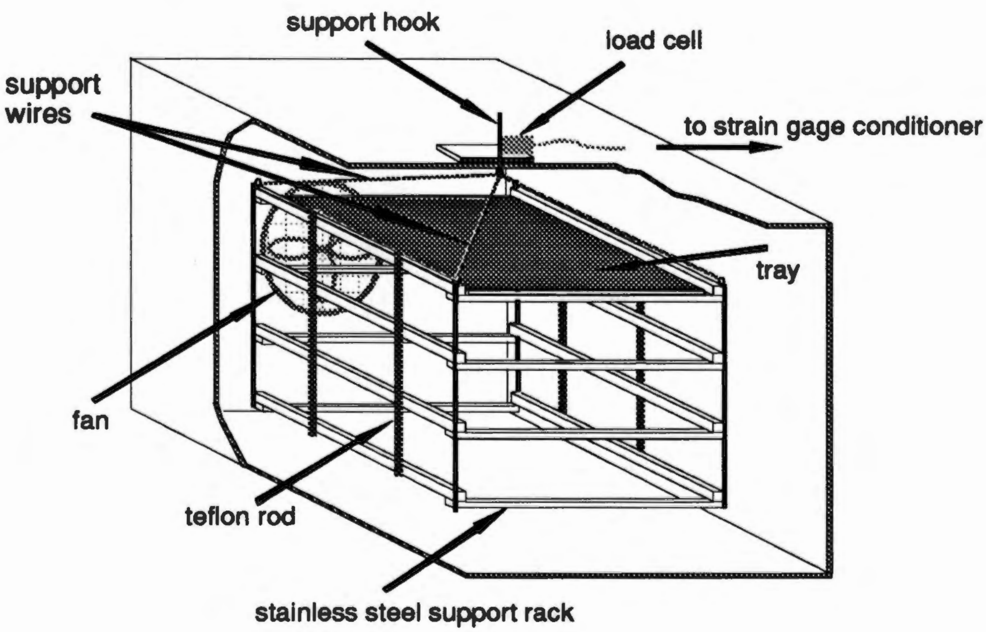


Figure 4.1. Sketch of weighing system installed in dehydrator.

A CSI 21x micrologger (Campbell Scientific, Inc.: Salt Lake City, Utah) collected data at 5 second intervals and averaged over 15 minute periods throughout each test. A Zenith notebook computer collected this processed data for storage on a floppy disk.

EXPERIMENTAL DESIGN

This experiment studied the effect of four different recirculation rates on energy consumption and drying rates. Two factors were potential error sources:

1. With four treatments and only four dehydrators, there could be substantial differences between batches of fruit and between weather condition from one drying period to another.
2. The four dehydrators, while outwardly similar, could vary in drying performance.

The Latin Square design was used to eliminate the above two sources of variability (Montgomery, 1984). This was accomplished by systematically allowing blocking in two directions. Presented in tabular form, the rows (dehydrators) and columns (tests) actually represented two restrictions on randomization (Montgomery, 1984). The design was a square arrangement, with the four recirculation rates 0, 70, 80, and 90% (treatments) denoted by the Latin letters A, B, C, and D as shown in Table 4.1.

Four dehydrators dried one batch of fruit during a single test. A total of four tests were required to complete the Latin square design. Recirculation rates of 0, 70, 80, and 90% (treatments) were applied to the individual batches of fruit in each test. The treatments were completely randomized in the first test. Treatments in the following three tests required a form of restrictive randomization, which ensured that

Table 4.1. Example of a 4x4 Latin square design

Dehydrators	Test 1	Test 2	Test 3	Test 4
1	A	B	C	D
2	B	A	D	C
3	C	D	B	A
4	D	C	A	B

Treatments: A is 0%, B is 70%, C is 80%, D is 90%.

Table 4.2. Latin square design used for all drying tests.

Test Plans	Varieties	Dehydrators	Test1	Test2	Test3	Test4
			(recirculation rates %)			
Fixed-Rate	Apples	1	C	A	D	B
		2	A	B	C	D
		3	B	D	A	C
		4	D	C	B	A
	Sun High Peaches	1	A	D	C	B
		2	B	C	D	A
		3	C	B	A	D
		4	D	A	B	C
	Red Haven Peaches	1	A	D	C	B
		2	B	C	D	A
		3	C	B	A	D
		4	D	A	B	C
Variable-Rate	Apples	1	A	B	D	C
		2	B	A	C	D
		3	D	C	A	B
		4	C	D	B	A

Treatments: A is 0%, B is 70%, C is 80%, D is 90%.

each recirculation rate occurred once and only once in each row (dehydrator) and column (tests). The experimental design for all apple and peach tests is shown in Table 4.2.

EXPERIMENTAL PROCEDURES

Determination of the Initial Moisture Content

Initial moisture content can be measured based upon the following mass balance principle:

$$\textit{sample weight} = \textit{initial moisture content} + \textit{dry weight} \tag{4.1}$$

Samples were dessicated at 70°C to obtained the total dry mass. Initial moisture content on a wet basis was then determined:

$$m_0 = \frac{wt_0 - wt_f}{wt_0} \tag{4.2}$$

where

m_0 is initial moisture content of the product, w.b

wt_0 is initial weight of the sample, g

wt_f is dry weight of the sample, g

The initial moisture content was used to predict the final sample weight at 25% moisture content.

Calibration of the Recirculation Rate

The amount of air recirculated during each run was calculated based upon an energy balance (Walker and Wilhelm, 1992):

$$(mc_p\Delta T)_{inlet} = (mc_p\Delta T)_{ex} + (mc_p\Delta T)_a \qquad (4.3)$$

where

m	is the mass flow rate, kg/s,
c_p	is the specific heat of the air, J/kg°C, assumed to be constant,
ΔT	is the temperature difference from a reference temperature, 0°C for this analysis.

The subscripts $_{inlet}$, $_{ex}$, and $_a$ are inlet duct, exhausted air, and ambient air temperatures. Rearrangement of Equation 4.3 yield:

$$T_{inlet} = T_a + R\,(T_{ex} - T_a) \qquad (4.4)$$

where R is the mass fraction of recirculated air (m_{ex}/m_{inlet}).

Peach Drying

Fixed-rate recirculation was used for all peach drying tests. Sixteen peach halves were placed on each of four trays in each dehydrator. During drying, the dehydrator was opened periodically to weigh each tray. The tray was then rotated 180 degrees horizontally and exchanged with another tray on a different level to ensure that all samples were dried uniformly. The samples were removed when their moisture content was reduced to approximately 25%. The entire peach drying process required 30 to 35 hours.

Apple Drying

Apple drying tests consisted of fixed recirculation rate and variable recirculation rate tests. For all tests, sixteen apple rings were placed on each tray with a total of 64 apple rings in each dehydrator. The four trays were suspended on a steel rack supported by a load cell which transmitted the load information to the computer data acquisition system. The dehydrator was opened only once during the process to exchange the position of trays. The apple drying process required about five hours.

The variable-rate tests began with the same four recirculation rates used in the fixed recirculation tests. After one hour of drying, the dampers were adjusted to maintain designated relative humidities. At 90% recirculation, the damper was adjusted to obtain a relative humidity of 30% at the dehydrator inlet. The same procedure was used to adjust 70 and 80 percent recirculation rates to 10 and 20% relative humidities respectively. The dampers were adjusted manually at 30 minute intervals to maintain the designated relative humidities as long as possible. No adjustment was made to the 0% recirculation dehydrator.

EXPERIMENTAL MEASUREMENTS

Psychrometric Properties

Measurements of psychrometric properties were made at five selected locations within each dehydrator and recirculation system. The locations and type of measurement were the same as Walker's (1992) measurements. These measurements were:

1. temperature and relative humidity of the ambient air at the entrance valve.
2. temperature and relative humidity of the mixed air in the recirculation duct.
3. temperature immediately downstream of the heating element.
4. temperature at the halfway point of the dehydrator trays.
5. wet and dry-bulb temperature at the dehydrator exit.

Type T (copper-constantan) thermocouples were used for all temperature measurements. The AM 416 multiplexor (Campbell Scientific, Inc.: Salt Lake City, Utah), with 32 channels interfaced most of the temperature sensors to the CSI 21x micrologger. Relative humidity probes (CSI Model 207) directly measured the relative humidity and temperature (with a thermistor) through single ended inputs to the CSI AM 416 multiplexor card. Unfortunately, those relative humidity probes did not perform as expected. At high recirculation rates, the duct temperatures were well above ambient. Under those conditions, the indicated relative humidity values were inaccurate.

The measurement of wet-bulb temperatures also presented some problems. These sensors were located at the dehydrator exit. At high recirculation rates, the exit (exhaust) air velocity was insufficient for satisfactory removal of moisture around the wet-bulb sensor. An additional occasional problem was the difficulty in maintaining proper thermocouple positions inside the wicks. The problems with relative humidity and wet-bulb temperature measurements were such that detailed energy balance analyses of the drying processes were not possible.

Energy Consumption

The energy required to dehydrate the peaches and apples to the approximate desired moisture (25% w.b.) was measured. The output from sensors was transferred to the 21x micrologger through the four pulse-channel inputs located on the micrologger's connector board. Manual dial readings were taken during peach drying and closely agreed with the measured values.

Final Moisture Content Estimation

The final target moisture content for all fruits was 25% (wet basis). This moisture was estimated from the known initial moisture content. Equation 4.2 was rearranged:

$$wt_f = wt_0 \; (1 \; - \; m_0) \tag{4.5}$$

and the final desired weight was estimated by following equation:

$$wt_{desired} = m_f\, wt_{ini} + wt_{ini}\,(1 - m_0) \tag{4.6}$$

where

$wt_{desired}$ is final desired weight, g,

m_f is final desired moisture content, w.b.

Weights of trays and the support rack (for apple drying only) were considered constant throughout each test. While the effect of these weights was considered in the analysis, they are omitted from the above equations.

CHAPTER 5

RESULTS AND DISCUSSION

During the apple and peach drying tests, the air velocity and the drying temperature were maintained constant. Different air recirculation rates were applied to evaluate the effects on energy consumption and drying time. The results of this study can be divided into two sections:

1. Effects of recirculation air on energy consumption and drying time,
2. Moisture diffusion models for apple and peach drying.

EFFECTS OF RECIRCULATION AIR ON ENERGY CONSUMPTION AND DRYING TIME

Fixed-Rate Drying of Apples and Peaches

The experimental data of energy consumption versus air recirculation rate and drying time versus air recirculation rate are summarized graphically in Figures 5.1 through 5.12. Actual numerical results are given in Tables 5.1 through 5.6. In these tables, latin letters represent air recirculation rates (treatments). A is 0%, B is 70%, C is 80%, and D is 90%. The results indicate that much more energy is saved with air recirculation rates of 70, 80, and 90% than with no recycled air. Figures 5.8, 5.10, and 5.12 show some variations in drying times from one test to another for a

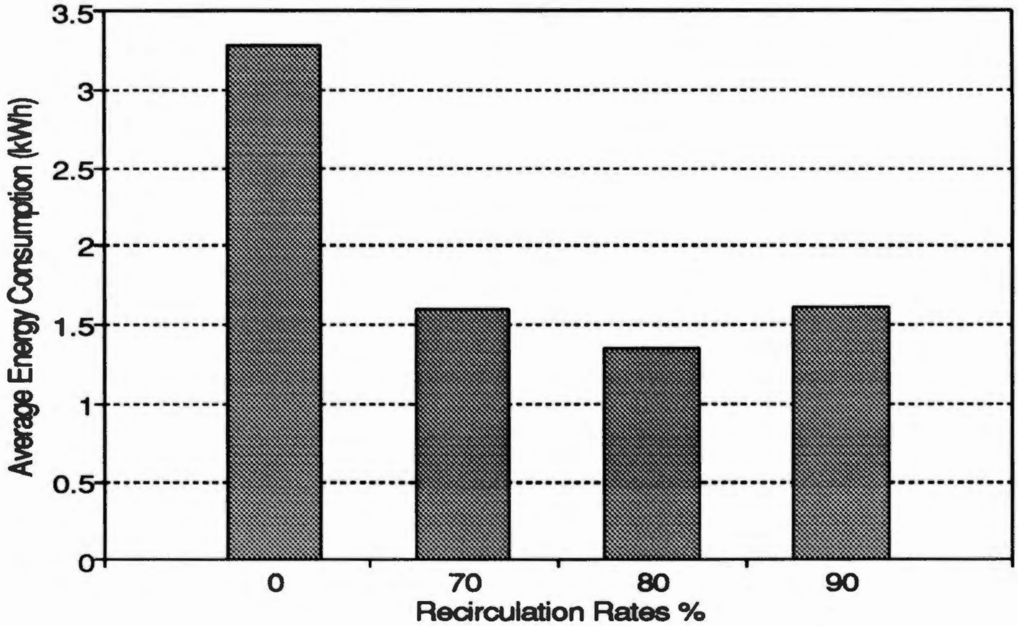


Figure 5.1. Effect of fixed-rate recirculated air on the average energy consumption during four apple drying tests.

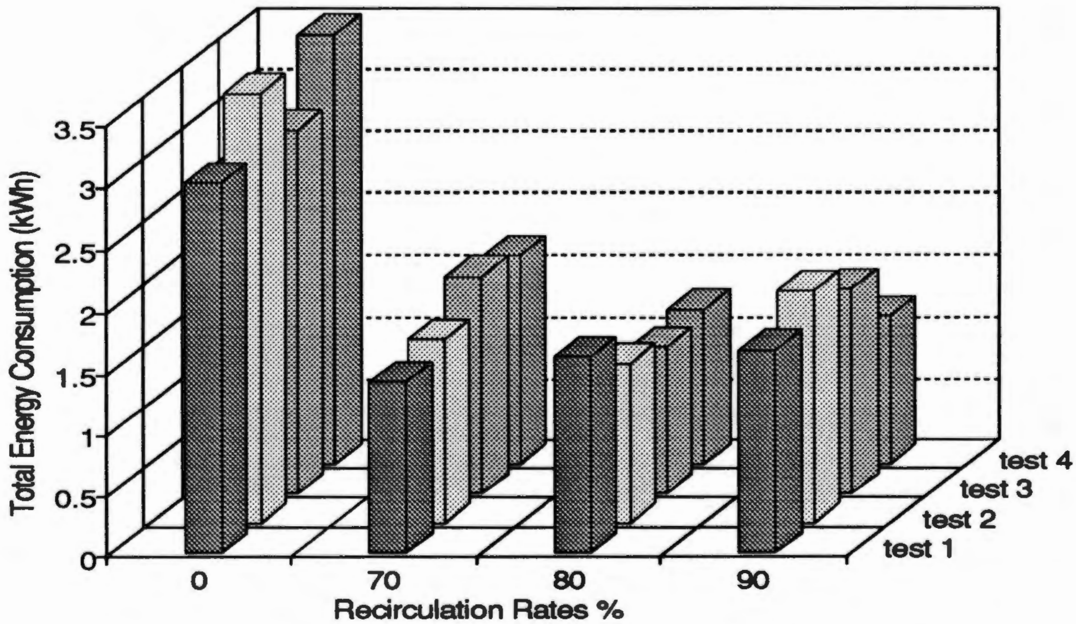


Figure 5.2. Effect of fixed-rate recirculated air on the total energy consumption during apple drying (tests 1-4).

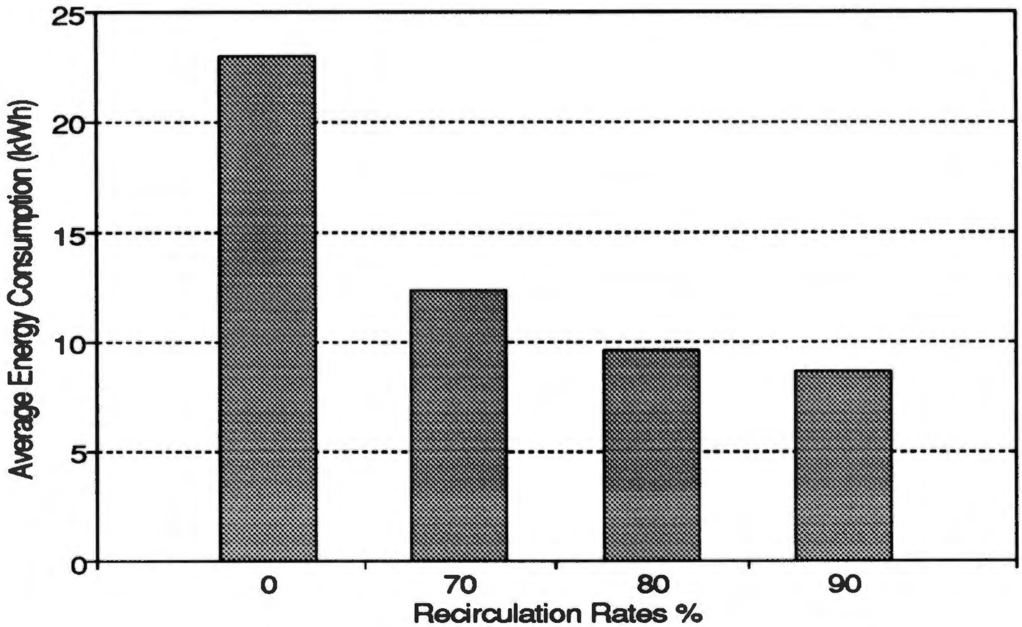


Figure 5.3. Effect of fixed-rate recirculated air on the average energy consumption during four drying tests using Sun High peaches.

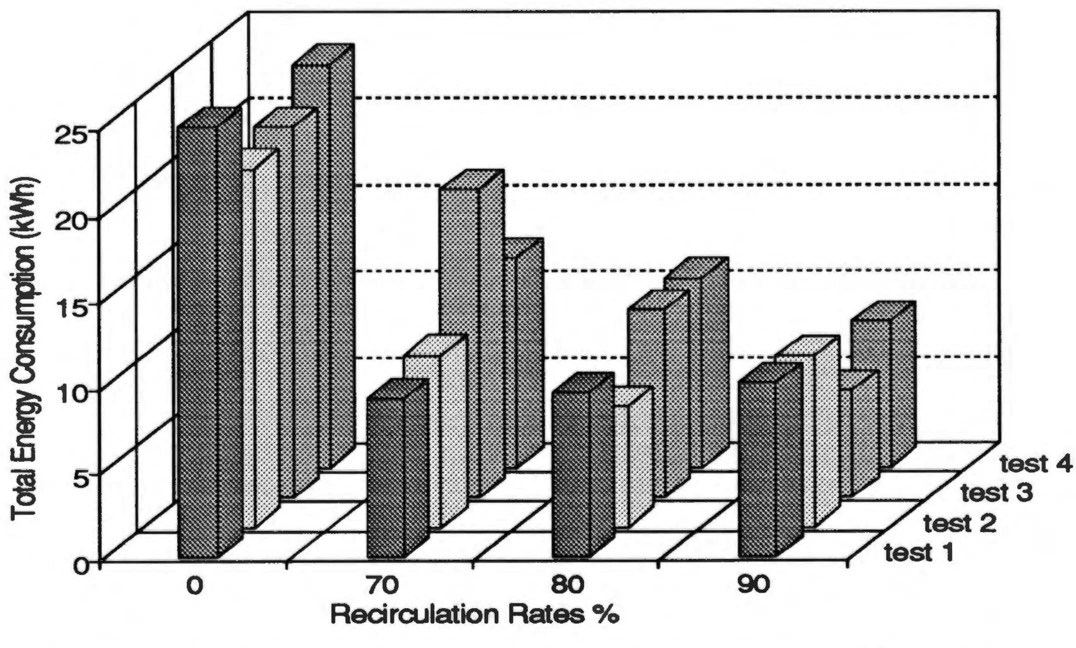


Figure 5.4. Effect of fixed-rate recirculated air on the total energy consumption during Sun High peach drying (tests 1-4).

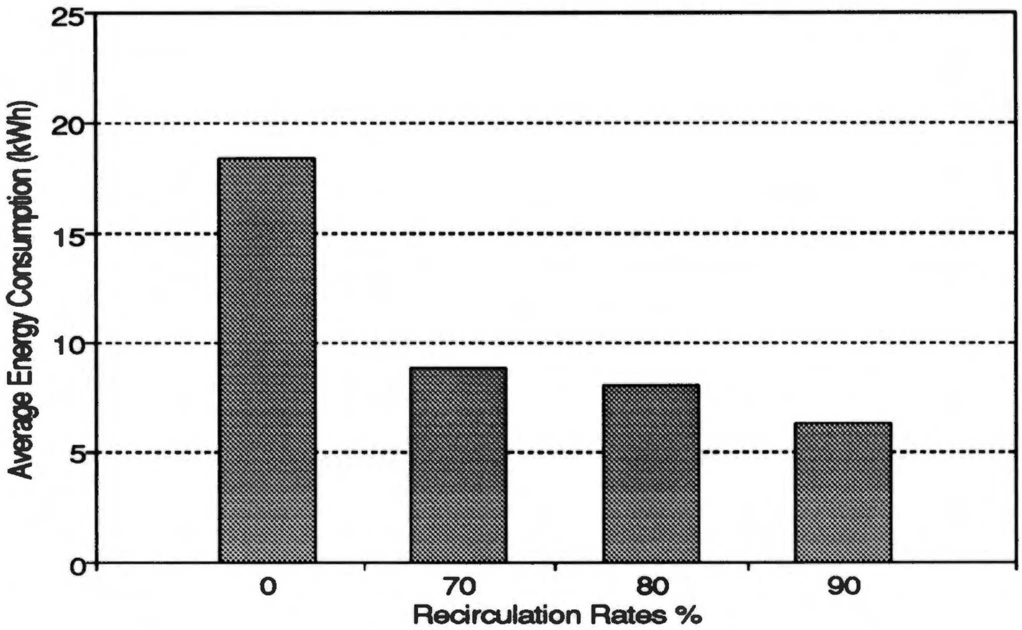


Figure 5.5. Effect of fixed-rate recirculated air on the average energy consumption during four drying tests using Red Haven peaches.

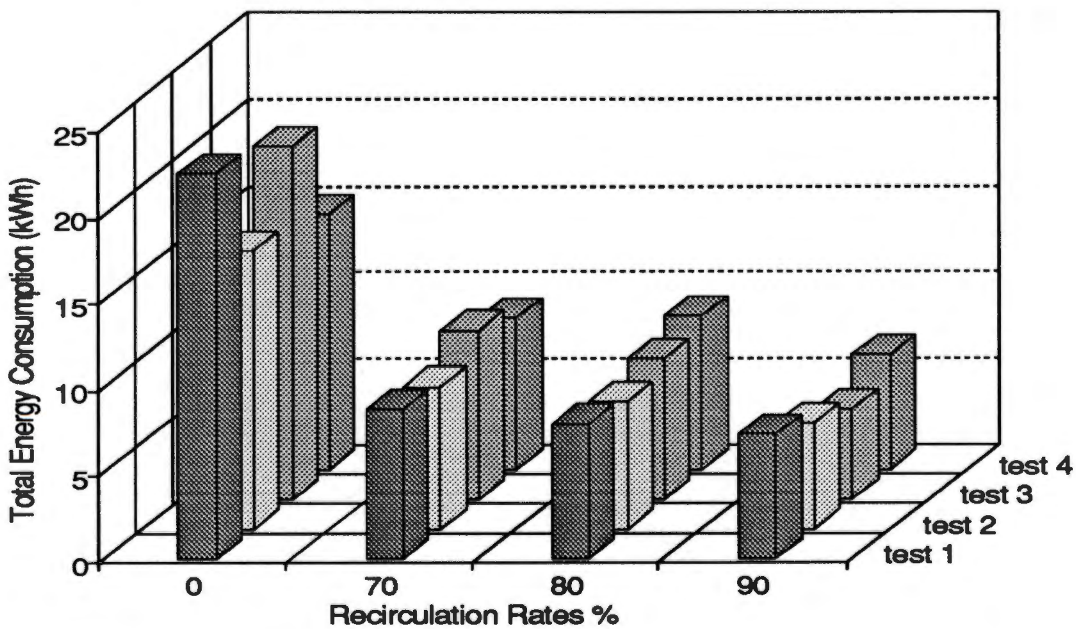


Figure 5.6. Effect of fixed-rate recirculated air on the total energy consumption during Red Haven peach drying (tests 1-4).

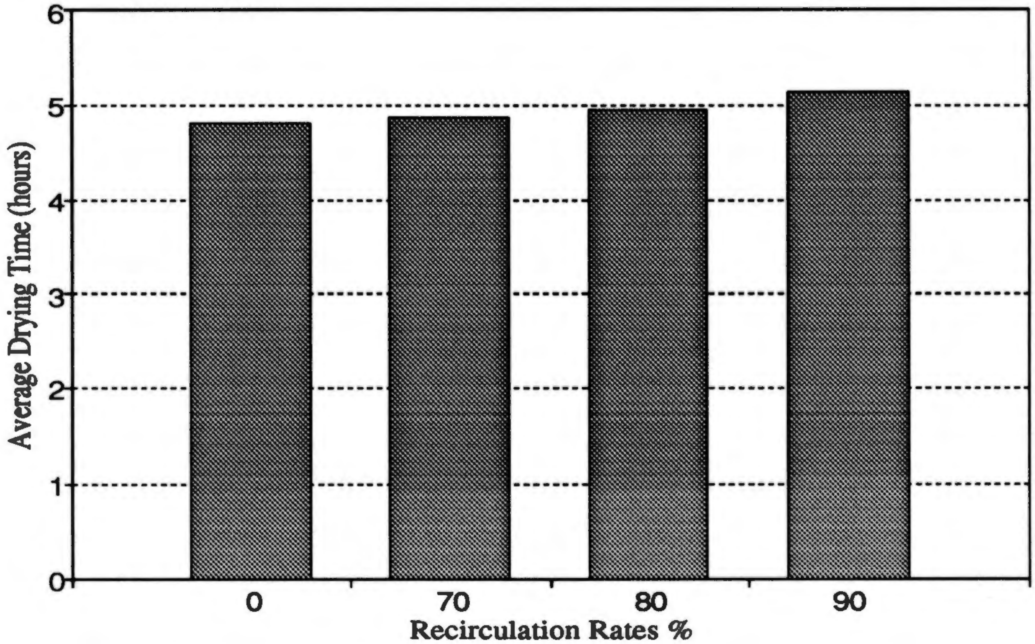


Figure 5.7. Effect of fixed-rate recirculated air on the average drying time during four apple drying tests.

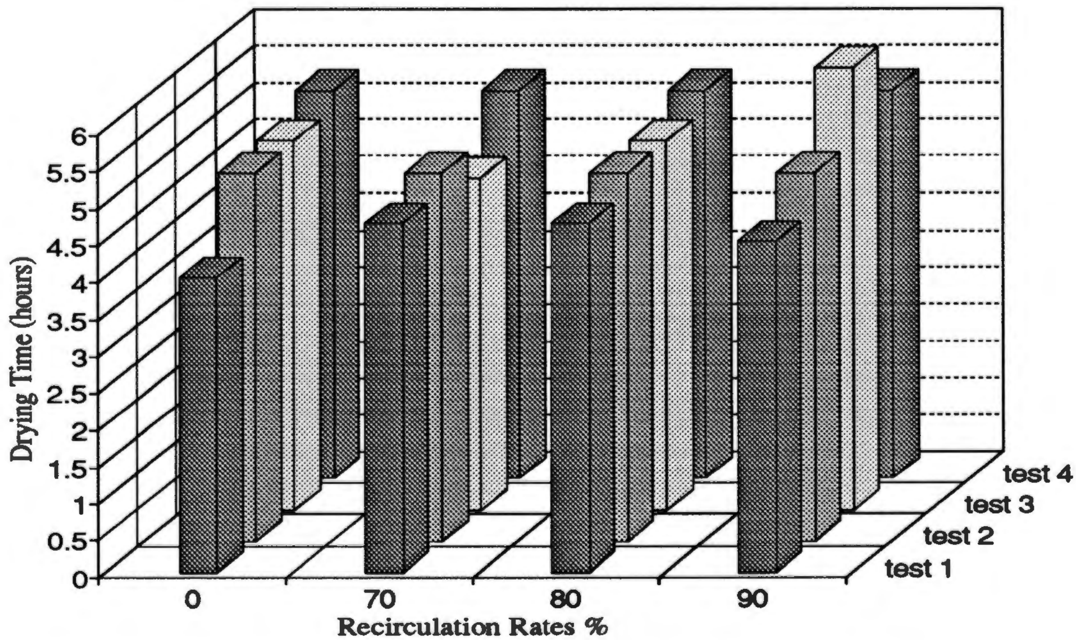


Figure 5.8. Effect of fixed-rate recirculated air on drying time during apple drying (tests 1-4).

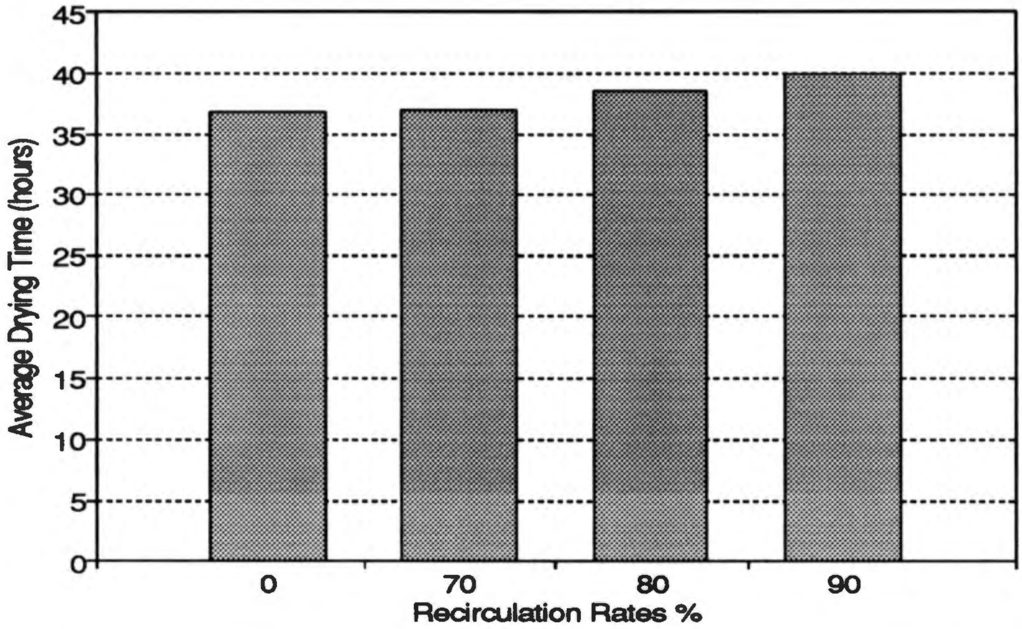


Figure 5.9. Effect of fixed-rate recirculated air on the average drying time during four drying tests using Sun High peaches.

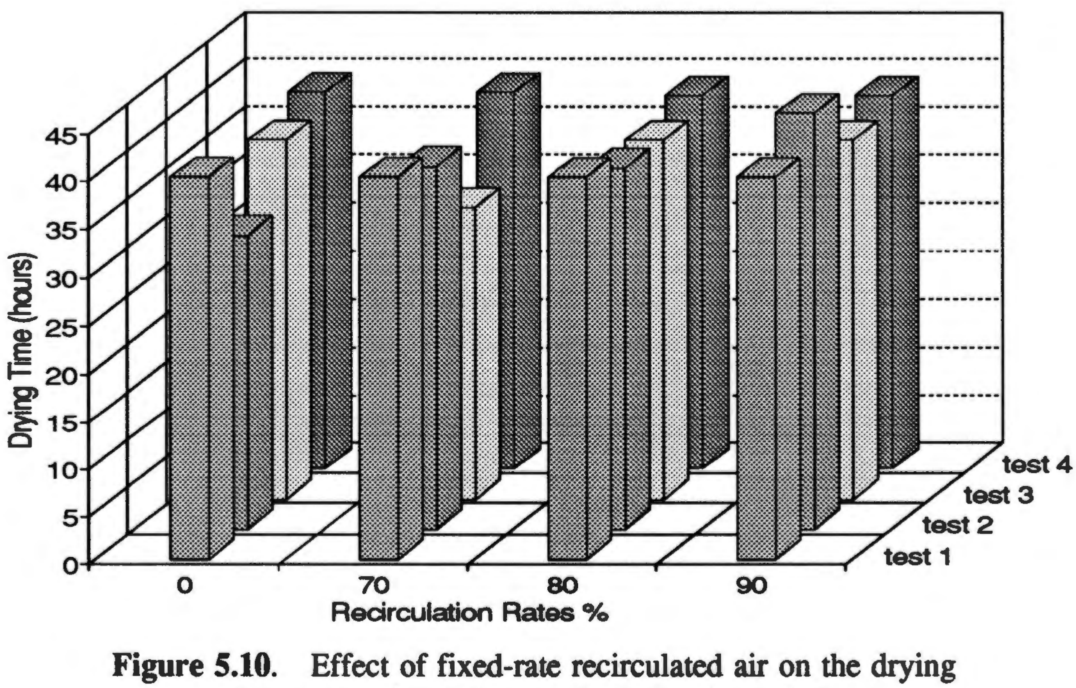


Figure 5.10. Effect of fixed-rate recirculated air on the drying time during Sun High peach drying (tests 1-4).

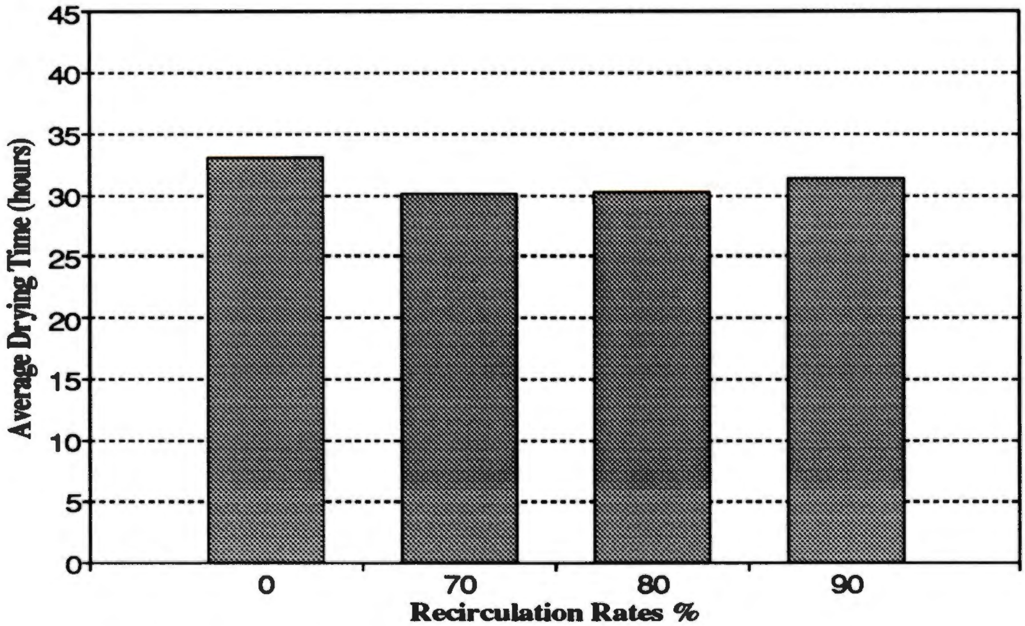


Figure 5.11. Effect of fixed-rate recirculated air on the average drying time during four drying tests using Red Haven peaches.

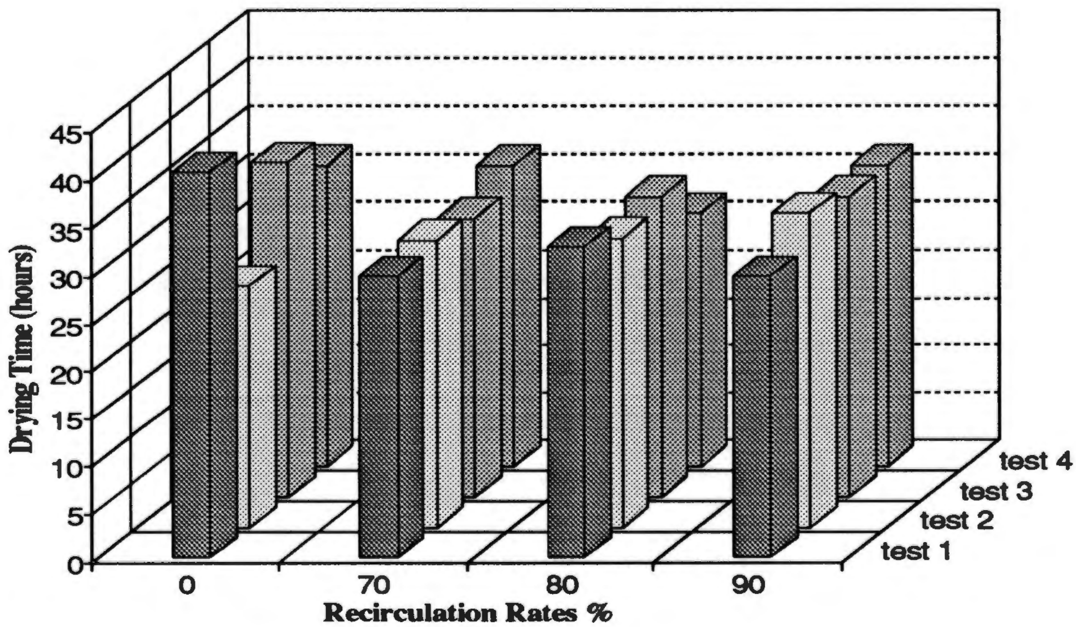


Figure 5.12. Effect of fixed-rate recirculated air on the drying time during Red Haven peach drying (tests 1-4).

Table 5.1. Total energy consumption during fixed-rate drying of apples

Dehydrator	Energy Consumption (kWh)			
	Test1	Test2	Test3	Test4
1	C=1.61	A=3.55	D=1.68	B=1.70
2	A=3.01	B=1.51	C=1.21	D=1.22
3	B=1.41	D=1.31	A=2.96	C=1.27
4	D=1.66	C=1.90	B=1.78	A=3.58

Table 5.2. Total drying time for fixed-rate drying of apples

Dehydrator	Drying Time (hours)			
	Test1	Test2	Test3	Test4
1	C=4.75	A=5.00	D=6.00	B=5.25
2	A=4.00	B=5.00	C=4.50	D=5.25
3	B=4.75	D=5.00	A=5.00	C=5.25
4	D=4.50	C=5.00	B=4.50	A=5.25

Table 5.3. Total energy consumption during drying of Sun High peaches

Dehydrator	Energy Consumption (kWh)			
	Test1	Test2	Test3	Test4
1	A=26.4	D=9.98	C=10.9	B=12.2
2	B=9.29	C=7.08	D=6.30	A=23.4
3	C=9.60	B=10.0	A=21.5	D=8.51
4	D=10.2	A=20.8	B=17.9	C=11.1

Table 5.4. Total drying time for drying of Sun High peaches

Dehydrator	Drying Time (hours)			
	Test1	Test2	Test3	Test4
1	A=40	D=43.50	C=37.5	B=39.25
2	B=40	C=37.75	D=37.5	A=39.25
3	C=40	B=38.00	A=37.5	D=39.00
4	D=40	A=37.50	B=30.5	C=39.00

Table 5.5. Total energy consumption during drying of Red Haven peaches

Dehydrator	Energy Consumption (kWh)			
	Test1	Test2	Test3	Test4
1	A=22.4	D=6.24	C=8.16	B=8.75
2	B=8.73	C=7.41	D=5.27	A=14.9
3	C=7.83	B=8.25	A=20.5	D=6.65
4	D=7.25	A=16.1	B=9.81	C=8.91

Table 5.6. Total drying time for drying of Red Haven peaches

Dehydrator	Drying Time (hours)			
	Test1	Test2	Test3	Test4
1	A=40.50	D=33.00	C=31.50	B=31.5
2	B=29.75	C=30.50	D=31.50	A=31.5
3	C=32.75	B=30.25	A=35.00	D=31.5
4	D=29.75	A=25.50	B=29.25	C=26.5

single treatment. However, within each test, drying times did not show clear variation with different recirculation rates. In Figure 5.8, two obvious drying time deviations were found for apple drying. The 0% recirculation rate treatment in test 1, dried faster than all other tests, while the 90% recirculation rate treatment in test 3 dried slower than all other tests. Figure 5.10 shows that 0% recirculation treatment dried faster while 90% recirculation treatment dried very slowly in test 2 of the Sun High peach drying experiment. This test was conducted during a period of high humidity, and at the 90% recirculation rate, a large amount of moisture was condensed on the dehydrator exit. Large variation was found among drying times for 0% recirculation rates test during Red Haven peach drying tests (Figure 5.12). Peaches in test 2 dried faster than those in other tests, while drying was slower in tests 1 and 3. The average drying times for recirculation rates show very little difference, although the average drying time tended to increase slightly with recirculation rate during apple drying and Sun High peach drying. The lowest energy consumption did not always occur at the highest air recirculation rate. While energy consumption usually decreased with increased recirculation rates, there were exceptions. These exceptions usually occurred during high humidity conditions. Under these conditions, higher recirculation rates reduced the moisture absorbing capacity of the air. As a result, longer drying times were required. This extra drying time resulted in added energy consumption.

To improve analysis of the experiments, an analysis of covariance was employed to test effects of recirculation rates on energy consumptions (Montgomery, 1984). The response variable is energy consumption. The major factor that influences energy consumption is air recirculation rate, although drying time may also be a factor. As shown in Appendices A, B, and C, energy consumption is linearly related to drying time for any given recirculation rate. Thus, analysis of covariance adjusts for the effects of an uncontrollable variable. The analyses of covariance are summarized in Tables 5.7 to 5.9.

For fixed-rate apple tests, as shown in Tables 5.7, there were significant differences ($p<0.05$) in energy consumption among dehydrators and among tests. For both varieties of peaches (Tables 5.8 and 5.9), there were no differences among tests or among dehydrators. Table 5.7, 5.8, and 5.9 show that for both apples and peaches, drying times did not affect energy consumption. Tables 5.7, 5.8 and 5.9 indicate that drying time, along with other variables (dehydrators, test, and treatment) did not affect energy consumption. Table 5.10 shows further test results of drying time as a function of recirculation rates. This test indicated that, for both apples and peaches, recirculation rates did not affect drying time. Walker (1992) obtained similar results in drying apples and peaches using air recirculation rates of 0, 25, 50, and 75%.

The above analysis of covariance tests show that recirculation rates significantly affected energy consumption, but it does not show which recirculation rate causes this difference. Tukey's multiple comparisons tests within SAS (SAS, 1985) was therefore performed to test mean differences among recirculation rates for energy consumption. The results of the mean separation through Tukey's Studentized Range test for energy consumption are presented in Table 5.11.

Table 5.7. Analysis of the effects of dehydrator, test, recirculation rate, and time on the energy consumption for fixed-rate apple drying

Source	DF	Type III SS	F Value	Pr > F
Dehydrator	3	0.7425	158.46	0.0001
Test	3	0.0693	14.79	0.0064
Treatment	3	8.7126	1859.26	0.0001
Time	1	0.0196	12.57	0.0165

Table 5.8. Analysis of the effects of dehydrator, test, recirculation rate, and time on the energy consumption for Sun High peach drying

Source	DF	Type III SS	F Value	Pr > F
Dehydrator	3	40.098	2.76	0.1510
Test	3	13.950	0.96	0.4790
Treatment	3	496.978	34.25	0.0009
Time	1	10.835	2.24	0.1947

Table 5.9. Analysis of the effects of dehydrator, test, recirculation rate, and time on the energy consumption for Red Haven peach drying

Source	DF	Type III SS	F Value	Pr > F
Dehydrator	3	13.691	2.47	0.1771
Test	3	0.1410	0.03	0.9938
Treatment	3	214.505	38.65	0.0007
Time	1	10.700	5.78	0.0612

Table 5.10. Analysis of effect of recirculation rates on drying times.

Products	DF	Type III SS	F Value	Pr > F
Apple	3	0.344	0.51	0.686
Sun Peach	3	0.137	0.88	0.480
Red Haven	3	22.23	0.60	0.628

Table 5.11. Tukey's test results for mean energy consumption

Fixed-Rate Drying Apples and Peaches	Recir. Rates %	Tukey's Test for Energy Consumption (kWh)
Apples	0	3.28^{a}
	70	1.60^{b}
	80	1.50^{bc}
	90	1.47^{c}
Sun High Peaches	0	23.0^{d}
	70	12.4^{e}
	80	9.68^{e}
	90	8.74^{e}
Red Haven Peaches	0	18.5^{f}
	70	8.89^{g}
	80	8.08^{g}
	90	6.36^{g}

Note: means for each product within a column followed by the same letter are not significantly different ($p < 0.05$).

In summary, for all fixed-rate drying tests without recirculating air, much more energy is consumed. Among 70, 80, and 90% recirculation rates in both peach drying tests, the average energy consumptions are not significantly different. In fixed-rate apple drying tests, the average energy consumption between 70 and 90%

recirculation rates are significantly different ($p<0.05$). Energy savings percentages calculated from Table 5.11 for each product are tabulated in Table 5.12. Drying time for both apple and peach tests were not affected by recirculation rates.

Table 5.12. Summary of energy savings by comparing 0% vs. 70, 80, and 90% air recirculation

Products	Energy Saved (%)
Apples	50 - 59
Sun High Peaches	46 - 62
Red Haven Peaches	52 - 66

Variable-Rate Drying Apples

During fixed-rate drying, the same recirculation rate was used throughout the drying process. Disadvantages of a fixed recirculation rate drying are:

1. When low recirculation rates are used, the air can become very dry as the drying process progresses. The surfaces of the product dry out quickly, and case hardening may occur.
2. When high recirculation rates are used, the air is very moist at the beginning of the process. This not only decreases the initial drying rate, but can also cause flavor change, color change, and mold growth under some conditions.

Variable-rate drying was accomplished by manually adjusting the recirculation damper during drying to control the humidity ratio of the drying air. Experimental data of energy consumption versus adjusted relative humidities and drying time versus recirculation rates are summarized in Figures 5.13 through 5.16. Corresponding numerical values are shown in Tables 5.13 and 5.14. In these Tables, letters, E, F, G, and H represent the designated relative humidities (r.h.). E represents no adjustment. F represents adjustments for 10% r.h. G represents adjustments for 20% r.h. H represents adjustments for 30% r.h. The analysis of covariance technique was also employed in this analysis. Results are tabulated in Table 5.15. It can be seen that there was a significant difference in total energy consumption when different variable recirculation rates are applied. The drying time was not affected by recirculation rates ($p > 0.05$) for the variable-rate drying tests. Thus it had no effect upon energy consumption. Table 5.16 compares energy consumptions and drying times for both fixed and variable rate drying of apples. As shown in Table 5.16, fixed-rate and variable-rate do not show significant differences in terms of drying time and energy consumption. This implies that for a fast drying product such as apple rings, the added complexity of variable rate drying is unnecessary. Thus, fixed recirculation rates can be used.

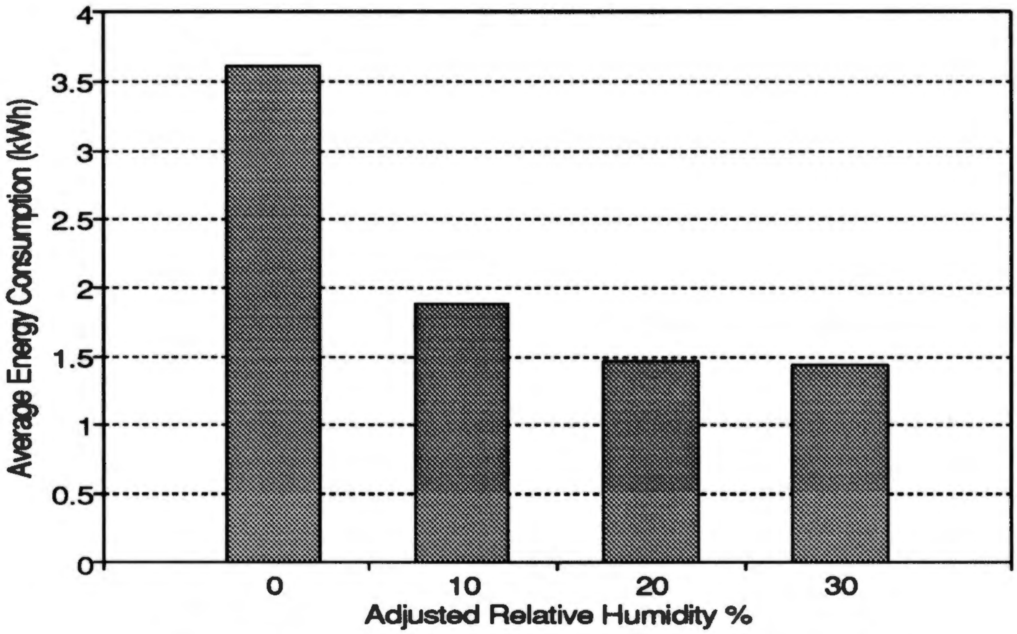


Figure 5.13. Effect of variable-rate air recirculation on the average energy consumption during apple drying.

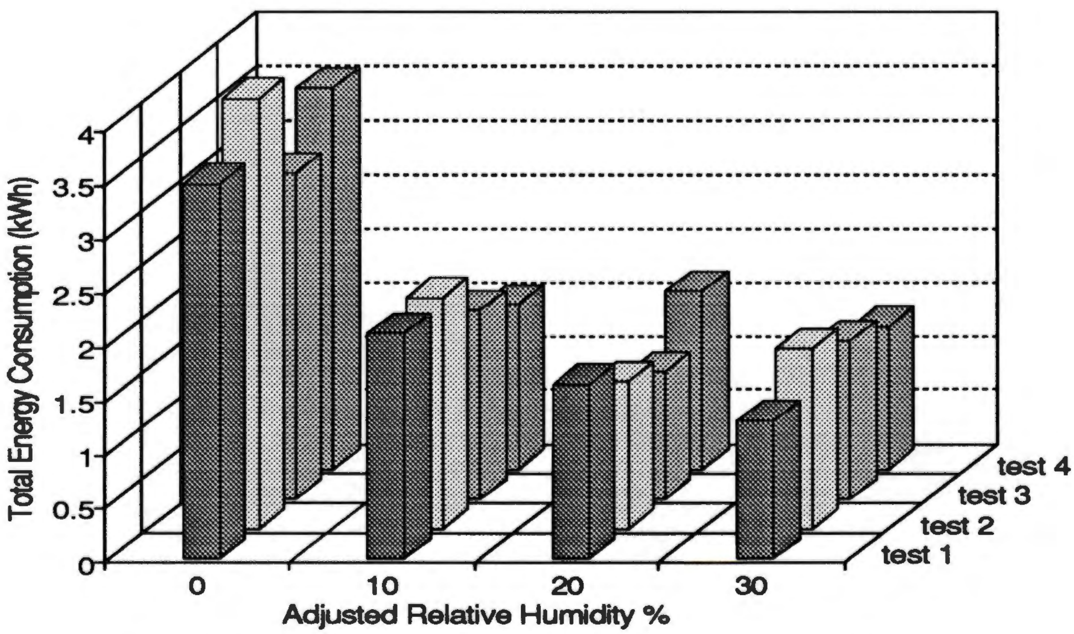


Figure 5.14. Effect of variable-rate air recirculation on the total energy consumption during apple drying (tests 1-4).

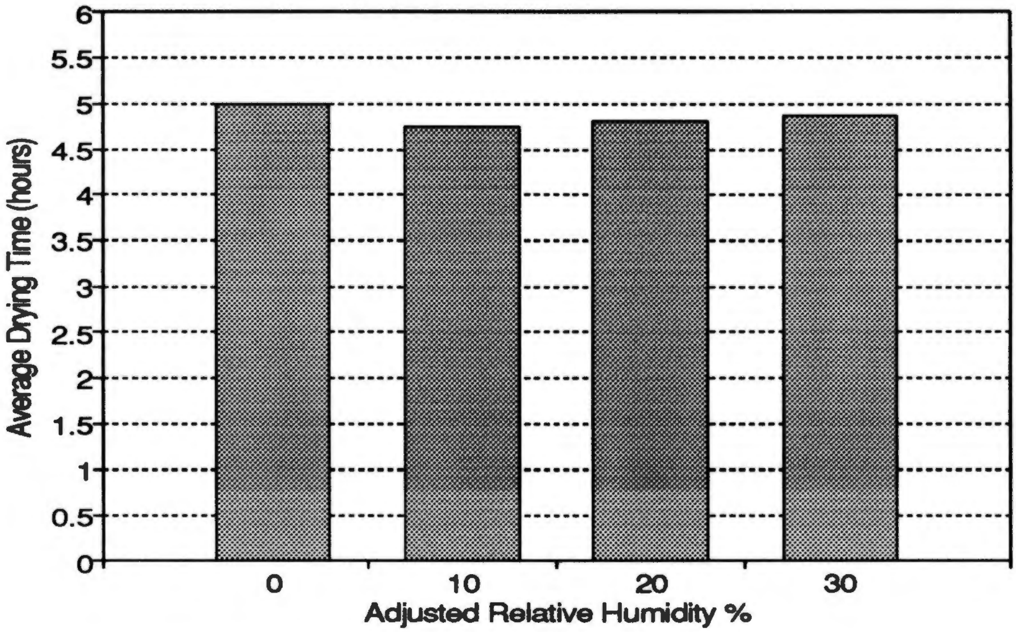


Figure 5.15. Effect of variable recirculated air on the average drying time.

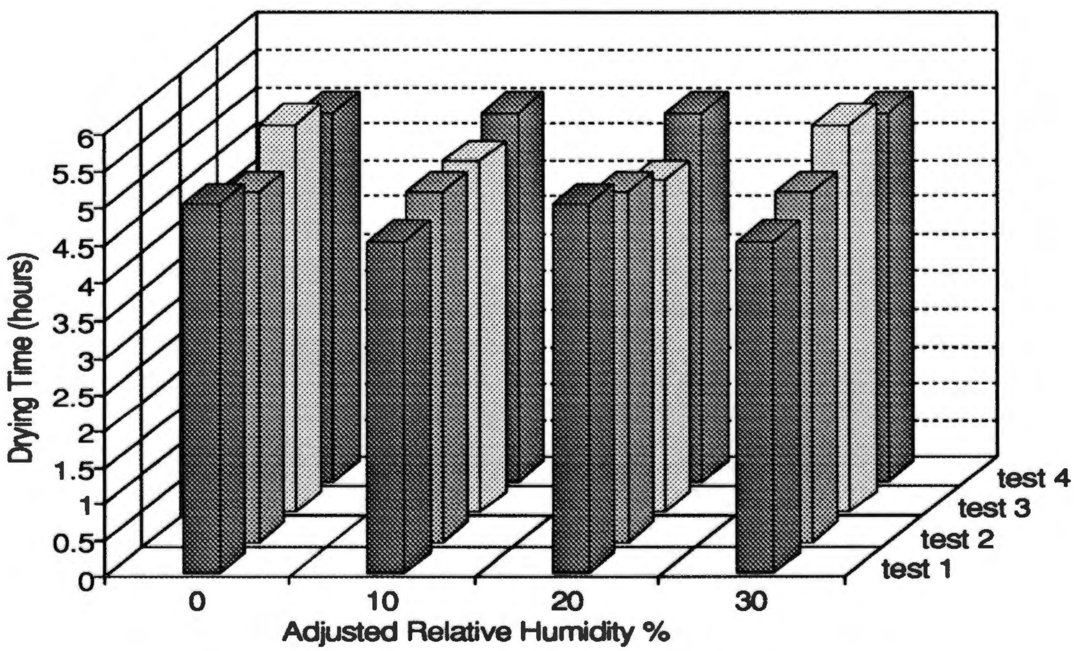


Figure 5.16. Effect of variable recirculated air on the drying time for tests 1-4.

Table 5.13. Total energy consumption during variable-rate drying of apples

Dehydrator	Energy Consumption (kWh)			
	Test1	Test2	Test3	Test4
1	E=3.48	F=2.15	H=1.46	G=1.66
2	F=2.09	E=4.39	G=1.18	H=1.32
3	H=1.28	G=1.36	E=3.03	F=1.52
4	G=1.62	H=1.68	F=1.75	E=3.54

Table 5.14. Total drying time for variable-rate drying of apples

Dehydrator	Drying Time (hours)			
	Test1	Test2	Test3	Test4
1	E=5.0	F=4.75	H=5.25	G=5
2	F=4.5	E=4.75	G=4.50	H=5
3	H=4.5	G=4.75	E=5.25	F=5
4	G=5.0	H=4.75	F=4.75	E=5

Table 5.15. Analysis of the effects of dehydrator, test, recirculation rate, and time on the energy consumption for red haven peach drying

Source	DF	Type III SS	F Value	Pr > F
Dehydrator	3	0.4872	2.18	0.2086
Test	3	0.5214	2.33	0.1909
Treatment	3	10.375	46.44	0.0004
Time	1	0.0035	0.05	0.8365

Table 5.16. Comparison of the average energy consumptions and drying times for both fixed and variable rates during apple drying.

	Drying Schedules	0%*	70%**	80%***	90%****
Energy Consumption (kWh)	Fixed-rate	3.28[a]	1.60[b]	1.50[b]	1.47[b]
	Variable-rate	3.61[a]	1.88[b]	1.46[b]	1.44[b]
Drying Time (hours)	Fixed-rate	5.00[c]	4.88[c]	4.86[c]	5.19[c]
	Variable-rate	4.81[c]	4.75[c]	4.81[c]	4.86[c]

Note: means followed by the same letter are not significantly different ($p < 0.05$).
* is no adjustment to relative humidity during variable-rate drying.
** is to adjust relative humidity to 10% during variable-rate drying.
*** is to adjust relative humidity to 20% during variable-rate drying.
**** is to adjust relative humidity to 30% during variable-rate drying.

MOISTURE DIFFUSION MODELS FOR DRYING

Drying Observations for All Tests

Experimental data for all tests are given in graphical and tabular form in Appendices A, B, C, and D. Weight ratio and time ratio are used to normalize the plots of apple and peach drying data. Weight ratio and time ratio are defined as:

$$weight\ ratio = \frac{wt_\theta}{wt_0} \tag{5.1}$$

and

$$time\ ratio = \frac{t_\theta}{t_{total}} \tag{5.2}$$

where

wt_θ is the fruit weight at any time during drying, g,

wt_0 is the fruit initial weight, g,

t_θ is the drying time corresponding to wt_θ for any recirculation rate,

t_{total} is the total drying time for each recirculation rate.

Selected weight ratio versus time ratio curves for drying apple slices and peach halves are shown in Figures 5.17 through 5.20. Two tests in apple drying showed variations for a single treatment (Appendix A, Figures A-2 and A-4). In test 1, the 0% recirculation showed more rapid drying than all other treatments, while the 90% recirculation rate exhibited slower drying than other treatments in test 3.

In all tests, the heaters were turned on when all fruit trays were loaded into the dehydrators. A few minutes were needed to heat the air and products to the designated temperature. Thus, there was a brief delay before the drying process began. Peach halves required about 35 hours to dry. Thus, a few minutes delay had no visible effect upon peach drying curves. Since the total drying time for apple rings was only about 5 hours, this delay is clearly visible in apple drying curves (Figures A-2 through A-5, and D-1 through D-4). Thus, the apple drying data were adjusted by subtracting 6 minutes from all drying times following startup. The effect of this adjustment applied to apple drying data is shown in Figure A-1. The adjusted data were used in all apple drying analyses and are reflected in the curves of Figures 5.21 through 5.30. All remaining figures present the unadjusted data.

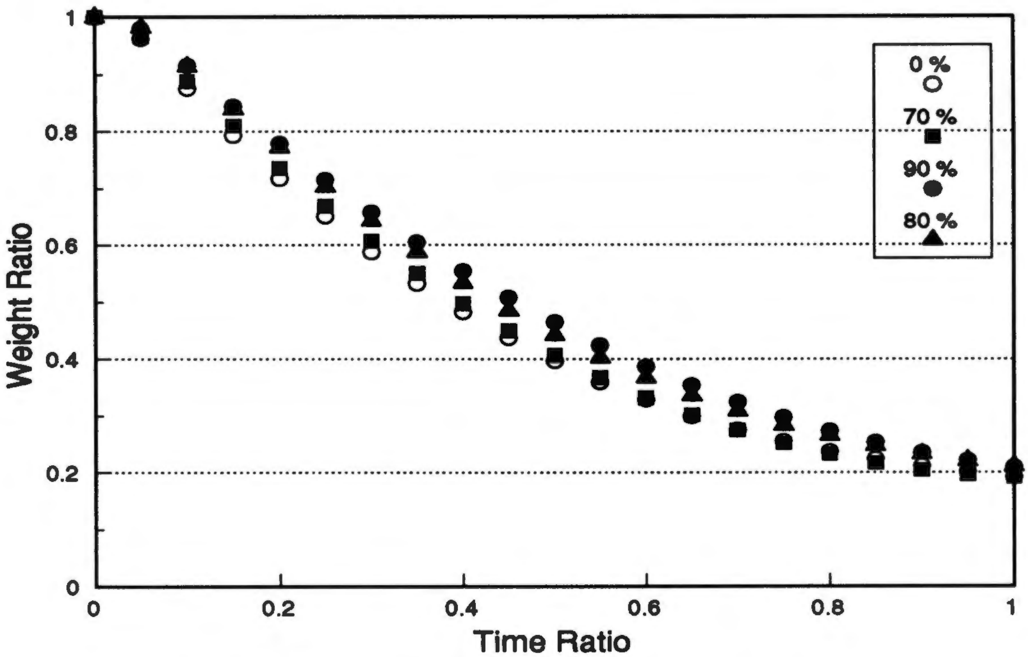


Figure 5.17. Effect of fixed-rate recirculated air on the moisture removal from apples (test 2).

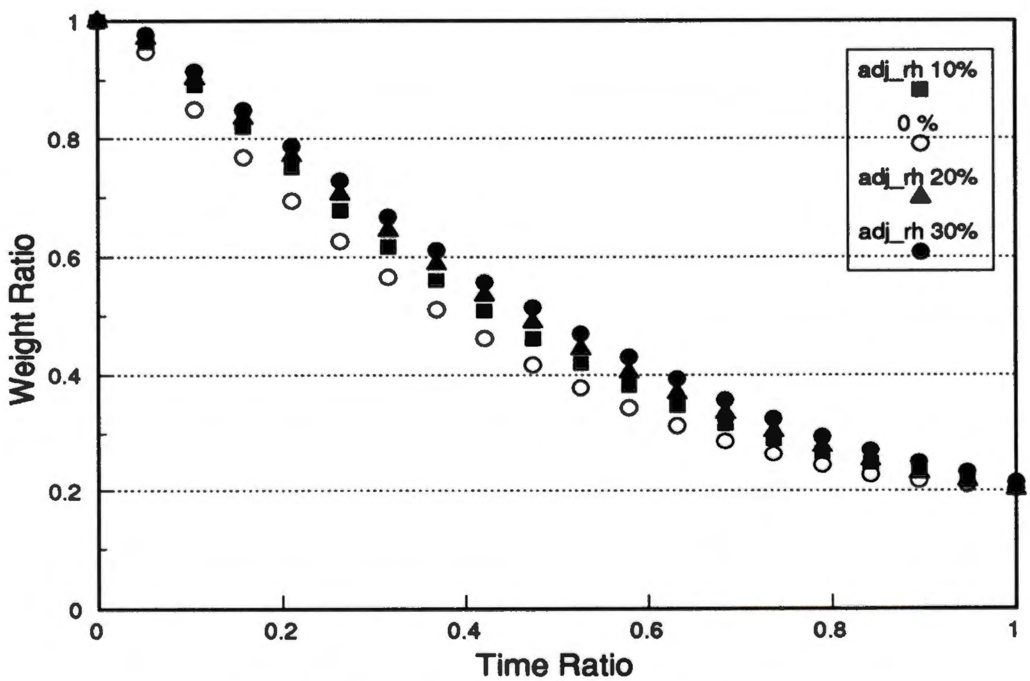


Figure 5.18. Effect of variable recirculation rates on moisture removal from apples (test 2).

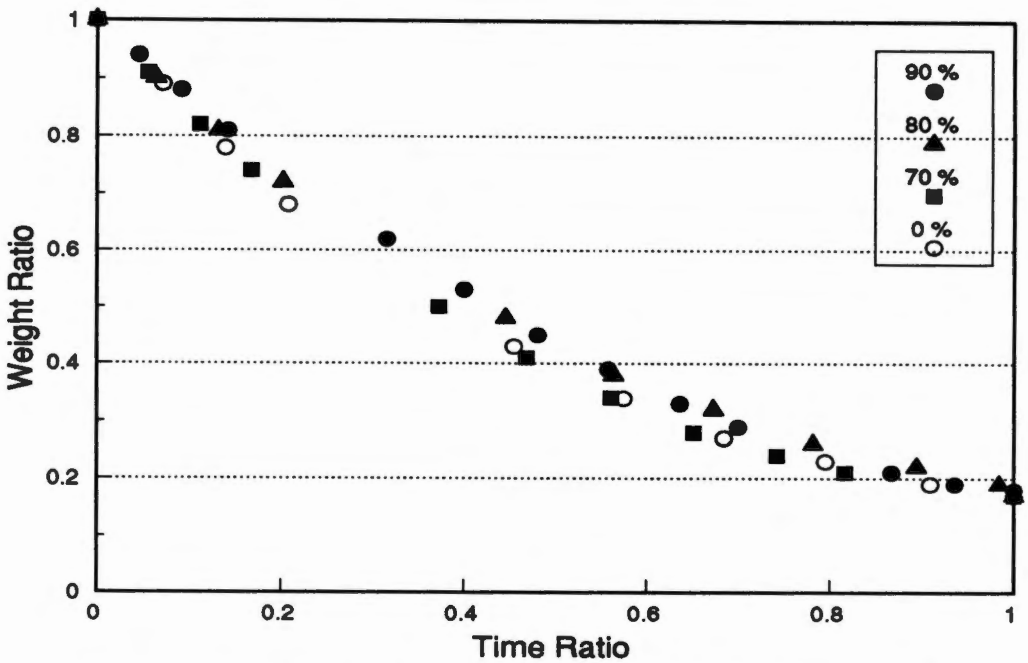


Figure 5.19. Effect of recirculated air on the moisture removal for Sun High peaches (test 2).

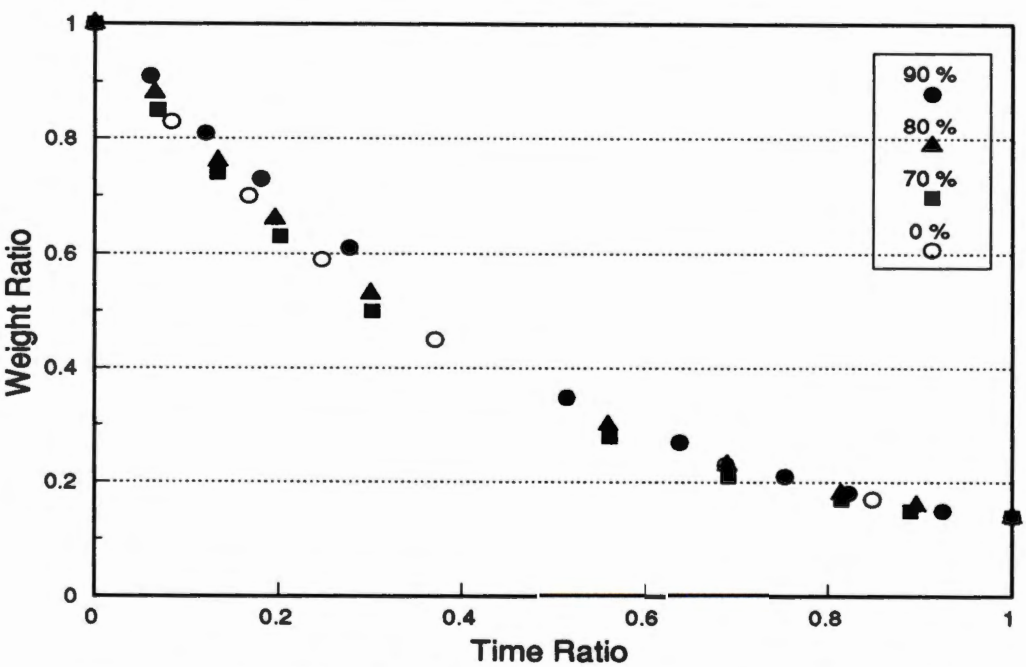


Figure 5.20. Effect of recirculated air on the moisture removal for Red Haven peaches (test 2).

Evaluation of Parameters for Apple Drying

The experimental data plots indicate small differences in drying rate due to different recirculation rates. To reduce the model residual errors, the experimental data were rearranged for further analyses. The rearranged data grouped together the same recirculation rates from the four tests. The moisture diffusion model of Equation 3.49 was then applied to each individual recirculation rate. Moisture ratio and drying time in the Equation 3.49 was expressed in the dimenssionless forms of weight ratio (wt_θ/wt_0) and time ratio (t_θ/t_{total}). Equation 3.49 thus can be rewritten as:

$$\frac{wt_\theta}{wt_0} = A\, e^{-\left(\frac{1}{q^2}+\frac{1}{l^2}\right)\pi^2 B \frac{t_\theta}{t_{total}}} \tag{5.3}$$

where

- A is a coefficient,
- B is an exponent,
- t_{total} is the total drying time for each recirculation rate, hour,
- q is apple ring thickness (5 mm).

To improve the model's precision, the startup delays (approximately 6 minutes for fixed and variable rate apple drying) were subtracted from drying time. This was the approximate time required to reach operating temperature after the dehydrators were loaded. Graphical comparison of the adjusted and unadjusted data are shown in Appendix A, Figure A-1. This adjustment resulted in no change or only minor changes to the resulting regression equations.

In Chapter 3, the apple ring was assumed to be a plane sheet with length l and thickness q. The average apple ring width (l=45 mm) is used as the plane sheet length, while the initial thickness (q) was 5 mm. In Equation 5.3, weight ratio was used as the dependent variable. By examining Equation 5.3, when time is 0 (or time ratio is 0), weight ratio must be 1. Thus, the coefficient A must be 1. The exponent B in Equation 5.3 must be determined from the experimental data. The exponent can be estimated by fitting the logarithmic form:

$$\log\left(\frac{wt_\theta}{wt_0}\right) = -B\left(\frac{1}{q^2} + \frac{1}{l^2}\right)\pi^2 \frac{t_\theta}{t_{total}} \qquad (5.4)$$

to the experimental data. To further simplify the analyses, Equation 5.3 may be reduced to diffusion in one direction for apple ring drying. As the drying process progresses, the thickness of apple rings becomes very small. Comparing diffusion in the q direction (thickness) and in the l direction (length), l is much larger than q. In fact, the q term of Equation 5.4 contributes 99 percent of the magnitude of $(1/q^2+1/l^2)$ in the equation. Therefore, it is reasonable to consider moisture diffusion in an apple ring is in the thickness direction only. Equation 5.3 then becomes:

$$\frac{wt_\theta}{wt_0} = e^{-B\left(\frac{\pi}{q}\right)^2 \frac{t_\theta}{t_{total}}} \qquad (5.5)$$

The exponent B in Equation 5.5 must be determined from the experimental data. The exponent was estimated by fitting the logarithmic form:

$$\log\left(\frac{wt_\theta}{wt_0}\right) = -B\left(\frac{\pi}{q}\right)^2 \frac{t_\theta}{t_{total}} \tag{5.6}$$

to the experimental data by the method of least squares using Quattro Pro Software (Borland, 1987). Equation 5.5 was found to fit the experimental data very well. The values of B with the associated coefficients of determination R^2 for each recirculation rate are shown in Tables 5.17 and 5.18.

Table 5.17. Coefficients and exponents for the empirical moisture transfer equation (5.5) along with the coefficient of determination R^2 during fixed-rate drying of apples

Recirculation Rates (%)	R^2	B
0	0.984	4.40
70	0.986	4.23
80	0.993	4.15
90	0.977	3.99

Table 5.18. Coefficients and exponents for the empirical moisture transfer equation (5.5) along with the coefficient of determination R^2 during variable-rate drying of apples

Adjusted Relative Humidity %	R^2	B
0	0.993	4.28
10	0.996	4.06
20	0.995	4.02
30	0.976	3.92

The predicted drying curves along with experimental data for both fixed and variable rate apple drying are presented in Figures 5.21 through 5.28. The exponent B is related to the recirculation rates, and controls the curvature of the drying curves. Based upon regression analysis using SAS (SAS, 1985), the B values within Table 5.17 and within Table 5.18 are not significantly different. The constant values of B implies that the recirculation rates do not affect the drying rate. Curves representing Equation 5.5 are shown in Figures 5.29 and 5.30. In fact, the B values in both Tables 5.17 and 5.18 are not significantly different ($p > 0.05$). This means that the drying rates for fixed recirculation and variable recirculation were not significantly different in this study.

The exponent B, as discussed above is a dimensionless coefficient. The moisture diffusivity can be determined by plotting experimental drying data in terms of $ln(wt_\theta/wt_0)$ versus $(\pi^2/q^2)t$ (Okos et al, 1992). The slope of the linear segments yields the effective diffusion coefficient (D_e). For 0% and 90% recirculation rates, D_e were 1.5×10^{-8} and 1.3×10^{-8} m^2/s respectively (Figures 5.31 and 5.32). These values of moisture diffusivity are much larger than the published value for apple (D_e=6.4×10^{-9} at T=66°C, Sarvacos and Charm, 1962). However, the published values are based upon the falling-rate portion of the drying process. The values determined in this study are larger than the published values because they take into account the entire drying process, including the constant rate drying during the initial drying period. Data plotted in Figures 5.31 and 5.32 show that the diffusivity would be substantially lower if only the last few points of the drying data are considered.

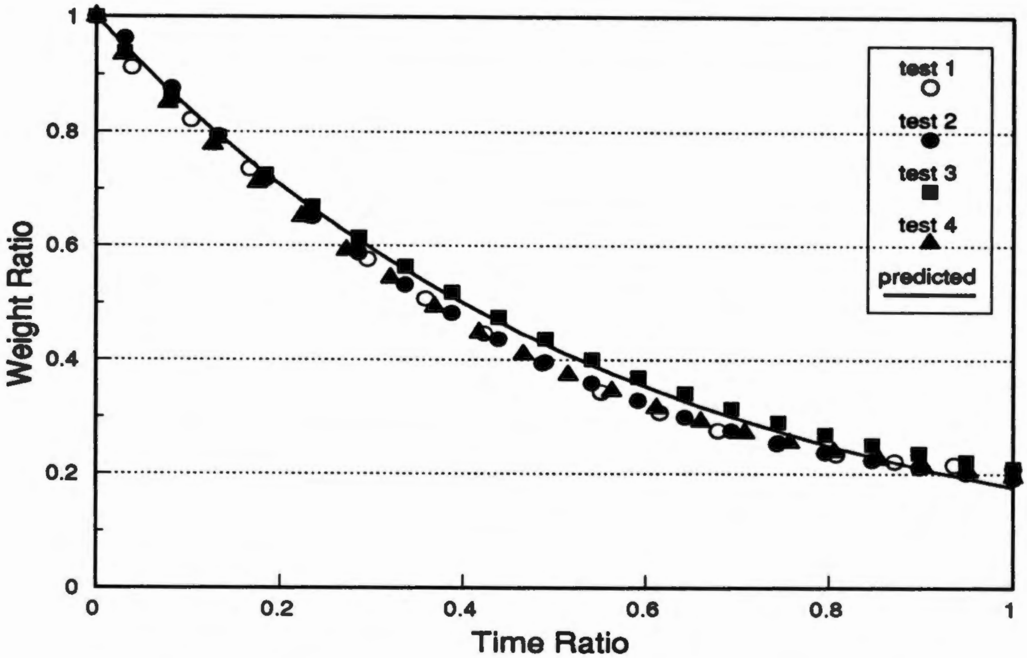


Figure 5.21. The predicted moisture loss curve along with the experimental data at 0% fixed recirculation rate for apples (R^2=0.984).

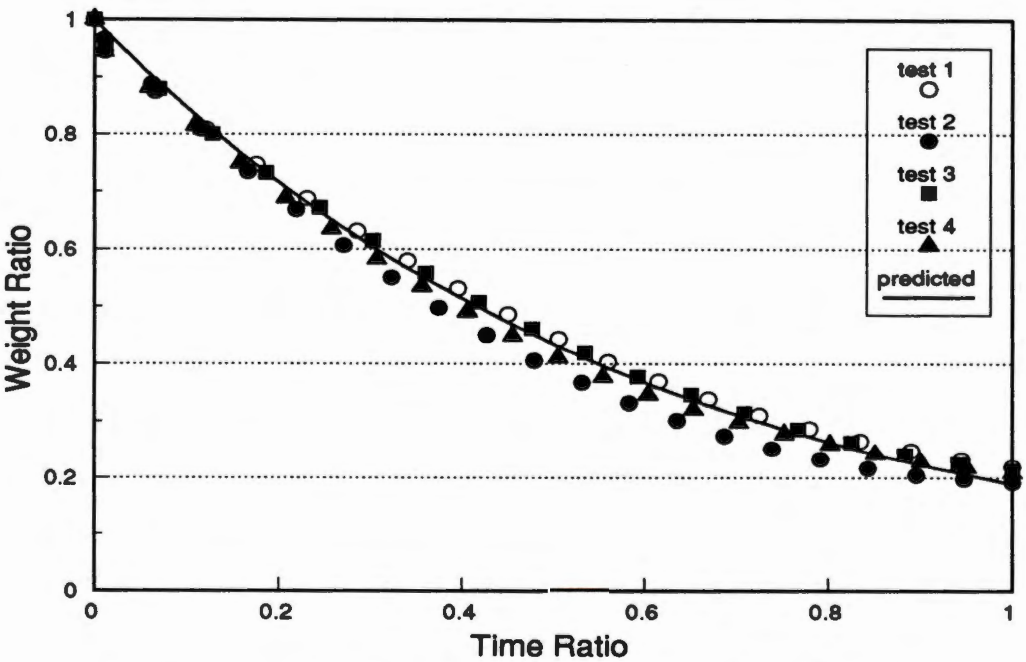


Figure 5.22. The predicted moisture loss curve along with the experimental data at 70% fixed recirculation rate for apples (R^2=0.986).

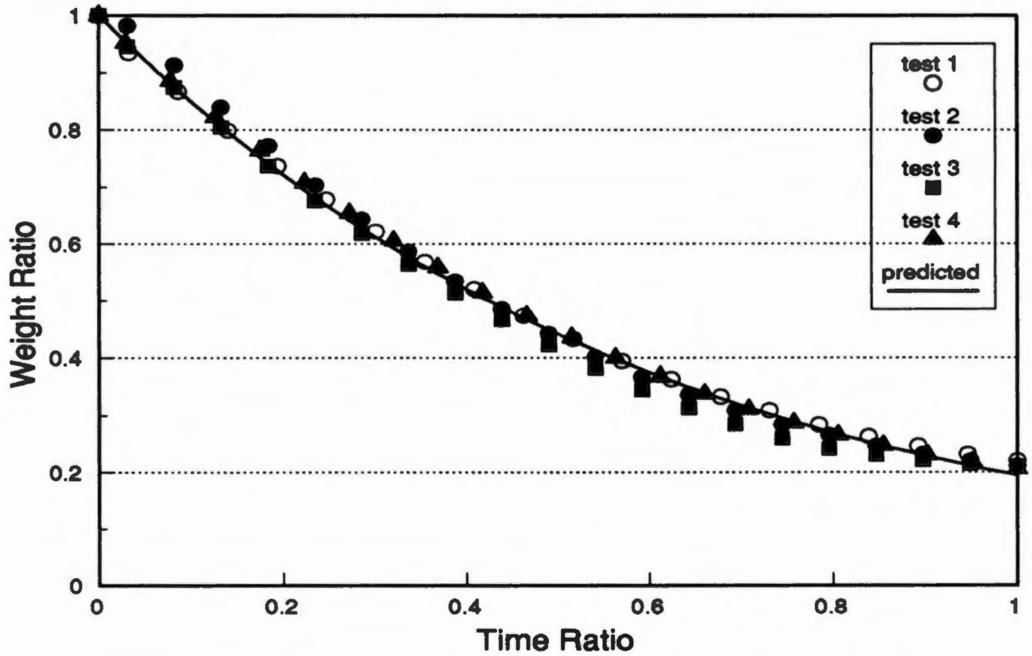


Figure 5.23. The predicted moisture loss curve along with the experimental data at 80% fixed recirculation rate for apples (R^2=0.993).

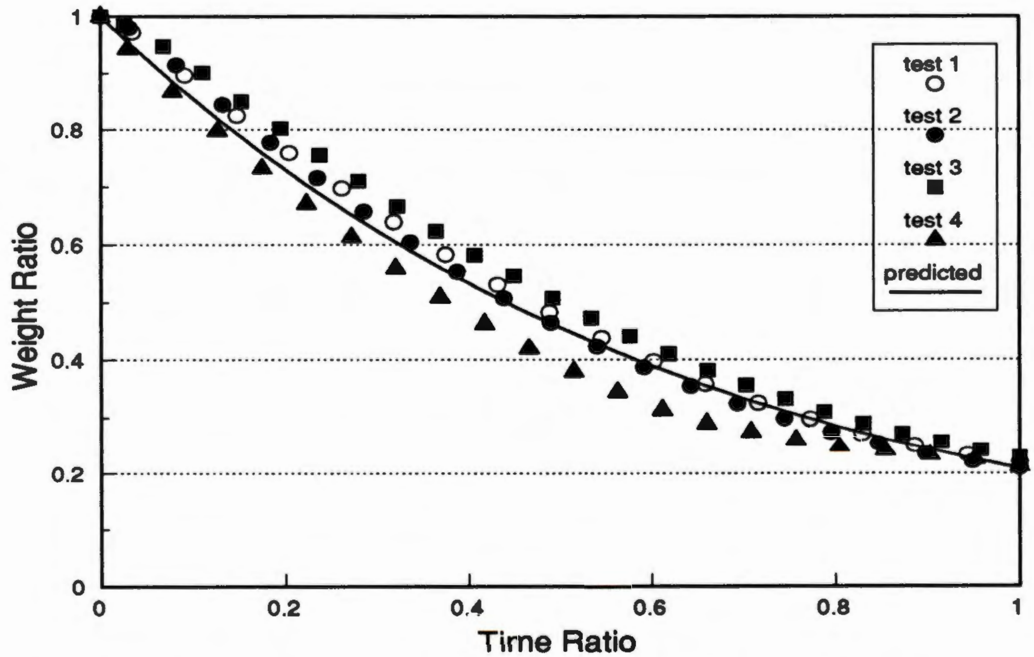


Figure 5.24. The predicted moisture loss curve along with the experimental data at 90% fixed recirculation rate for apples (R^2=0.977).

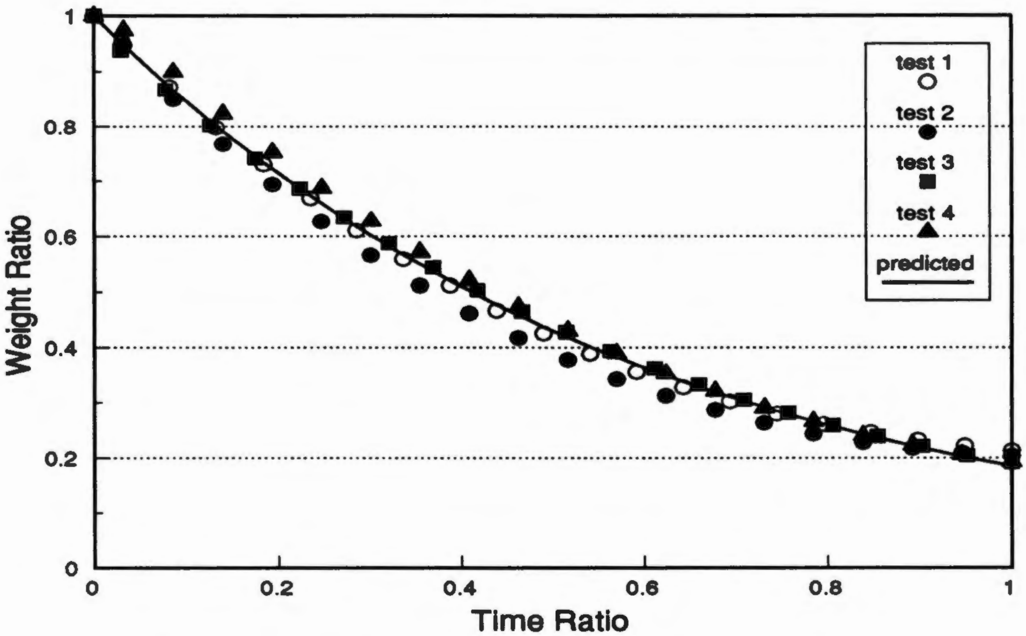


Figure 5.25. The predicted moisture loss curve along with the experimental data during variable-rate apple drying (started at 0%, no adjustment to relative humidity, R^2=0.993).

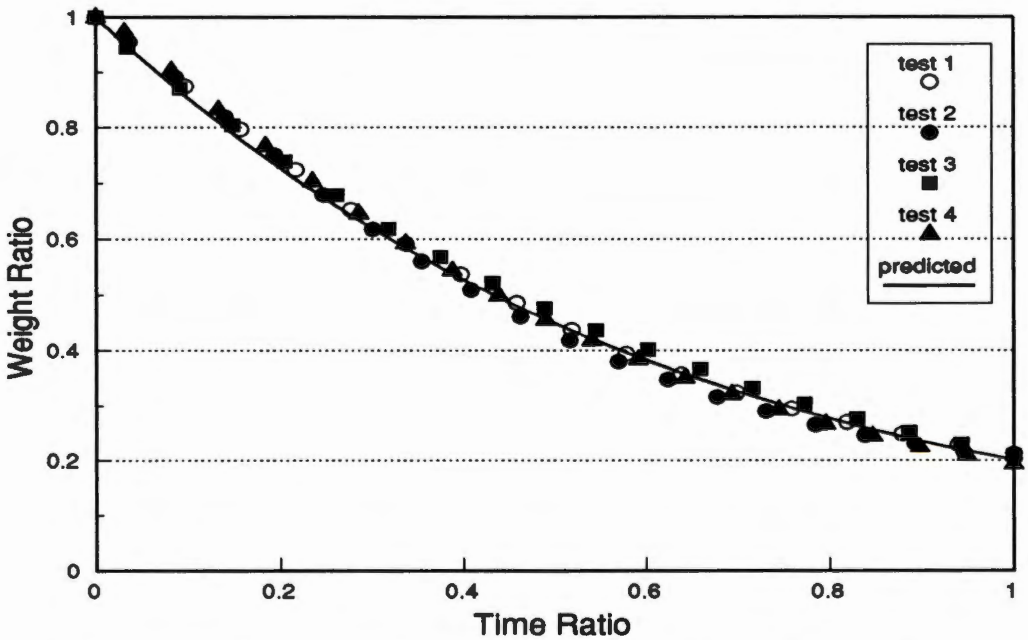


Figure 5.26. The predicted moisture loss curve along with the experimental data during variable-rate apple drying (started at 70%, adjusting relative humidity of 10%, R^2=0.996).

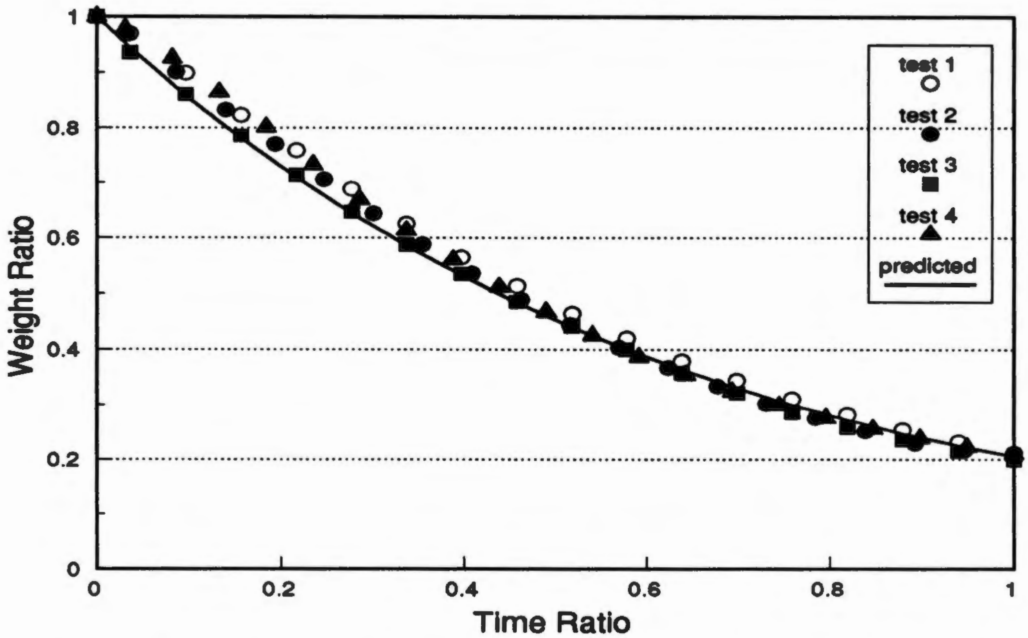


Figure 5.27. The predicted moisture loss curve along with the experimental data during variable-rate apple drying (started at 80%, adjusting relative humidity of 20%, R^2=0.995).

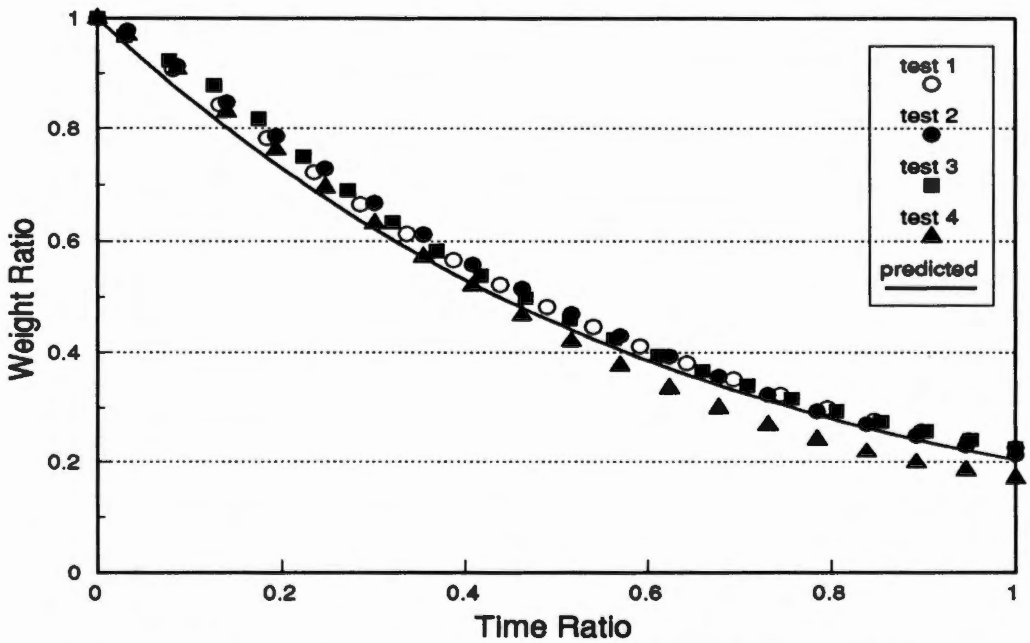


Figure 5.28. The predicted moisture loss curve along with the experimental data during variable-rate apple drying (started at 90%, adjusting relative humidity of 30%, R^2=0.976).

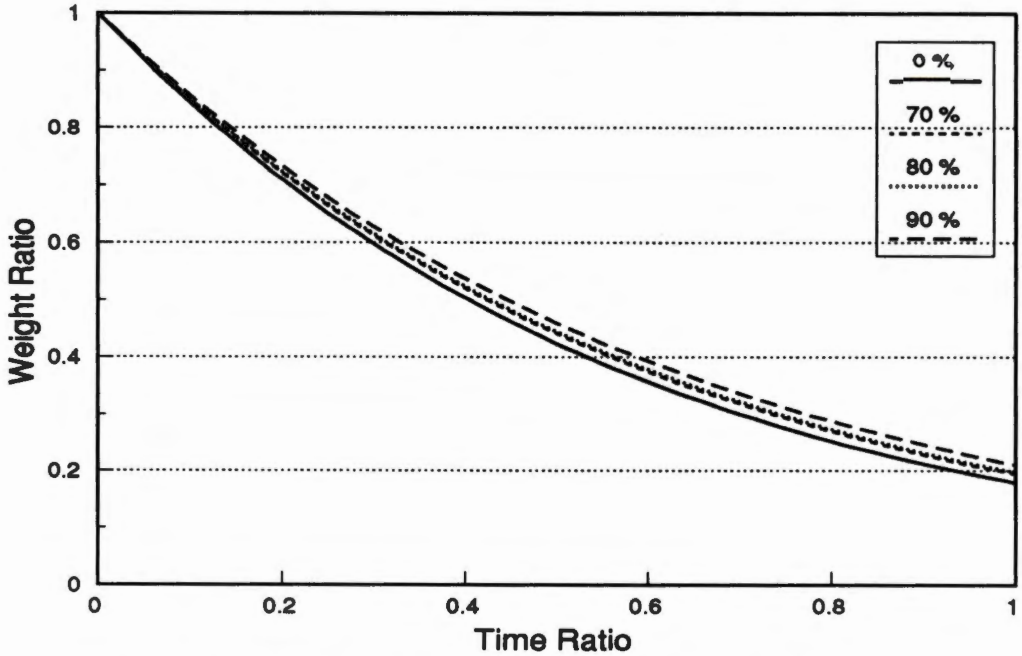


Figure 5.29. Predicted moisture loss curves for drying apples (fixed-rate).

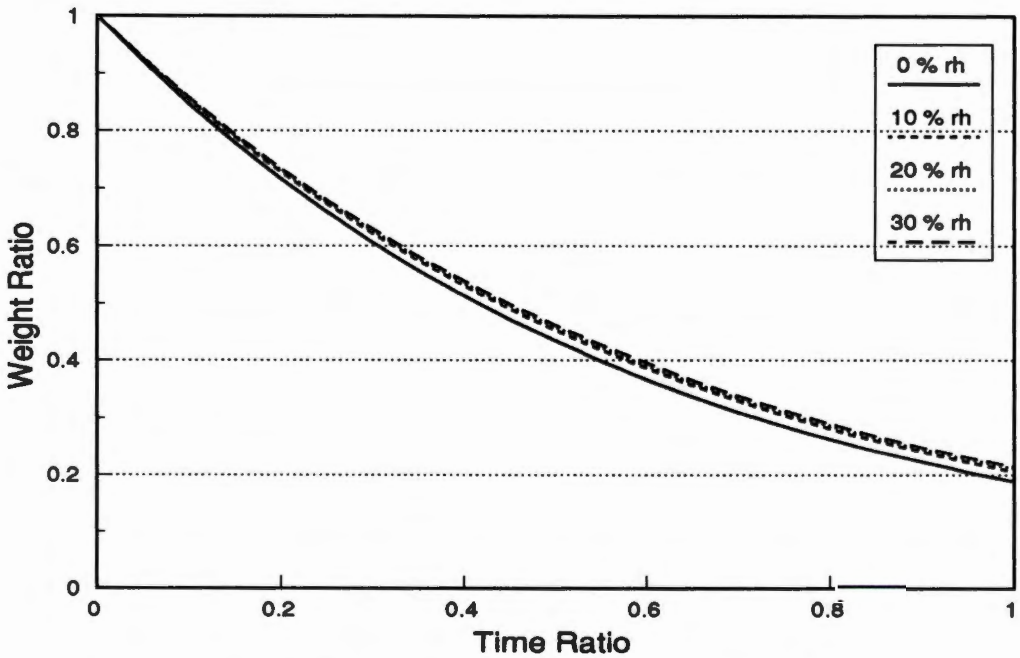


Figure 5.30. Predicted moisture loss curves for drying apples (variable-rate).

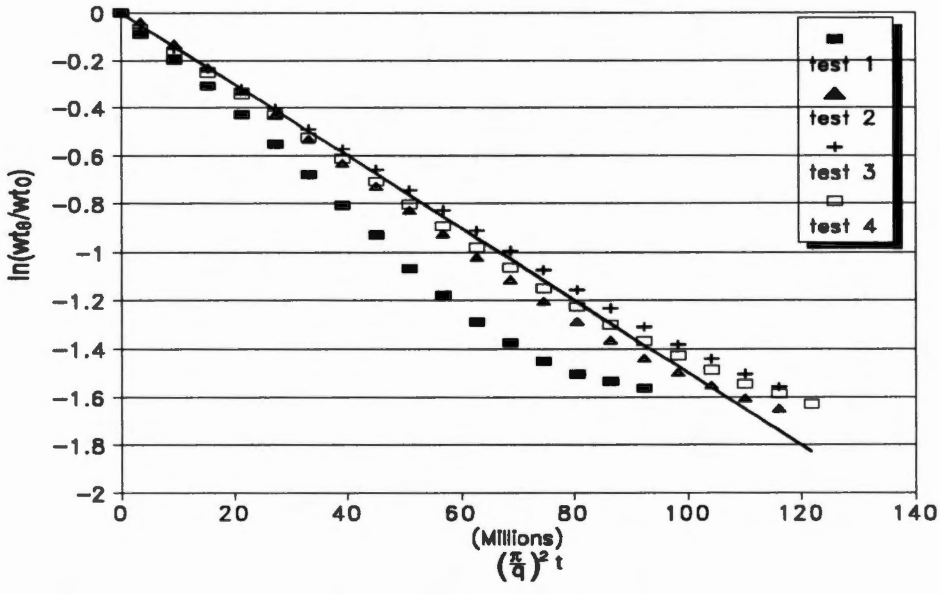


Figure 5.31. 0% fixed recirculation rate during apple drying test (D_e=-1.5 x 10^{-8} m^2/s, R^2=0.948).

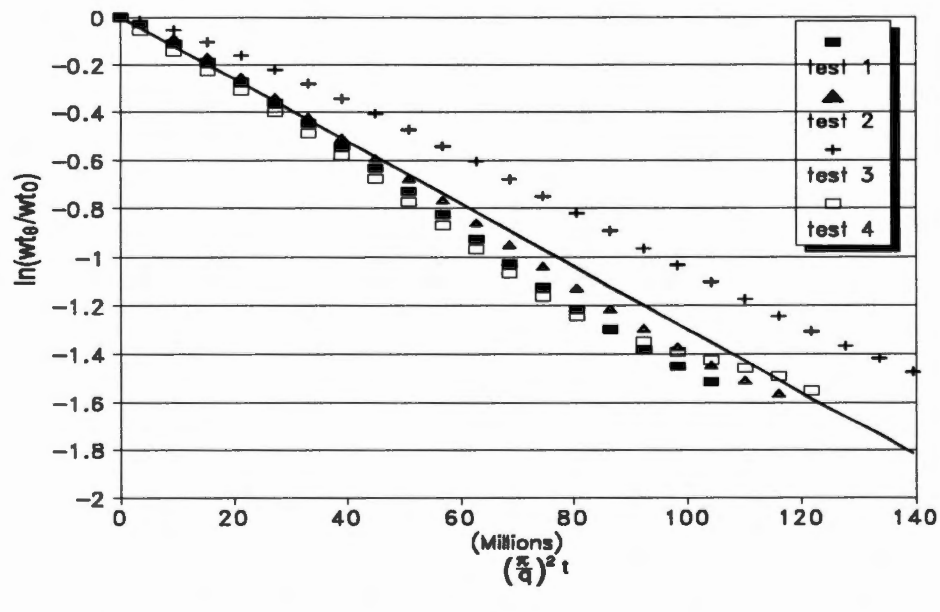


Figure 5.32. 90% fixed recirculation rate during apple drying test (D_e=-1.3 x 10^{-8} m^2/s, R^2=0.923).

Evaluation of Parameters for Peach Drying

During peach drying experiments, peaches were cut into halves as shown in Figure 5.33. Since skin cells and cells near the skin are very dense (Charley, 1970), they act as a barrier to moisture diffusion. Drying occurs much more readily through the cut surface. Therefore, it is reasonable to assume that most moisture diffusion in

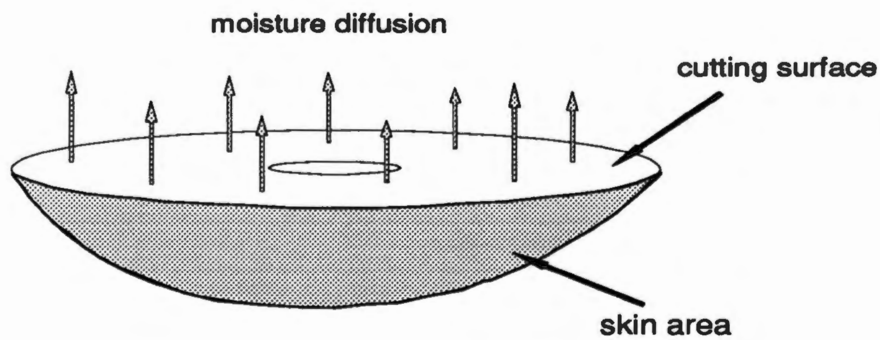


Figure 5.33. Moisture diffusion in a peach half.

a peach half is in one direction. It is further assumed that as the drying process progresses, the peach half approaches the shape of a slab. Therefore, Equation 3.49 was also applied to peach drying. The thickness for Sun High variety was taken as 3.5 cm (the average radius) and for Red Haven variety, 3.1 cm (the average radius). Equation 3.49 becomes:

$$\frac{wt_\theta}{wt_0} = A\, e^{-B\left(\frac{\pi}{q}\right)^2 \frac{t_\theta}{t_{total}}} \tag{5.7}$$

where

A is a coefficient,

B is an exponent.

As for apple drying, the coefficient A is 1 and exponent B is to be determined from the experimental data. Equation 5.7 is also estimated by fitting the logarithmic form:

$$\log\left(\frac{wt_\theta}{wt_0}\right) = -B\left(\frac{\pi}{q}\right)^2 \frac{t_\theta}{t_{total}} \tag{5.8}$$

to the experimental data by the method of least squares using Quattro Pro software (Borland, 1987). The values of B with the associated coefficients of determination R^2 for each recirculation rate are shown in Tables 5.19 and 5.20. The predicted moisture loss curve along with the experimental data for peach drying are shown in Figures 5.34 through 5.41. The prediction curves for all recirculation rates are combined on a single graph for each variety in Figures 5.42 and 5.43.

The air velocity and the drying temperature were maintained constant during all drying tests. The major remaining factor affecting moisture removal is air recirculation rate. Therefore, the exponent B is a function of recirculation rate. Tables 5.19 and 5.20 indicate that the exponent B did not vary greatly from one recirculation rate to another. By performing regression analysis using SAS (SAS,

Table 5.19. Coefficients and exponents for the empirical moisture transfer equation (5.7) along with the coefficient of determination R^2 during Sun High peach drying

Recirculation Rates (%)	R^2	B
0	0.983	2.45
70	0.983	2.41
80	0.968	2.38
90	0.978	2.38

Table 5.20. Coefficients and exponents for the empirical moisture transfer equation (5.7) along with the coefficient of determination R^2 during Red Haven peach drying

Recirculation Rates (%)	R^2	B
0	0.994	2.00
70	0.977	2.07
80	0.996	2.01
90	0.990	2.06

1985), it was found that exponent B was not significantly affected by the recirculation rates in the peach drying tests. The parameter evaluation indicated that recirculation rates did not affect the drying rates in this study.

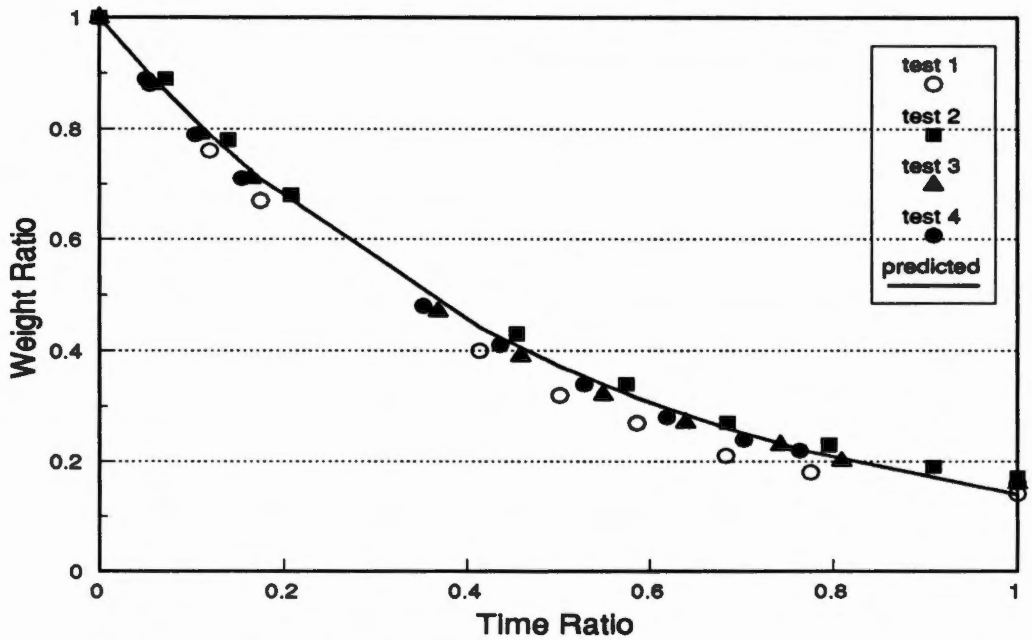


Figure 5.34. The predicted moisture loss curve along with the experimental data at 0% recirculation rate during Sun High peach drying (R^2=0.983).

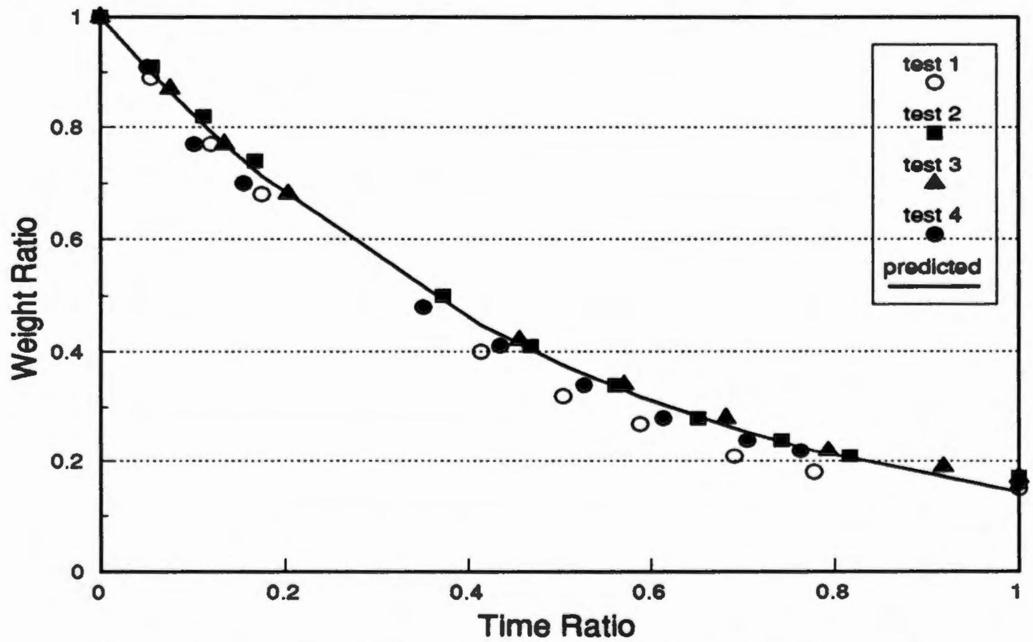


Figure 5.35. The predicted moisture loss curve along with the experimental data at 70% recirculation rate during Sun High peach drying (R^2=0.983).

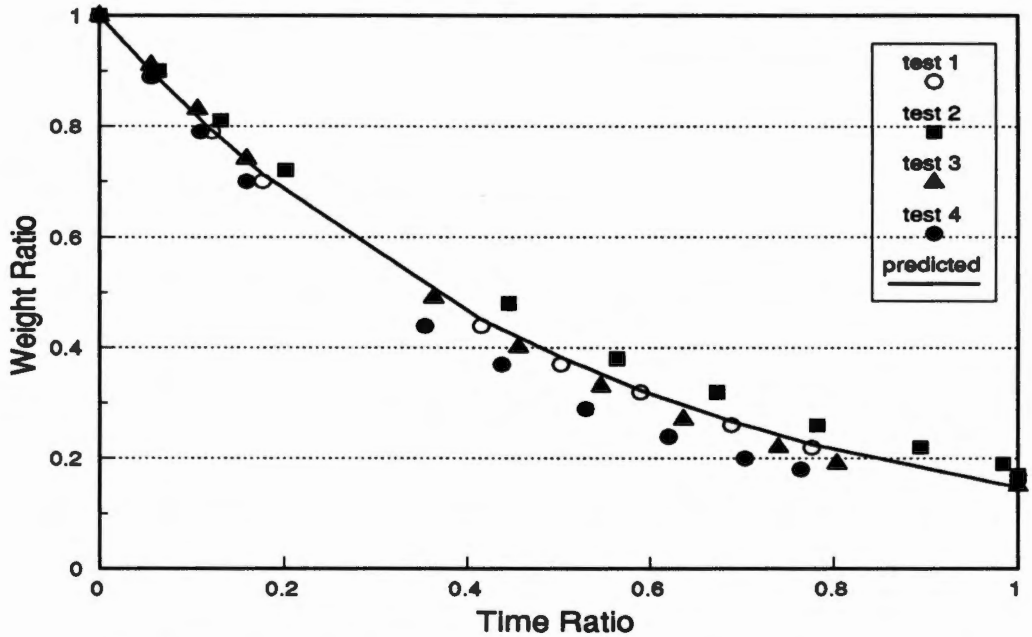


Figure 5.36. The predicted moisture loss curve along with the experimental data at 80% recirculation rate during Sun High peach drying (R^2=0.968).

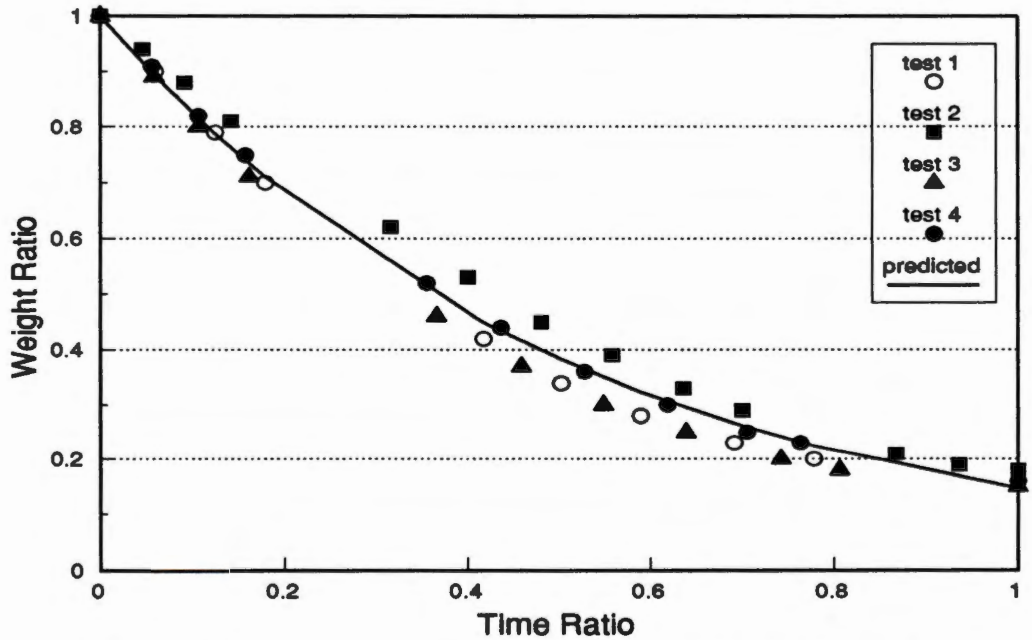


Figure 5.37. The predicted moisture loss curve along with the experimental data at 90% recirculation rate during Sun High peach drying (R^2=0.978).

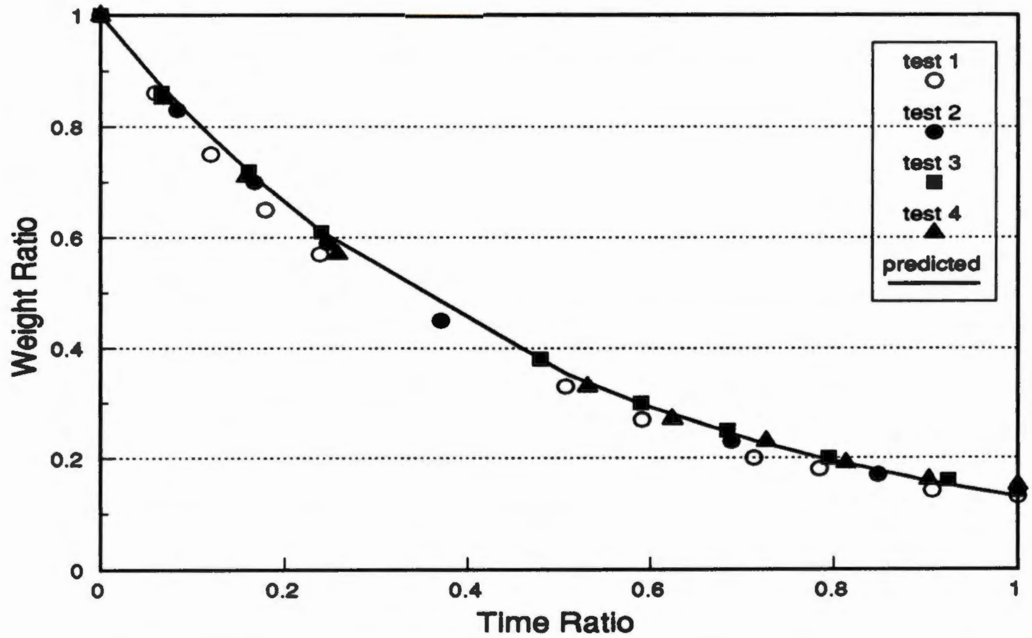


Figure 5.38. The predicted moisture loss curve along with the experimental data at 0% recirculation rate during Red Haven peach drying (R^2=0.994).

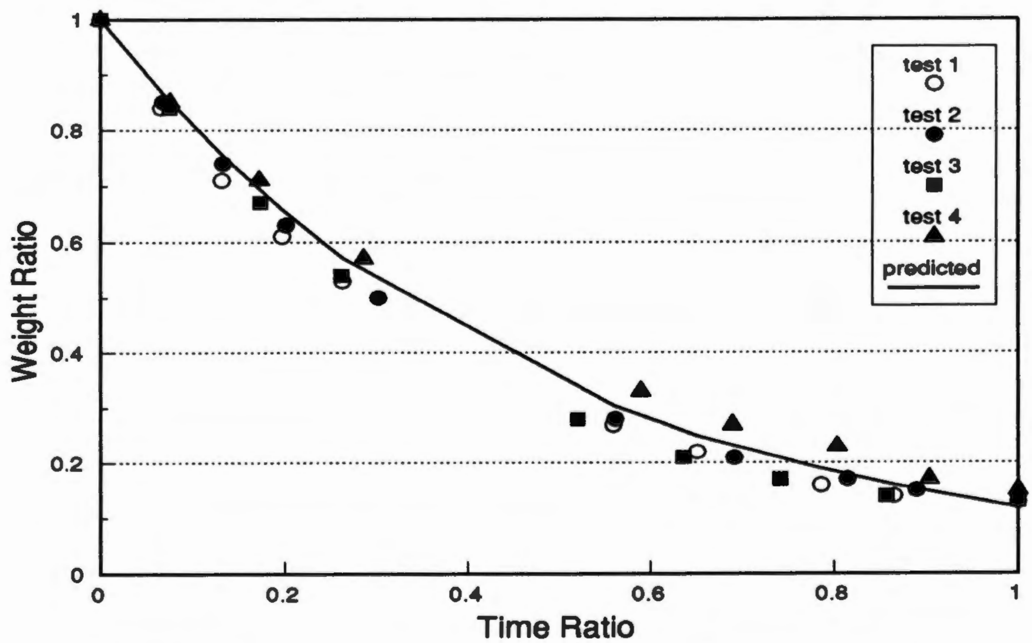


Figure 5.39. The predicted moisture loss curve along with the experimental data at 70% recirculation rate during Red Haven peach drying (R^2=0.977).

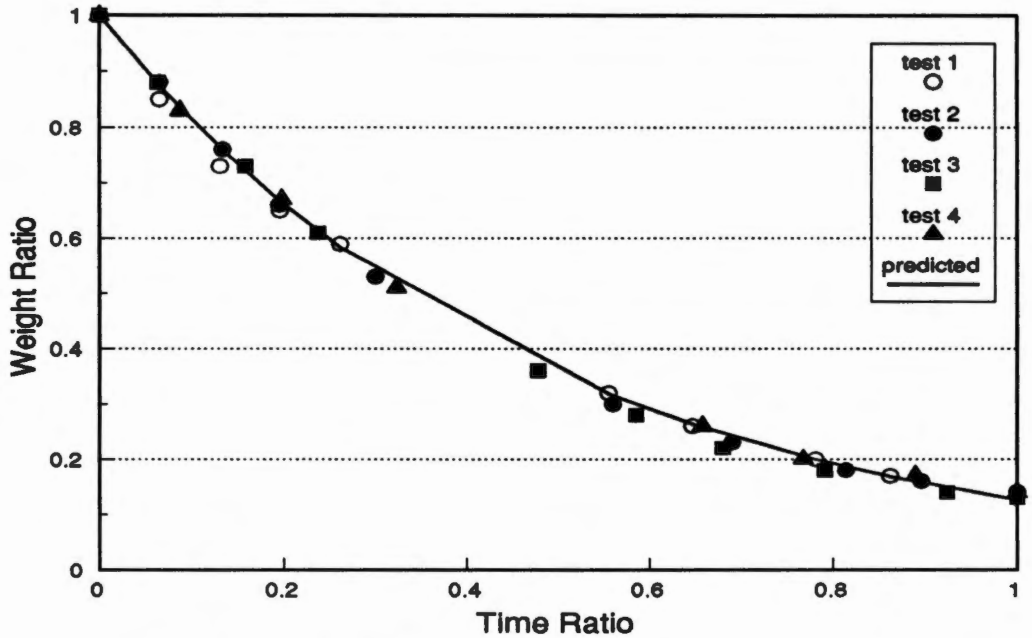


Figure 5.40. The predicted moisture loss curve along with the experimental data at 80% recirculation rate during Red Haven peach drying (R^2=0.996).

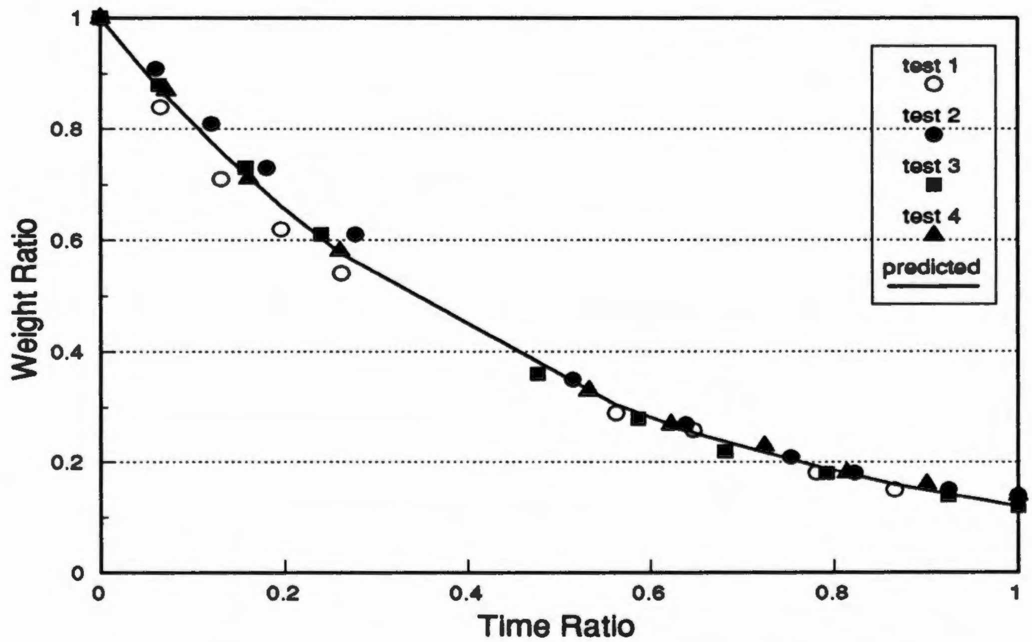


Figure 5.41. The predicted moisture loss curve along with the experimental data at 90% recirculation rate during Red Haven peach drying (R^2=0.99).

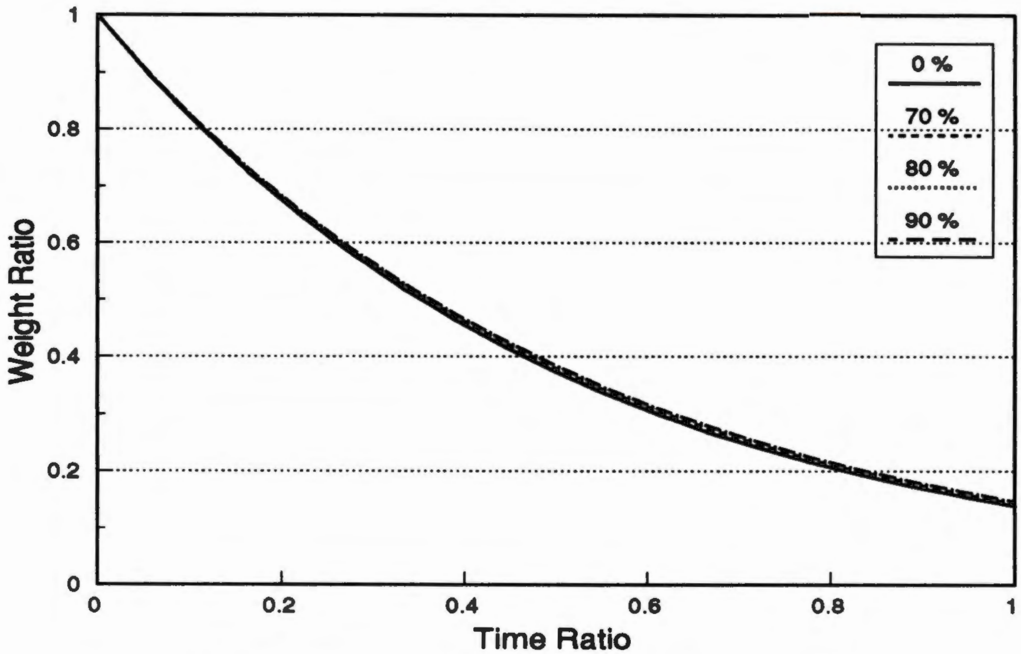


Figure 5.42. Predicted moisture loss curves for drying Sun High peaches.

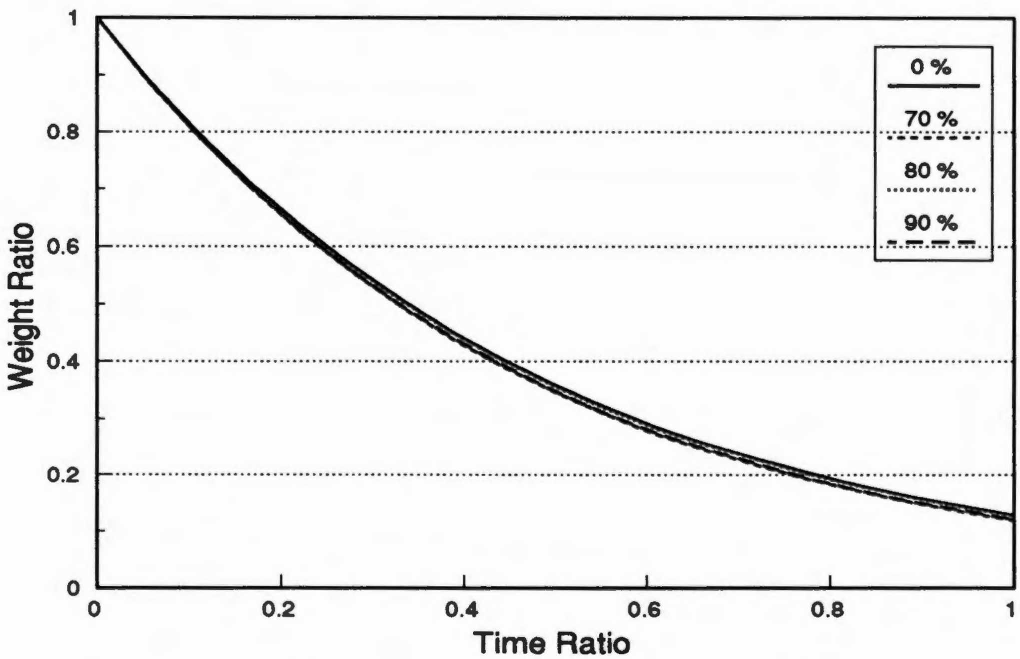


Figure 5.43. Predicted moisture loss curves for drying Red Haven peaches.

Energy consumption and drying rate were evaluated for both apple and peach drying. The experimental data show two significant findings:

1. The 0% recirculation rate required much more energy to dry fruit to the target moisture content than recirculation rates of 70, 80, and 90%. Recirculation rates of 70, 80, and 90% were not significantly different in energy consumption.
2. The total drying times were nearly the same for all recirculation rates for all apple drying tests and for all peach drying tests.

The 70 and 80% recirculation rates always showed similar energy savings and drying times, while the 90% recirculation rate sometimes performed erratically. Based upon the results of this study, there appears to be no advantage to variable rate recirculation. A fixed recirculation rate of up to 80% appears acceptable for apple drying. This could produce energy savings of up to 50%. Peach drying requires a much longer process time and involves significantly greater moisture removal. All tests with 70% and 80% recirculation rates produced comparable results. Additionally, energy savings for 70% and 80% recirculation were similar. Thus, selecting the 70% recirculation rate as the preferred level for peach drying allows an additional safety factor during adverse drying conditions. Energy savings at the 70% recirculation would be approximately 46%.

CHAPTER 6

SUMMARY AND CONCLUSION

SUMMARY

An air recirculation system was used to reduce energy cost for batch food dehydration. Advantages for using recirculation air include reducing drying cost and preventing casehardening. This study tested fixed and variable recirculation rates up to 90%, and evaluated the effects of air recirculation rates on energy consumption and drying rate for fruit materials such as apples and peaches. The major objective of the evaluation was to determine a reasonable drying schedule such that maximum energy savings could be achieved without decreasing drying rates.

Apples and two varieties of peaches were dried using fixed-rates of 0, 70, 80, and 90%. Variable-rate drying was applied to apple drying only. In variable-rate drying, air recirculation rates began with the same four rates. After one hour of drying, the dampers were adjusted to maintain designated relative humidity. Apple drying took approximately 5 hours, while peach drying took approximately 35 hours to reach the target moisture content (25% w.b.).

The specific tests conducted for this research include:

1. testing the effect of each recirculation rate air on energy consumption and drying time.
2. evaluating and comparing variable-rate drying versus fixed-rate drying.

3. modelling moisture diffusion in apples and peaches and comparing the models with drying data.

In analysis of the effect of recirculation rate on energy consumption, the analysis of covariance technique was used. For all fixed-rate and variable-rate tests, the results indicated that the recirculation rates did not affect drying time. Also, variable-rate drying had the same energy consumption and drying time as the fixed-rate drying. Tukey's test was performed to separate mean differences of the energy consumption under different air recirculation rates. The results show that 0% recirculation required much more energy to dry fruit to the target moisture content. Among 70, 80, and 90% of recirculation rates, energy consumption did not show significant differences. Moisture diffusion models were applied to apple and peach drying. Apple rings were treated as a plane sheet with thickness q. Peach halves were treat as slabs. Good agreement was obtained between experimental data and predicted values. The exponents in the model were evaluated. The exponents for all recirculation rates were not significantly different among apple tests or peach tests. This finding suggested that different high recirculation rates did not affect drying rates.

CONCLUSION

Based upon the above analysis, the following conclusion were drawn from the study results:

1. For both apple and peach drying, substantial energy savings were observed at 70% and higher recirculation rates. Recirculation rates of 70, 80, and 90% did not differ significantly in energy savings. The 70% or higher recirculation rate produced an energy savings over no recirculation of approximately 50% for drying apples and 46% for drying peaches.
2. In two tests under adverse drying conditions, 90% recirculation resulted in increased drying time. The somewhat erratic results at 90% recirculation were not observed at 70 and 80% recirculation rates. Recirculation rates of 70 and 80% always produced maximum energy savings without increasing drying time.
3. Variable-rate drying of apples did not show significantly different drying time and energy consumption compared with fixed-rate tests.
4. Moisture diffusion models used for both apple and peach drying provided very good predictions of experimental data. The model results suggest that high recirculation rates did not affect drying rate.
5. It is suggest that a fixed-rate of 80% can be applied to drying apples, and a fixed-rate of 70% can be applied to drying peaches for increased energy savings without increasing drying time.

BIBLIOGRAPHY

BIBLIOGRAPHY

Babbit, J. D. 1950. The Differential Equation of Diffusion. Canadian Journal of Research A(28):449-474.

Becker, H. A. 1959. A Study of Diffusion in Solids of Arbitrary Shape with Application to the Drying of the Wheat kernel. Journal of Applied Polymer Science (1):212-226.

Berger, D. and D. C. Pei. 1973. Drying of Hygroscopic Capillary Porous Solids -- A Theoretical Approach. International Journal of Heat and Mass Transfer (16):293-302.

Brooker, D. B., F. W. Bakker-Arkema and C. W. Hall. 1974. Drying Cereal Grains. The Avi Publishing Company, Inc.. Westport, Connecticut.

Charley, H. 1970. Food Science. The Ronald Press Company. New York.

Chen, C. S. and W. H. Johnson. 1969. Kinetics of Moisture Movement in Hygroscopic Materials -- I. Theoretical Consideration of Drying Phenomena. Transactions of the ASAE 12(1):109-113.

Chen, H. 1990. Modeling of Two-Stage Drying of Pistachios. ASAE Paper No. 90-65526. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Chittenden, D. H. and A. Hustrulid. 1966. Determining Drying Constants of Shelled Corn. Transactions of the ASAE 9(1):52-55.

Chung, J. H., L. R. Verma and M. P. Mailander. 1991. Simulation of a Rice Drying System. Transactions of the ASAE 34(5):2065-2072.

Colson, K. H. and J. H. Young. 1990. Two-Component Thin-Layer Drying Model for Unshelled. Transaction of the ASAE 33(1):241-246.

Converse, J. O. 1972. A Commercial Crossflow-Counterflow Grain Dryer. ASAE Paper No.72-828. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Cook, D. F., J. S. Cundiff and D. H. Vaughan. 1982. Energy Savings from Air Recirculation in Peanut Drying. ASAE Paper No.82-3574. American Society of Agricultural Engineers, St. Joseph. MI 49085.

Crafts, A. S. 1944. Cellular Changes in Certain Fruits and Vegetables during Blanching and Dehydration. Food Research (9):442-452.

Crank, J. 1956. The Mathematics of Diffusion. Oxford University Press, London.

Crank, J. 1975. The Mathematics of Diffusion. Second Edition. Clarendon Press. Oxford.

Cruess, W. V. 1958. Commercial Fruit and Vegetable Products. Fourth Edition. McGraw-Hill Book Company. New York.

DeMan, J. M., P. W. Voisey, V. F. Rasper, and D. W. Stanley. 1976. Rheology and Texture in Food Quality. The Avi Publishing Company, Inc.. Westport, Connecticut.

Geankoplis, C. J. 1978. Transport Processes and Unit Operations. Allyn and Bacon, Inc.. Boston.

Hamdy, M. Y. and H. J. Barre. 1969. Evaluating Film Coefficient in Single-Kernel Drying. Transactions of the ASAE 12(2):205-208

Harner, J. P., A. J. Lambert, J. L. Baker, D. H. Vaughan, and J. L. Steele. 1981. Improving Peanut Curing Efficiency with Air Recirculation. ASAE Paper No. 81-3545. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Hayashi, Hiromichi. 1989. Drying Technologies of Foods - Their History and Future. Drying Technology 7(2):315-369.

Henderson, S. M. and S. Pabis. 1961. Grain Drying Theory: I. Temperature Effect on Drying Coefficient. Journal of Agricultural Engineering Research 6(3):169-174.

Henderson, S. M. and R. L. Perry. 1976. Agricultural Process Engineering. Third Edition. The Avi Publishing Company, Inc.. Westport Connecticut.

Husain, A. 1972. Mathematical Simulation of Simultaneous Mass and Heat Diffusion in Biological Materials. Ph.D Thesis. University of Massachusetts, Amherst, MA.

King, C. J. 1968. Rates of Moisture Sorption and Desorption in Porous, Dried Foodstuffs. Food Technology 4(22):165-171.

Krischer, O. 1938. Fundamental Laws of the Movement of Moisture in Bodies Being Dried; capillary water movement and water vapor diffusion. Z. Ver. deut. Ing. (82)373-378.

Lerew, L. E., F. W. Bakker-Arkema, and R. C. Brook. 1972. Simulation of a Commercial Crossflow Dryer: The Heat-Carter Model. ASAE Paper No.72-8729. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Liou J. K. and S. Bruin. 1981. A Model for Watermigration in Porous Hygroscopic Materials Caused by Temperature Gradients. Lebensmittel-Wississenschaft u.-Technolgie (14):206-212.

Luikov, A. V. 1966. Heat and Mass Transfer in Capillary-Porous Bodies. Pergamon Press. Oxford.

Matz, S. A. 1962. Food Texture. The Avi Publishing Company, Inc.. Westport Connecticut.

Mohsenin, N. N. 1970. Physical Properties of Plant and Animal Materials, volume I, structure, physical characteristics and mechanical properties. Gordon and Breach Science Publishers. New York.

Montgomery, D. C. 1984. Design and Analysis of Experiments. Second Edition. John Wiley & Sons, Inc.. New York.

Muhidong, J., L. H. Chen, and D. B. Smith. 1992. Thin-Layer Drying of Kenaf. Transactions of the ASAE 35(6):1941-1944.

Nassikas, A. A. and C. B. Akritidis. 1989. Minimum Energy Cycles in Drying. Drying Technology 7(4):723-745.

Newman, A. B. 1931. The Drying of Porous Solids: Diffusion and Surface Emission Equations. Transactions of the American Institute of Chemical Engineers (27):203-220.

Noyes, R. T. 1977. Superb - "Optimum" Continuous Crossflow Commercial Grain Dryer. ASAE Paper No.77-3015. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Okos, M. R., G. Narshimhan, R. K. Singh and A. C. Weitnauer. 1992. Food Dehydration. In Handbook of Food Engineering, Heldman and Lund (ed.). Marcel Dekker, Inc.. New York, pp 437-562.

Osborn, G. S., G. M. White and L. R. Walton. 1991. Thin-layer Moisture Adsorption Equation for Soybeans. Transactions of the ASAE 34(1):201-206.

Page, C. 1949. Factors Influencing the Maximum Rates of Air Drying of Shelled Corn in Thin Layers. M.S Thesis. Purdue University, Lafayette, IN.

Philip, J. R. and D. A. DE Vries. 1957. Moisture Movement in Porous Materials under Temperature Gradients. Transactions American Geophysical Union (38):223-232. The American Geophysical Union of the National Academy of Sciences. National Research Council. Washington, D. C.

Quattro Pro. 1987. Borland International, Inc., 1800 Green Hills Road, Scotts Valley, CA 95066.

Reeve, R. M. and L. R. Leinbach. 1953. Histological Investigations of Texture in Apples. I. composition and influence of heat on structure. Food Research (18):592-603.

Reeve, R. M. 1953. Histological Investigations of Texture in Apples. II. structure and intercellular spaces. Food Research (18):604-617.

Reeve, R. M. 1959a. Histological and Histochemical Changes in Developing and Ripening Peaches. I. the catechol tannins. American Journal of Botany (46):210-217.

Reeve, R. M. 1959b. Histological and Histochemical Changes in Developing and Ripening Peaches. II. the cell walls and pectins. American Journal of Botany (46):241-248.

Rumsey, T. R., J. F. Thompson and J. Young. 1981. Simulation of Fixed Bed Drying of English Walnuts. ASAE Paper No.81-3547. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Saravacos, G. D. and S. E. Charm. 1962. A Study of the Mechanism of Vegetable and Fruit Dehydration. Food Technology 16:78.

SAS Institute Inc. 1985. SAS User's Guide: Statistics Version 5 edition. Cary, NC: SAS Institute Inc.

Singh, R. K. 1983. Kinetics and Computer Simulation of Storage Stability in Intermediate Moisture Foods. Ph.D Thesis. The University of Wisconsin-Madison, WI.

Smith, E. A., D. S. Jayas, W. E. Muir, K. Alagusundaram, and V. H. Kalbande. 1992. Simulation of Grain Drying in Bins with Partially Perforated Floods. Part II: Calculation of Moisture Content. Transactions of the ASAE 35(3):917-922.

Sokhansanj, S. and F. W. Sosulski. 1981. Drying Performance and Grain Quality in a Recirculation Grain Dryer. ASAE Paper No.81-6516. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Thompson, J. F., M. S. Chhinnan, M. W. Miller and G. D. Kuntson. 1981. Energy Conservation in Drying of Fruits in Tunnel Dehydrators. Journal of Food Process Engineering (4):155-169.

Thompson, T. L. 1967. Predicted Performances and Optimal Designs of Convection Grain Dryers. Ph.D Thesis. Purdue University, Lafayette, IN.

Thompson, T. L., R. M. Peart and G. H. Foster. 1968. Mathematical Simulation of Corn Drying -- A New Model. Transactions of the ASAE 11(14):582-586.

Troeger, J. M. and J. L. Butler. 1979. Simulation of Solar Peanut Drying. Transactions of the ASAE 22(4):906-911.

Troeger, J. M. and W. V. Hukill. 1971. Mathematical Description of the Drying Rate of Fully Exposed Corn. Transactions of the ASAE 14(16):1153-1165,1162.

Van Arsdel, W. B., M. J. Copley and A. I. Morgan. 1973a. Food Dehydration. Volume I. The Avi Publishing Company, Inc.. Westport, Connecticut.

Van Arsdel, W. S., M. J. Copley and A. I. Morgan. 1973b. Food Dehydration. Volume II. The Avi Publishing Company, Inc.. Westport, Connecticut.

Walker, H. T. 1992. Drying Cut Fruits with Recirculated Air for Energy Savings. The Master thesis. The University of Tennessee, Knoxville, TN.

Walker, H. T. and L. R. Wilhelm. 1992. Drying Fruit with Recirculated Air for Energy Saving. ASAE Paper No.92-6535. American Society of Agricultural Engineers, St. Joseph, MI 49085.

Wang, J. K. and C. W. Hall. 1961. Moisture Movement in Hygroscopic Materials -- A Mathematical Analysis. Transactions of the ASAE 4(1):33-36.

Whitaker, T. B. and J. H. Young. 1972. Simulation of Moisture Movement in Peanut Kernels: Evaluation of the Diffusion Equation. Transactions of the ASAE 15(1):163-166.

Wilhelm, L. R. 1975. Numerical Calculation of Psychrometric Properties. ASAE Paper No.75-4019. American Society of Agricultural Engineers, St. Joseph, MI 49085.

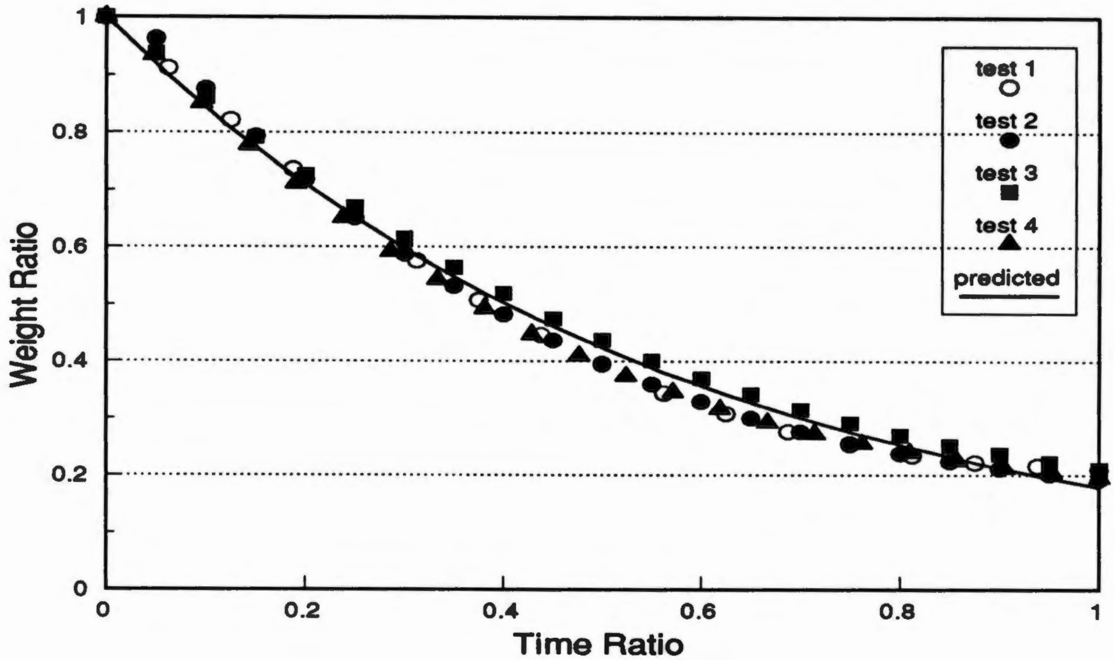
Young, J. H. 1984. Energy Conservation by Partial Recirculation of Peanut Drying Air. Transactions of the ASAE (3):928-934.

Zhou, L., V. M. Puri, R. C. Anantheswaran, and S. Roy. 1992. Material Property Measurement for Simultaneous Heat and Mass Transfer in Food Products. ASAE Paper No.92-6594. American Society of Agricultural Engineers, St. Joseph, MI 49085.

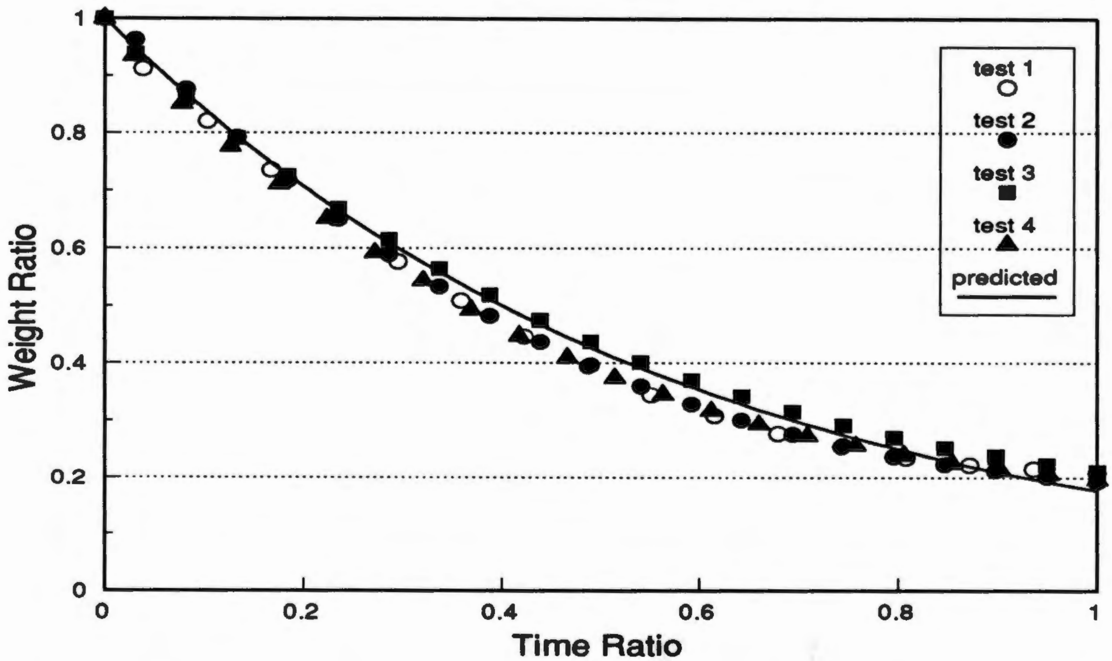
APPENDICES

APPENDIX A

Fixed-Rate Drying of Apples



(a)



(b)

Figure A-1. The predicted moisture loss curve along with the experimental data at 0% fixed recirculation rate; (a) original data (b) adjusted data.

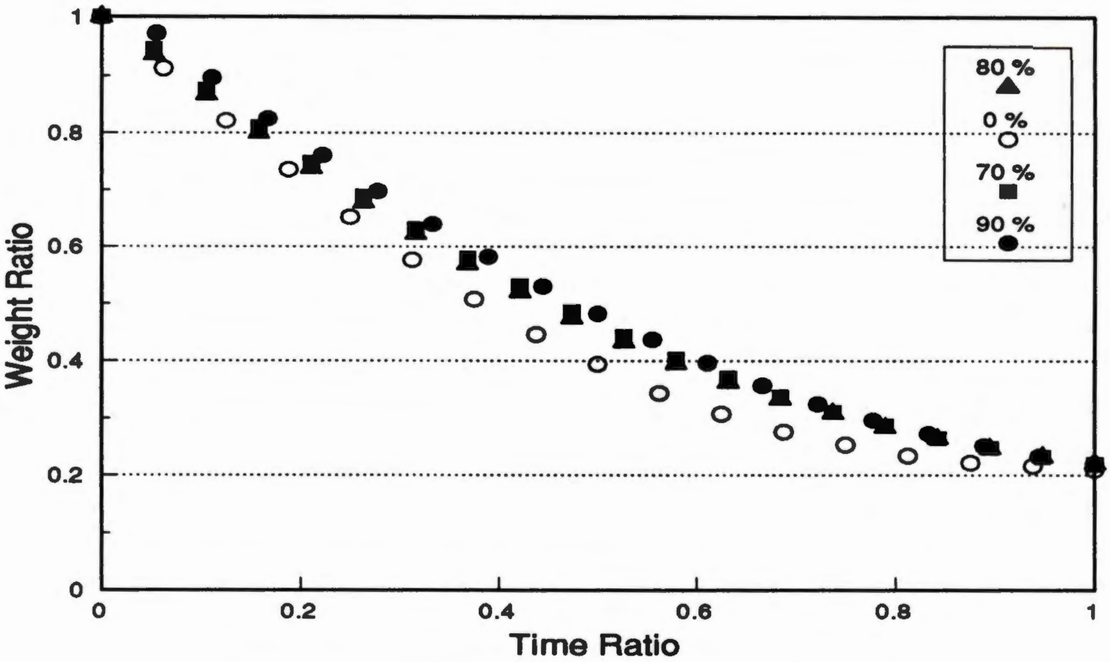


Figure A-2. Effect of fixed-rate recirculation air on the moisture removal from apples (test 1).

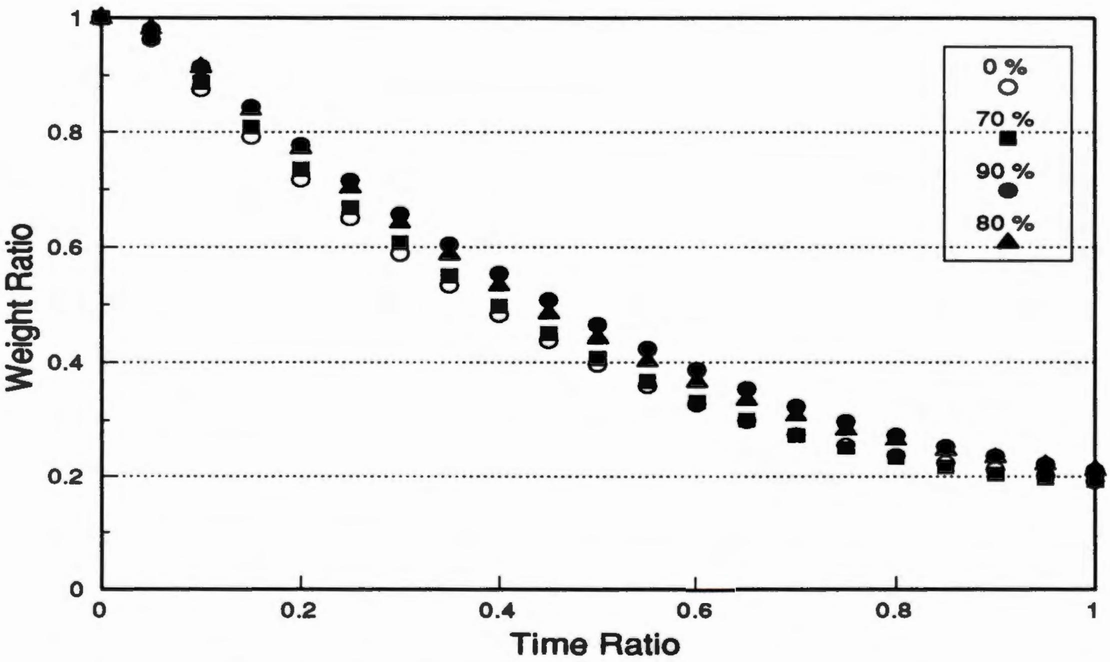


Figure A-3. Effect of fixed-rate recirculation air on the moisture removal from apples (test 2).

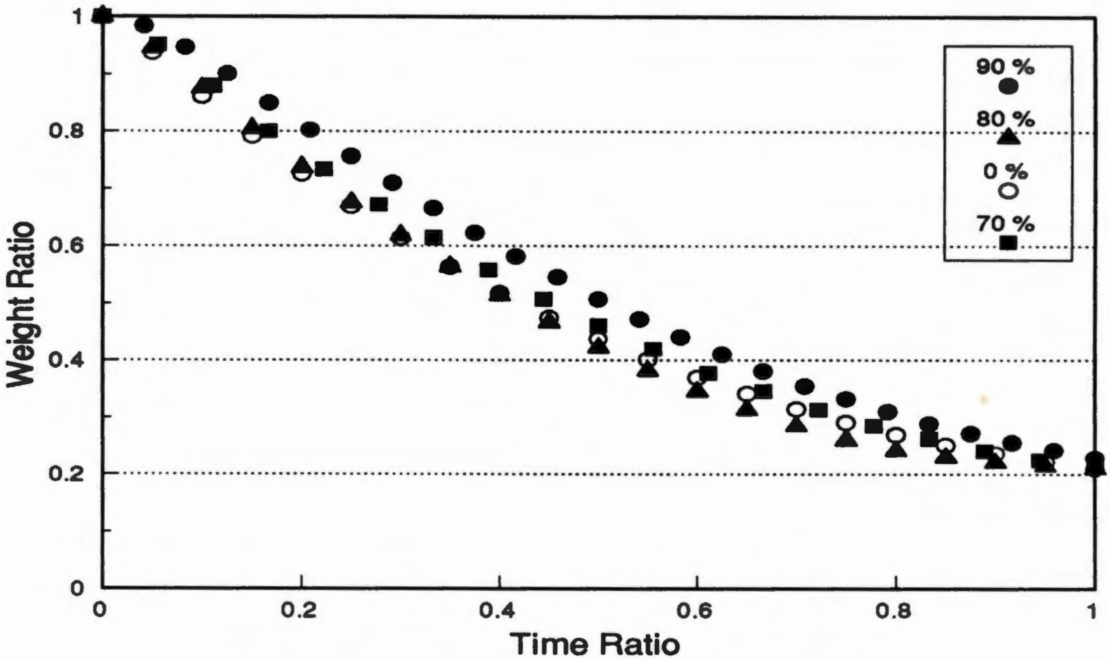


Figure A-4. Effect of fixed-rate recirculation air on the moisture removal from apples (test 3).

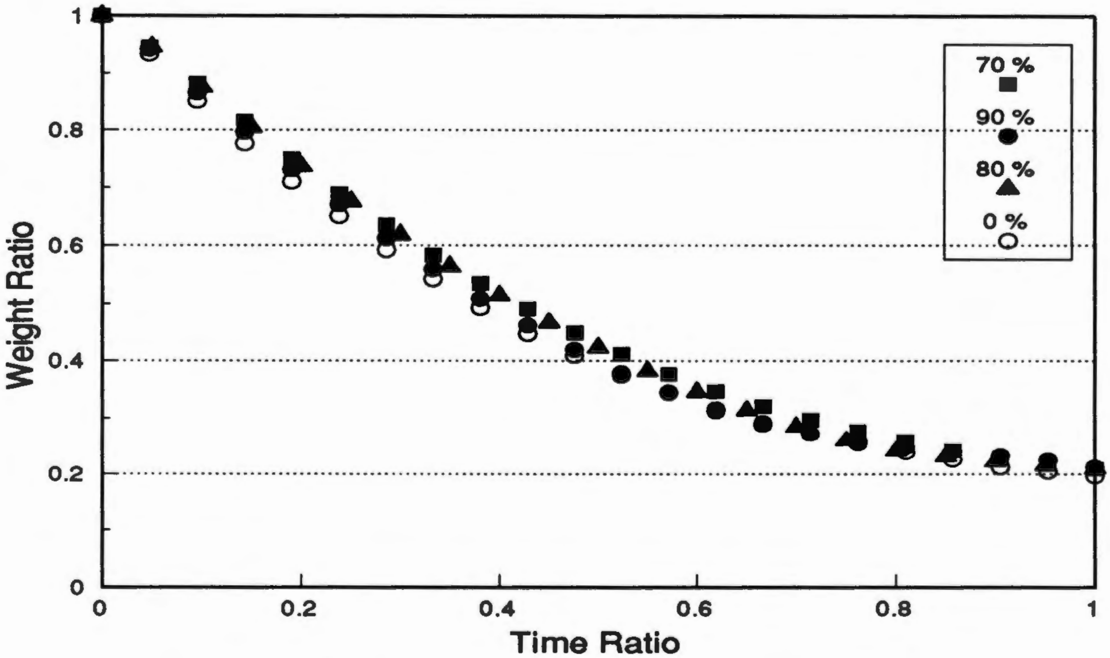


Figure A-5. Effect of fixed-rate recirculation air on the moisture removal from apples (test 4).

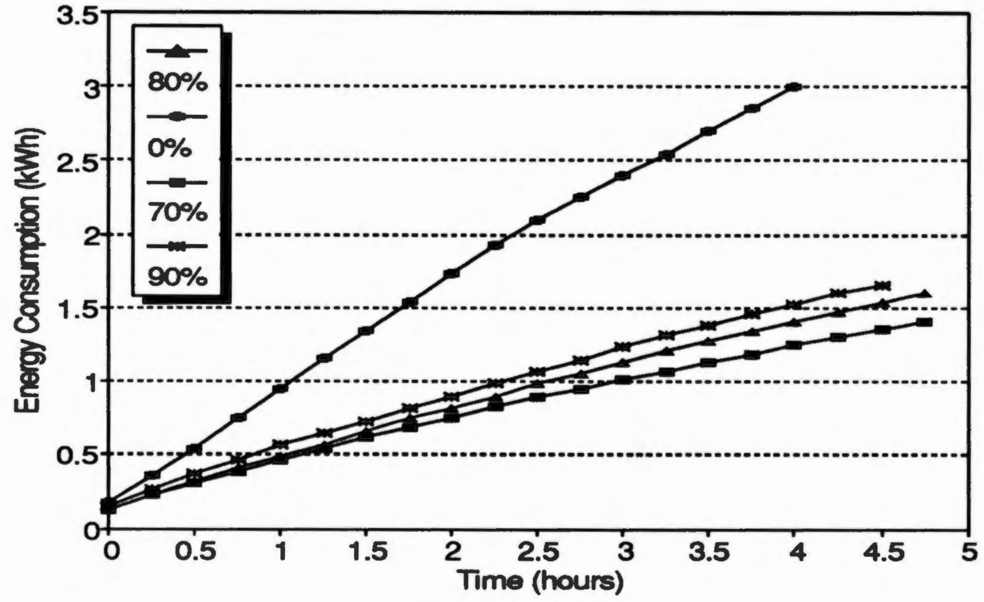


Figure A-6. The experimental data of cumulative energy consumption versus time for fixed-rate apple drying (test 1).

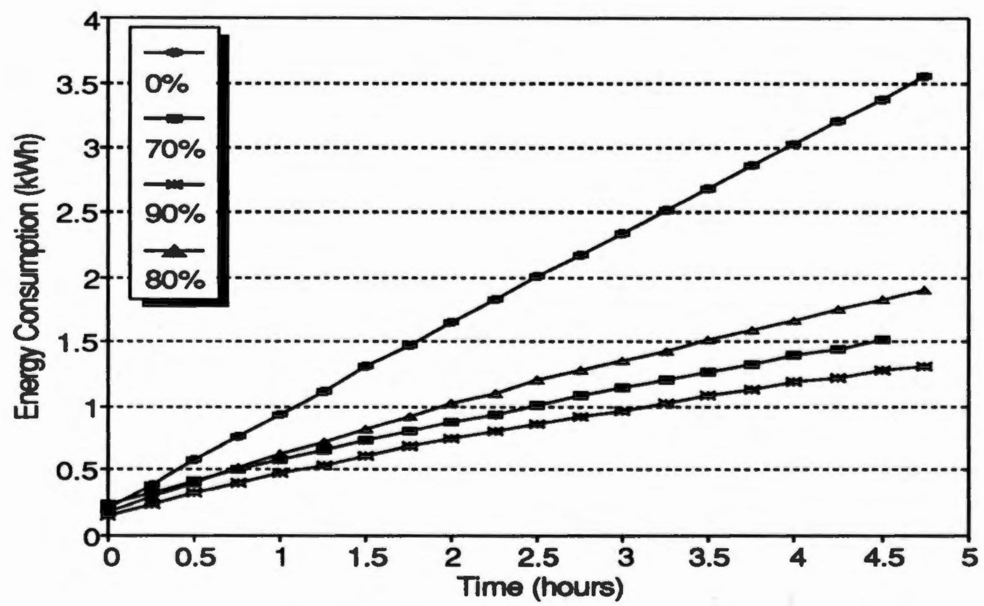


Figure A-7. The experimental data of cumulative energy consumption versus time for fixed-rate apple drying (test 2).

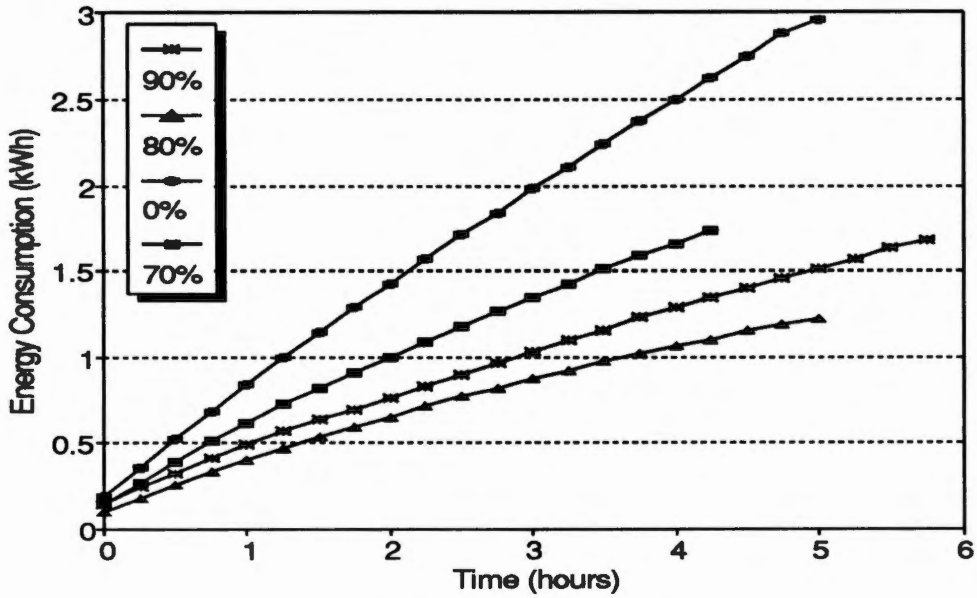


Figure A-8. The experimental data of cumulative energy consumption versus time for fixed-rate apple drying (test 3).

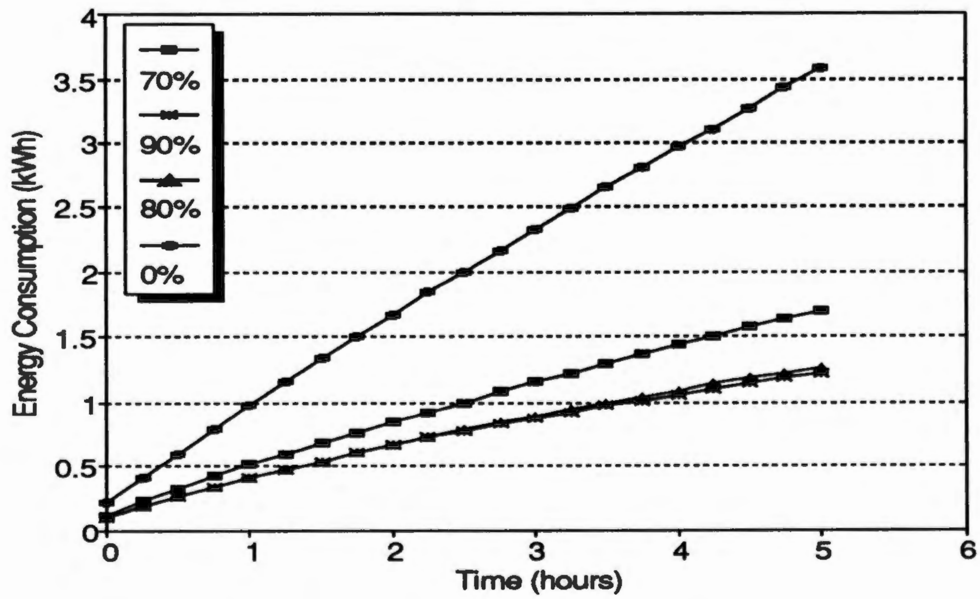


Figure A-9. The experimental data of cumulative energy consumption versus time for fixed-rate apple drying (test 4).

Table A-1. Time, energy consumption, total fruit weights and weight ratio for fixed-rate apple drying tests.

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	A	80	0	0	0	838.25	1
1	A	80	0.25	67	0.1206	783.99	0.93527
1	A	80	0.5	124	0.2232	726.50	0.86669
1	A	80	0.75	177	0.3186	670.31	0.79965
1	A	80	1	229	0.4122	618.08	0.73735
1	A	80	1.25	275	0.4950	568.05	0.67766
1	A	80	1.5	320	0.5760	521.07	0.62162
1	A	80	1.75	369	0.6642	476.61	0.56858
1	A	80	2	416	0.7488	435.46	0.51949
1	A	80	2.25	455	0.8190	397.26	0.47392
1	A	80	2.5	500	0.9000	362.68	0.43266
1	A	80	2.75	546	0.9828	330.99	0.39486
1	A	80	3	587	1.0566	304.04	0.36271
1	A	80	3.25	628	1.1304	279.25	0.33313
1	A	80	3.5	669	1.2042	258.76	0.30869
1	A	80	3.75	707	1.2726	238.12	0.28407
1	A	80	4	743	1.3374	221.33	0.26404
1	A	80	4.25	780	1.4040	206.65	0.24653
1	A	80	4.5	819	1.4742	194.35	0.23185
1	A	80	4.75	856	1.5408	184.63	0.22026
1	B	0	0	0	0	829.29	1
1	B	0	0.25	93	0.1674	756.17	0.91183
1	B	0	0.5	196	0.3528	680.99	0.82117
1	B	0	0.75	302	0.5436	610.27	0.73589
1	B	0	1	416	0.7488	540.72	0.65203
1	B	0	1.25	529	0.9522	478.17	0.57660
1	B	0	1.5	643	1.1574	421.27	0.50799
1	B	0	1.75	746.5	1.3437	370.83	0.44717
1	B	0	2	858	1.5444	327.60	0.39504
1	B	0	2.25	966	1.7388	285.06	0.34374
1	B	0	2.5	1075	1.9350	255.25	0.30779
1	B	0	2.75	1170	2.1060	229.22	0.27641
1	B	0	3	1252	2.2536	210.15	0.25341
1	B	0	3.25	1335	2.4030	194.26	0.23425
1	B	0	3.5	1418	2.5524	183.92	0.22178
1	B	0	3.75	1503	2.7054	178.87	0.21569

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	B	0	4	1589	2.8602	173.53	0.20925
1	C	70	0	0	0	813.36	1
1	C	70	0.25	71	0.1278	768.58	0.94494
1	C	70	0.5	118	0.2124	712.25	0.87569
1	C	70	0.25	162	0.2916	658.65	0.80979
1	C	70	0.5	208	0.3744	608.56	0.74820
1	C	70	0.75	247	0.4446	559.84	0.68831
1	C	70	1	288	0.5184	513.97	0.63191
1	C	70	1.25	326	0.5868	471.65	0.57988
1	C	70	1.5	364	0.6552	432.21	0.53139
1	C	70	1.75	407	0.7326	394.93	0.48555
1	C	70	2	444	0.7992	360.60	0.44335
1	C	70	2.25	477	0.8586	328.45	0.40382
1	C	70	2.5	508	0.9144	301.42	0.37059
1	C	70	2.75	538	0.9684	275.39	0.33858
1	C	70	3	574	1.0332	252.86	0.31088
1	C	70	3.25	605	1.0890	233.17	0.28668
1	C	70	3.5	637	1.1466	215.59	0.26506
1	C	70	3.75	666	1.1988	201.77	0.24807
1	C	70	4	698	1.2564	188.68	0.23198
1	C	70	4.25	728	1.3104	178.09	0.21896
1	D	90	0	0	0	827.57	1
1	D	90	0.25	85	0.1530	804.74	0.97241
1	D	90	0.5	153	0.2754	741.68	0.89621
1	D	90	0.75	207	0.3726	683.08	0.82540
1	D	90	1	260	0.4680	629.23	0.76033
1	D	90	1.25	312	0.5616	577.50	0.69783
1	D	90	1.5	359	0.6462	529.46	0.63978
1	D	90	1.75	405	0.7290	482.25	0.58273
1	D	90	2	455	0.8190	439.09	0.53058
1	D	90	2.25	500	0.9000	399.04	0.48218
1	D	90	2.5	550	0.9900	362.26	0.43774
1	D	90	2.75	596	1.0728	328.48	0.39692
1	D	90	3	640	1.1520	296.11	0.35781
1	D	90	3.25	686	1.2348	268.89	0.32492
1	D	90	3.5	730	1.3140	245.37	0.29649

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	D	90	3.75	766	1.3788	225.35	0.27230
1	D	90	4	809	1.4562	207.47	0.25070
1	D	90	4.25	849	1.5282	193.46	0.23377
1	D	90	4.5	887	1.5966	182.19	0.22015
2	A	0	0	0	0	855.46	1
2	A	0	0.25	108	0.1944	823.81	0.96300
2	A	0	0.5	212	0.3816	749.47	0.87610
2	A	0	0.75	316	0.5688	678.58	0.79323
2	A	0	1	419	0.7542	614.56	0.71840
2	A	0	1.25	521	0.9378	556.87	0.65096
2	A	0	1.5	620	1.116	503.12	0.58813
2	A	0	1.75	723	1.3014	455.88	0.53291
2	A	0	2	821	1.4778	413.28	0.48311
2	A	0	2.25	920	1.656	374.51	0.43779
2	A	0	2.5	1017	1.8306	339.3	0.39663
2	A	0	2.75	1116	2.0088	307.71	0.35970
2	A	0	3	1209	2.1762	281.05	0.32854
2	A	0	3.25	1305	2.349	256.62	0.29998
2	A	0	3.5	1403	2.5254	235.95	0.27582
2	A	0	3.75	1495	2.691	219.25	0.25629
2	A	0	4	1593	2.8674	203.11	0.23743
2	A	0	4.25	1688	3.0384	191.36	0.22369
2	A	0	4.5	1780	3.204	181.4	0.21205
2	A	0	4.75	1877	3.3786	172.22	0.20132
2	A	0	5	1974	3.5532	164.62	0.19243
2	B	70	0	0	0	859.27	1
2	B	70	0.25	73	0.1314	829.87	0.96578
2	B	70	0.5	130	0.234	762.95	0.88790
2	B	70	0.75	182	0.3276	695.8	0.80976
2	B	70	1	230	0.414	631.99	0.73550
2	B	70	1.25	276	0.4968	574.96	0.66913
2	B	70	1.5	320	0.576	521.91	0.60739
2	B	70	1.75	362.5	0.6525	472.49	0.54987
2	B	70	2	404	0.7272	427.73	0.49778
2	B	70	2.25	444	0.7992	386.31	0.44958
2	B	70	2.5	484	0.8712	349.32	0.40653

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
2	B	70	2.75	522	0.9396	315.95	0.36770
2	B	70	3	560	1.008	285.11	0.33180
2	B	70	3.25	597	1.0746	259.08	0.30151
2	B	70	3.5	633	1.1394	235.88	0.27451
2	B	70	3.75	669	1.2042	216.34	0.25177
2	B	70	4	704	1.2672	200.06	0.23283
2	B	70	4.25	738	1.3284	186.44	0.21697
2	B	70	4.5	772	1.3896	175.53	0.20428
2	B	70	4.75	806	1.4508	169.57	0.19734
2	B	70	5	839	1.5102	165.25	0.19231
2	C	90	0	0	0	882.04	1
2	C	90	0.25	78	0.1404	864.42	0.98002
2	C	90	0.5	129	0.2322	806.94	0.91486
2	C	90	0.75	177	0.3186	745.13	0.84478
2	C	90	1	220	0.396	686.5	0.77831
2	C	90	1.25	258	0.4644	631.16	0.71557
2	C	90	1.5	299	0.5382	580.17	0.65776
2	C	90	1.75	339	0.6102	533.09	0.60438
2	C	90	2	376	0.6768	488.84	0.55422
2	C	90	2.25	410	0.738	447.6	0.50746
2	C	90	2.5	446	0.8028	409.41	0.46416
2	C	90	2.75	478	0.8604	373.41	0.42335
2	C	90	3	509	0.9162	341.13	0.38675
2	C	90	3.25	538	0.9684	312.26	0.35402
2	C	90	3.5	571	1.0278	285.94	0.32418
2	C	90	3.75	599	1.0782	262.28	0.29736
2	C	90	4	627	1.1286	241.71	0.27404
2	C	90	4.25	655	1.179	223.95	0.25390
2	C	90	4.5	681	1.2258	208.06	0.23588
2	C	90	4.75	706	1.2708	195.44	0.22158
2	C	90	5	730	1.314	184.96	0.20970
2	D	80	0	0	0	897.82	1
2	D	80	0.25	92	0.1656	881.2	0.98149
2	D	80	0.5	158	0.2844	820.21	0.91356
2	D	80	0.75	221	0.3978	753.67	0.83944
2	D	80	1	283	0.5094	692.78	0.77162

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
2	D	80	1.25	342	0.6156	631.06	0.70288
2	D	80	1.5	396	0.7128	577.3	0.64300
2	D	80	1.75	451	0.8118	527.22	0.58722
2	D	80	2	512	0.9216	478.99	0.53350
2	D	80	2.25	566	1.0188	434.92	0.48442
2	D	80	2.5	613	1.1034	396.96	0.44214
2	D	80	2.75	664	1.1952	361.01	0.40210
2	D	80	3	713	1.2834	329.14	0.36660
2	D	80	3.25	754	1.3572	301.1	0.33537
2	D	80	3.5	799	1.4382	277.07	0.30860
2	D	80	3.75	843	1.5174	255.28	0.28433
2	D	80	4	888	1.5984	238.49	0.26563
2	D	80	4.25	931	1.6758	221.68	0.24691
2	D	80	4.5	974	1.7532	208.85	0.23262
2	D	80	4.75	1016	1.8288	197.93	0.22046
2	D	80	5	1057	1.9026	189.62	0.21120
3	A	90	0	0	0	929.29	1
3	A	90	0.25	77	0.1386	914.63	0.98422
3	A	90	0.5	134	0.2412	879.85	0.94680
3	A	90	0.75	181	0.3258	837.43	0.90115
3	A	90	1	227	0.4086	790.23	0.85036
3	A	90	1.25	272	0.4896	745.98	0.80274
3	A	90	1.5	311	0.5598	702.44	0.75589
3	A	90	1.75	349	0.6282	659.88	0.71009
3	A	90	2	383	0.6894	618.93	0.66602
3	A	90	2.25	422	0.7596	579.05	0.62311
3	A	90	2.5	458	0.8244	540.82	0.58197
3	A	90	2.75	495	0.891	507.46	0.54607
3	A	90	3	534	0.9612	471.3	0.50716
3	A	90	3.25	570	1.026	439.29	0.47272
3	A	90	3.5	608	1.0944	409.54	0.44070
3	A	90	3.75	643	1.1574	380.99	0.40998
3	A	90	4	680	1.224	354.15	0.38110
3	A	90	4.25	713	1.2834	329.69	0.35478
3	A	90	4.5	746	1.3428	308.48	0.33195
3	A	90	4.75	775	1.395	287.49	0.30937

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
3	A	90	5	806	1.4508	268.28	0.28869
3	A	90	5.25	838	1.5084	252	0.27117
3	A	90	5.5	870	1.566	237.43	0.25550
3	A	90	5.75	904	1.6272	224.54	0.24163
3	A	90	6	934	1.6812	212.72	0.22891
3	B	80	0	0	0	893.41	1
3	B	80	0.25	53	0.0954	844.53	0.94529
3	B	80	0.5	99	0.1782	781.86	0.87514
3	B	80	0.75	143	0.2574	718.84	0.80460
3	B	80	1	185	0.333	658.51	0.73707
3	B	80	1.25	223	0.4014	603.36	0.67535
3	B	80	1.5	260	0.468	552.29	0.61818
3	B	80	1.75	295	0.531	503.85	0.56396
3	B	80	2	329	0.5922	458.73	0.51346
3	B	80	2.25	361.5	0.6507	416.73	0.46645
3	B	80	2.5	393	0.7074	377.67	0.42273
3	B	80	2.75	424	0.7632	341.23	0.38194
3	B	80	3	454	0.8172	308.39	0.34518
3	B	80	3.25	482	0.8676	279.81	0.31319
3	B	80	3.5	510	0.918	254.28	0.28462
3	B	80	3.75	536	0.9648	232.6	0.26035
3	B	80	4	562	1.0116	215.88	0.24164
3	B	80	4.25	587	1.0566	205.89	0.23045
3	B	80	4.5	611	1.0998	197.99	0.22161
3	B	80	4.75	635	1.143	192.34	0.21529
3	B	80	5	659	1.1862	187.4	0.20976
3	C	0	0	0	0	822.1	1
3	C	0	0.25	100	0.18	771.11	0.93798
3	C	0	0.5	195	0.351	708.22	0.86148
3	C	0	0.75	290	0.522	650.2	0.79090
3	C	0	1	378	0.6804	596.83	0.72598
3	C	0	1.25	466	0.8388	549.87	0.66886
3	C	0	1.5	552	0.9936	504.9	0.61416
3	C	0	1.75	634	1.1412	463.62	0.56395
3	C	0	2	715	1.287	426.03	0.51822
3	C	0	2.25	792	1.4256	390.54	0.47505

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
3	C	0	2.5	870	1.566	359.86	0.43773
3	C	0	2.75	948	1.7064	329.94	0.40134
3	C	0	3	1023	1.8414	304.18	0.37000
3	C	0	3.25	1098	1.9764	280.5	0.34120
3	C	0	3.5	1170	2.106	258.78	0.31478
3	C	0	3.75	1243	2.2374	239.08	0.29082
3	C	0	4	1316	2.3688	221.68	0.26965
3	C	0	4.25	1388	2.4984	206.58	0.25128
3	C	0	4.5	1456	2.6208	194.33	0.23638
3	C	0	4.75	1526	2.7468	182.64	0.22216
3	C	0	5	1600	2.88	172.86	0.21027
3	D	70	0	0	0	991.42	1
3	D	70	0.25	77	0.1386	943.4	0.95156
3	D	70	0.5	144	0.2592	872.22	0.87977
3	D	70	0.75	214	0.3852	793.73	0.80060
3	D	70	1	283	0.5094	726.51	0.73280
3	D	70	1.25	342	0.6156	665.99	0.67175
3	D	70	1.5	400	0.72	608.93	0.61420
3	D	70	1.75	452	0.8136	552.95	0.55774
3	D	70	2	505	0.909	503.57	0.50793
3	D	70	2.25	554	0.9972	456.9	0.46085
3	D	70	2.5	601	1.0818	416.42	0.42002
3	D	70	2.75	651	1.1718	374.92	0.37816
3	D	70	3	699	1.2582	343.18	0.34615
3	D	70	3.25	744	1.3392	310.78	0.31347
3	D	70	3.5	790	1.422	282.71	0.28516
3	D	70	3.75	837	1.5066	260.4	0.26265
3	D	70	4	882	1.5876	239.28	0.24135
3	D	70	4.25	919	1.6542	223.52	0.22545
3	D	70	4.5	963	1.7334	211.13	0.21296
4	A	70	0	0	0	940	1
4	A	70	0.25	66	0.1188	888.54	0.94526
4	A	70	0.5	128	0.2304	829.15	0.88207
4	A	70	0.75	181	0.3258	766.22	0.81513
4	A	70	1	231	0.4158	704.9	0.74989
4	A	70	1.25	283	0.5094	647.77	0.68912

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
4	A	70	1.5	328	0.5904	596.56	0.63464
4	A	70	1.75	375	0.675	547.65	0.58261
4	A	70	2	424	0.7632	502.39	0.53446
4	A	70	2.25	467	0.8406	461.24	0.49068
4	A	70	2.5	514	0.9252	421.45	0.44835
4	A	70	2.75	557	1.0026	386.63	0.41131
4	A	70	3	597	1.0746	354.48	0.37711
4	A	70	3.25	640	1.152	325.43	0.34620
4	A	70	3.5	682	1.2276	300.67	0.31986
4	A	70	3.75	718	1.2924	279.17	0.29699
4	A	70	4	760	1.368	260.74	0.27738
4	A	70	4.25	801	1.4418	243.66	0.25921
4	A	70	4.5	836	1.5048	227.72	0.24226
4	A	70	4.75	875	1.575	213.58	0.22721
4	A	70	5	910	1.638	204.03	0.21705
4	A	70	5.25	947	1.7046	195.74	0.20823
4	B	90	0	0	0	970.15	1
4	B	90	0.25	58	0.1044	914.68	0.94282
4	B	90	0.5	104	0.1872	840.67	0.86654
4	B	90	0.75	146	0.2628	774.12	0.79794
4	B	90	1	186.5	0.3357	710.7	0.73257
4	B	90	1.25	225	0.405	650.72	0.67074
4	B	90	1.5	262	0.4716	594.63	0.61293
4	B	90	1.75	298.5	0.5373	542.12	0.55880
4	B	90	2	333	0.5994	493.39	0.50857
4	B	90	2.25	367	0.6606	448.39	0.46219
4	B	90	2.5	399	0.7182	406.62	0.41913
4	B	90	2.75	429	0.7722	367.76	0.37908
4	B	90	3	458	0.8244	333.41	0.34367
4	B	90	3.25	486	0.8748	303.07	0.31239
4	B	90	3.5	513	0.9234	280.11	0.28873
4	B	90	3.75	539	0.9702	265.1	0.27326
4	B	90	4	563	1.0134	251.65	0.25939
4	B	90	4.25	587	1.0566	241.23	0.24865
4	B	90	4.5	611	1.0998	233.16	0.24033
4	B	90	4.75	634	1.1412	225.65	0.23259

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
4	B	90	5	656	1.1808	217.97	0.22468
4	B	90	5.25	678	1.2204	205.58	0.21191
4	C	80	0	0	0	968.58	1
4	C	80	0.25	55	0.099	922.37	0.95229
4	C	80	0.5	101	0.1818	858.16	0.88600
4	C	80	0.75	145	0.261	797.04	0.82290
4	C	80	1	185	0.333	740.18	0.76419
4	C	80	1.25	225	0.405	685.29	0.70752
4	C	80	1.5	262	0.4716	633.57	0.65412
4	C	80	1.75	299	0.5382	586.11	0.60512
4	C	80	2	333	0.5994	541.13	0.55868
4	C	80	2.25	367	0.6606	497.72	0.51387
4	C	80	2.5	399	0.7182	458.64	0.47352
4	C	80	2.75	436	0.7848	421.61	0.43529
4	C	80	3	465	0.837	387.14	0.39970
4	C	80	3.25	497	0.8946	356.05	0.36760
4	C	80	3.5	523	0.9414	326.88	0.33748
4	C	80	3.75	552	0.9936	300.97	0.31073
4	C	80	4	579	1.0422	277.5	0.28650
4	C	80	4.25	608	1.0944	257.24	0.26558
4	C	80	4.5	634	1.1412	239.28	0.24704
4	C	80	4.75	658	1.1844	223.43	0.23068
4	C	80	5	682	1.2276	210.54	0.21737
4	C	80	5.25	703	1.2654	199.27	0.20573
4	D	0	0	0	0	991.88	1
4	D	0	0.25	117	0.2106	926.67	0.93426
4	D	0	0.5	223	0.4014	844.19	0.85110
4	D	0	0.75	330	0.594	770.43	0.77674
4	D	0	1	438	0.7884	704.98	0.71075
4	D	0	1.25	544	0.9792	645.92	0.65121
4	D	0	1.5	645	1.161	586.67	0.59147
4	D	0	1.75	744	1.3392	538.42	0.54283
4	D	0	2	836	1.5048	489.01	0.49301
4	D	0	2.25	931	1.6758	443.88	0.44751
4	D	0	2.5	1026	1.8468	406.31	0.40964
4	D	0	2.75	1114	2.0052	371.07	0.37411

Table A-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
4	D	0	3	1204	2.1672	342.43	0.34523
4	D	0	3.25	1293	2.3274	313.63	0.31620
4	D	0	3.5	1384	2.4912	290.4	0.29278
4	D	0	3.75	1472	2.6496	270.45	0.27266
4	D	0	4	1558	2.8044	253.16	0.25523
4	D	0	4.25	1648	2.9664	237.48	0.23942
4	D	0	4.5	1730	3.114	223.6	0.22543
4	D	0	4.75	1817	3.2706	210.64	0.21236
4	D	0	5	1903	3.4254	202.86	0.20452
4	D	0	5.25	1990	3.582	194.28	0.19587

Cum_Eng = (Counts x 1.8)/1000

APPENDIX B

Fixed-Rate Drying of Sun High Peaches

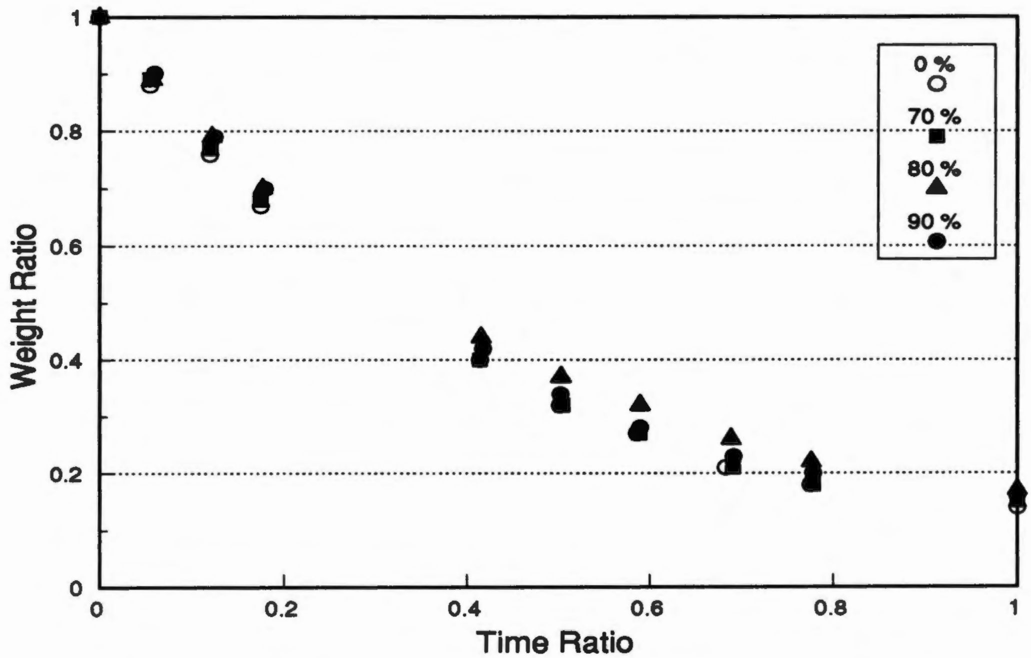


Figure B-1. Effect of recirculated air on the moisture removal for Sun High peaches (test 1).

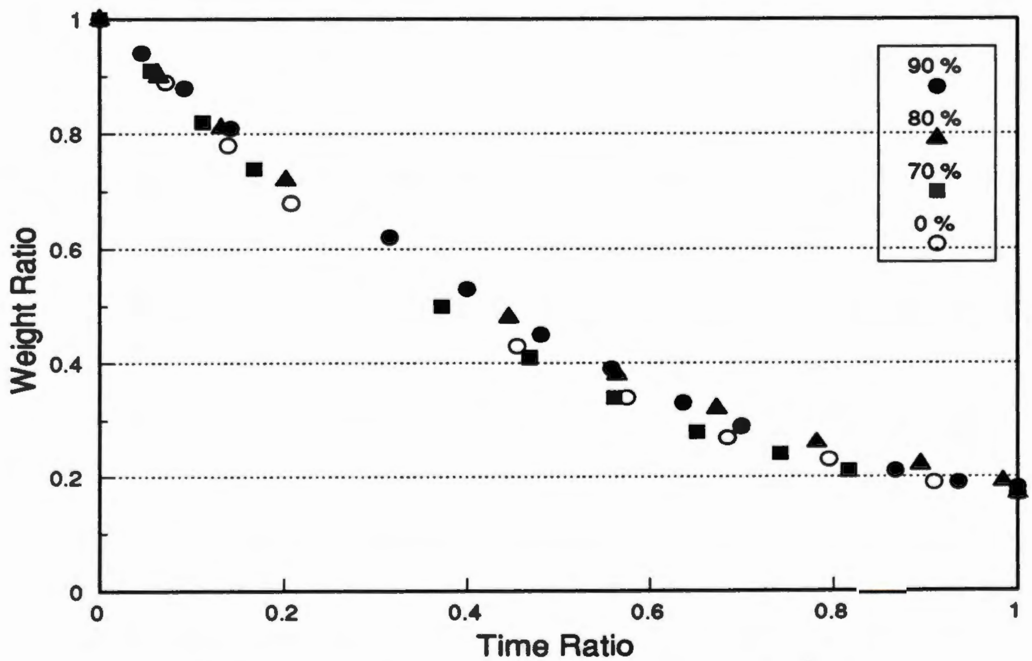


Figure B-2. Effect of recirculated air on the moisture removal for Sun High peaches (test 2).

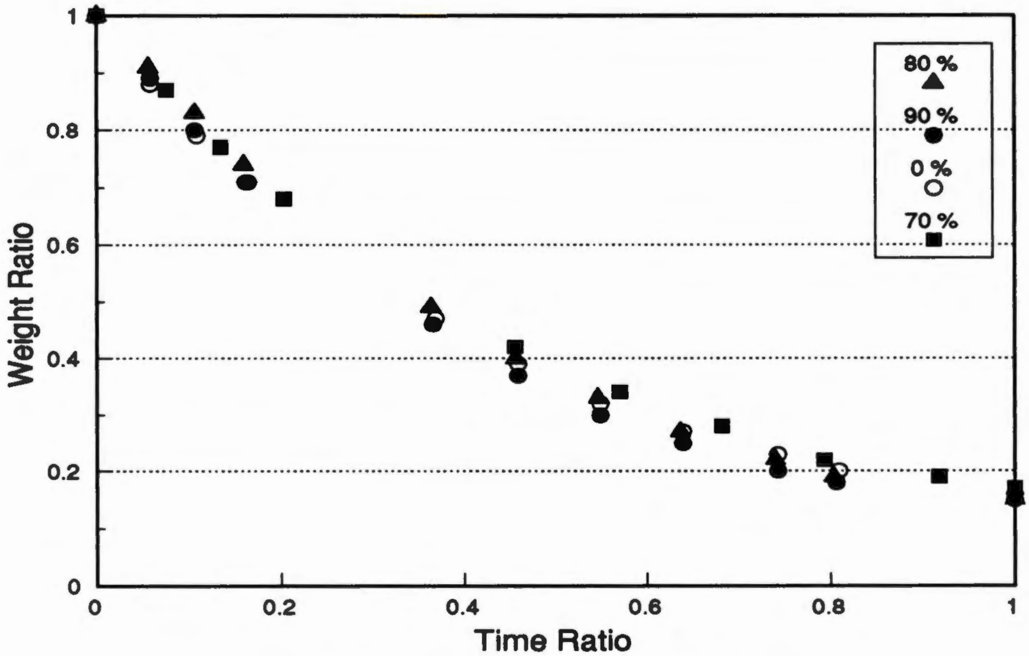


Figure B-3. Effect of recirculated air on the moisture removal for Sun High peaches (test 3).

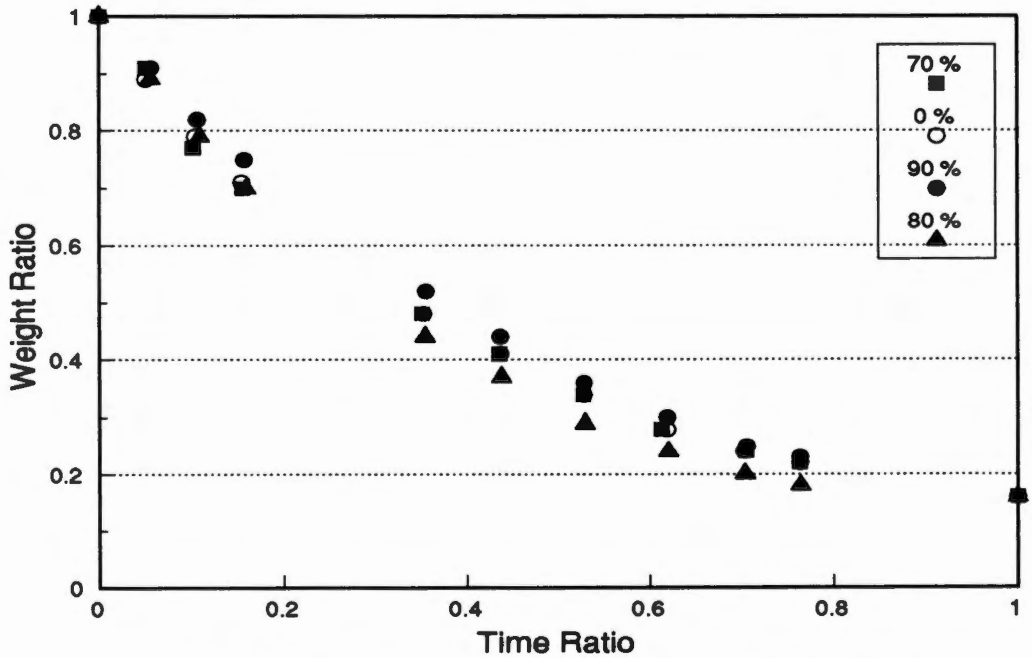


Figure B-4. Effect of recirculated air on the moisture removal for Sun High peaches (test 4).

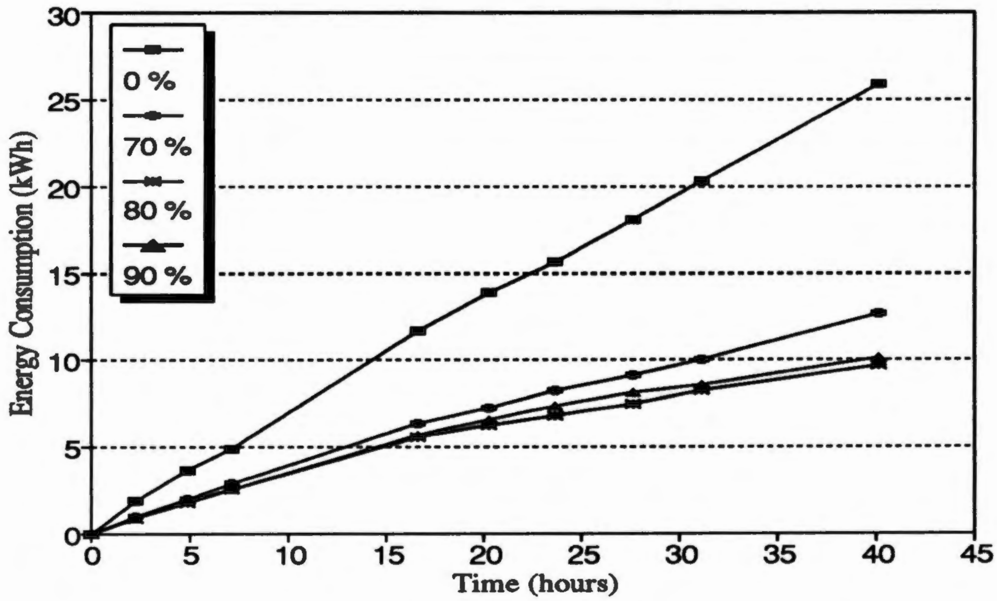


Figure B-5. The experimental data of cumulative energy consumption versus time for dried Sun High peaches (test 1).

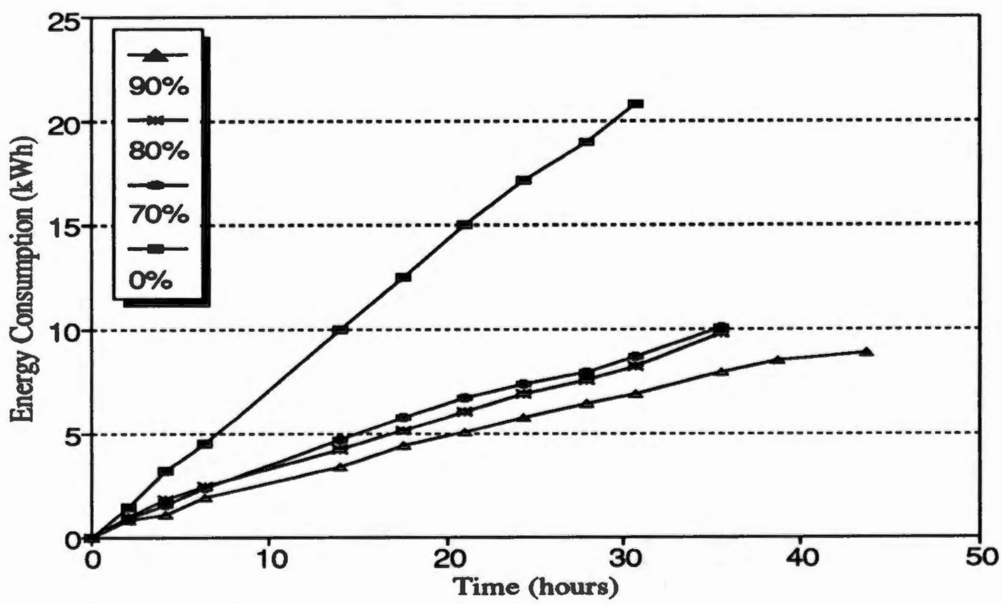


Figure B-6. The experimental data of cumulative energy consumption versus time for dried Sun High peaches (test 2).

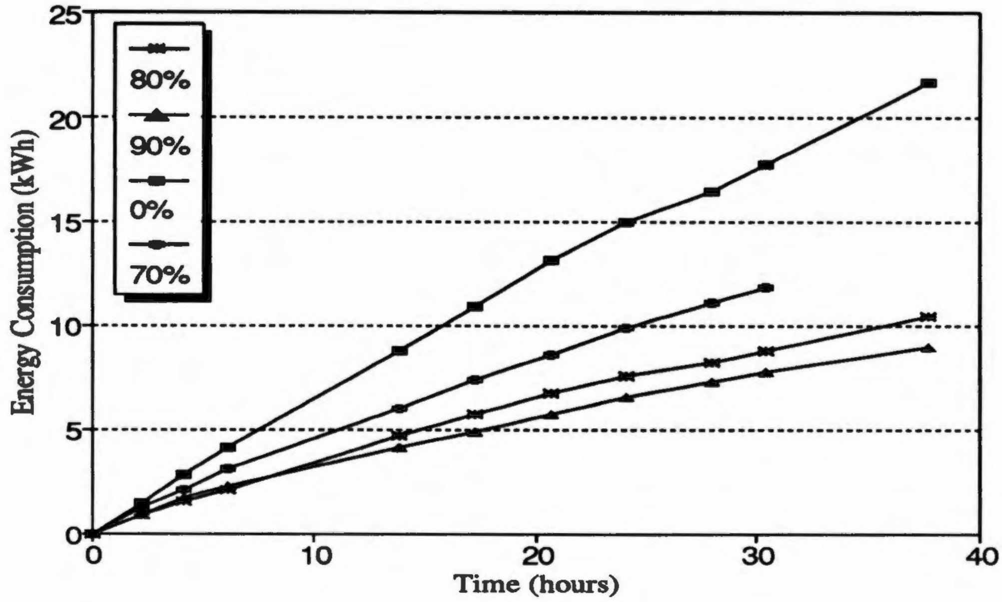


Figure B-7. The experimental data of cumulative energy consumption versus time for dried Sun High peaches (test 3).

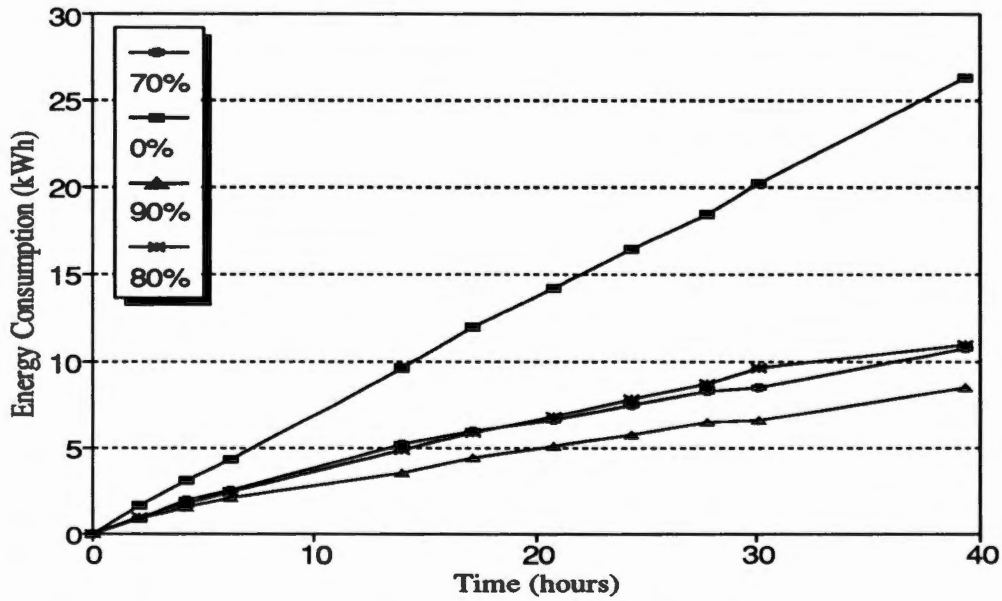


Figure B-8. The experimental data of cumulative energy consumption versus time for dried Sun High peaches (test 4).

Table B-1. Time, energy consumption, and total fruit weights for Sun High peach tests.

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
1	A	0	0.0	0.0	1929.8	1973.6	1930.7	2090.2
1	A	0	2.2	1.9	1752.8	1745.7	1715.9	1894.5
1	A	0	4.8	3.6	1556.7	1565.2	1499.1	1670.3
1	A	0	7.0	4.9	1397.9	1415.9	1356.9	1484.9
1	A	0	16.6	11.7	898.2	920.4	931.9	1019.0
1	A	0	20.1	13.9	786.2	772.2	797.4	895.9
1	A	0	23.5	15.7	699.4	683.5	696.5	777.9
1	A	0	27.4	18.1	617.0	602.3	606.2	664.9
1	A	0	31.1	20.3	569.6	548.9	559.5	604.4
1	A	0	40.1	25.9	514.0	487.0	483.1	527.2
1	B	70	0.0	0.0	1958.4	2029.5	2087.3	1982.2
1	B	70	2.2	1.0	1779.5	1814.8	1884.4	1776.5
1	B	70	4.8	2.0	1567.5	1633.4	1648.2	1562.8
1	B	70	7.0	2.9	1408.5	1479.2	1499.9	1388.0
1	B	70	16.6	6.3	910.6	980.6	984.7	931.7
1	B	70	20.2	7.2	791.6	832.2	845.4	802.4
1	B	70	23.6	8.2	698.3	736.7	732.6	695.1
1	B	70	27.7	9.1	603.4	646.2	640.1	598.8
1	B	70	31.2	10.0	553.9	589.4	585.4	550.9
1	B	70	40.1	12.7	487.3	515.4	512.5	495.0
1	C	80	0.0	0.0	2071.4	1932.1	2007.9	2097.7
1	C	80	2.3	0.9	1865.8	1719.4	1819.6	1953.5
1	C	80	4.9	1.8	1677.1	1552.7	1625.5	1725.3
1	C	80	7.1	2.6	1533.6	1411.5	1480.9	1581.9
1	C	80	16.7	5.5	1058.1	958.2	1010.2	1095.0
1	C	80	20.2	6.2	940.7	836.4	887.8	962.1
1	C	80	23.7	6.8	850.0	764.3	809.5	864.1
1	C	80	27.7	7.4	736.6	661.2	713.7	742.5
1	C	80	31.2	8.2	666.6	603.1	647.7	671.9
1	C	80	40.2	9.6	548.4	515.3	545.9	555.1
1	D	90	0.0	0.0	2127.4	1991.0	2146.9	2077.9
1	D	90	2.4	0.9	1894.6	1777.5	1993.4	1946.9
1	D	90	5.0	1.9	1723.6	1570.5	1745.6	1743.9
1	D	90	7.2	2.6	1582.0	1452.9	1565.4	1555.3
1	D	90	16.8	5.6	999.4	985.6	1117.3	963.8

Table B-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
1	D	90	20.2	6.5	849.7	834.4	965.6	839.6
1	D	90	23.7	7.3	755.4	721.8	833.3	740.2
1	D	90	27.8	8.1	664.0	636.1	713.8	642.0
1	D	90	31.3	8.6	603.4	581.4	653.3	589.3
1	D	90	40.2	10.1	529.7	511.6	560.4	527.2
2	A	90	0.0	0.0	1924.5	2033.0	1942.2	1929.5
2	A	90	2.0	0.8	1848.2	1907.7	1832.9	1832.3
2	A	90	4.0	1.1	1741.0	1822.0	1711.8	1712.5
2	A	90	6.2	1.9	1618.1	1712.8	1630.8	1594.6
2	A	90	13.8	3.4	1271.6	1343.8	1269.2	1350.3
2	A	90	17.5	4.4	1150.3	1168.2	1115.7	1183.3
2	A	90	21.0	5.1	1025.5	1061.9	984.4	1037.1
2	A	90	24.4	5.8	903.6	948.1	890.2	912.5
2	A	90	27.8	6.5	808.1	836.8	791.2	823.6
2	A	90	30.6	6.9	747.0	758.7	723.2	748.9
2	A	90	37.9	8.0	623.6	630.9	593.0	594.3
2	A	90	40.9	8.5	585.6	590.0	558.9	553.8
2	A	90	43.7	8.9	565.0	563.0	536.4	553.8
2	B	80	0.0	0.0	2123.7	2044.8	1993.6	1868.2
2	B	80	2.0	1.0	1986.6	1872.0	1787.7	1690.7
2	B	80	4.1	1.8	1799.4	1719.9	1611.7	1524.8
2	B	80	6.3	2.5	1630.2	1568.3	1473.4	1367.3
2	B	80	13.9	4.3	1162.5	1122.8	1059.7	998.1
2	B	80	17.6	5.2	988.2	960.8	889.4	846.7
2	B	80	21.0	6.1	864.3	848.7	764.1	732.0
2	B	80	24.4	7.0	758.7	752.1	670.5	640.8
2	B	80	27.9	7.6	677.8	671.3	602.0	579.3
2	B	80	30.7	8.2	628.7	620.9	555.9	542.3
2	B	80	31.2	8.3	549.0	546.9	549.4	*
2	C	70	0.0	0.0	2002.3	2069.3	1936.5	1856.6
2	C	70	2.1	0.9	1812.2	1935.5	1808.6	1708.0
2	C	70	4.2	1.6	1673.1	1776.4	1639.7	1547.9
2	C	70	6.3	2.4	1529.6	1615.0	1501.6	1417.1
2	C	70	14.0	4.7	1132.6	1180.8	1080.4	1026.2
2	C	70	17.6	5.8	964.4	1017.5	931.2	877.4

Table B-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
2	C	70	21.1	6.7	850.2	897.8	811.6	767.7
2	C	70	24.5	7.4	751.9	790.9	723.3	674.5
2	C	70	27.9	8.0	677.0	708.2	646.9	606.6
2	C	70	30.7	8.7	627.5	652.6	599.7	561.0
2	C	70	37.6	10.1	570.8	571.7	522.0	471.4
2	D	0	0.0	0.0	2061.6	1947.8	1923.3	1832.3
2	D	0	2.2	1.4	1827.1	1729.6	1751.3	1707.7
2	D	0	4.3	3.2	1669.8	1517.9	1533.9	1534.1
2	D	0	6.4	4.5	1524.3	1392.6	1343.7	1359.6
2	D	0	14.0	10.0	988.9	1010.2	1013.9	889.7
2	D	0	17.7	12.5	818.7	824.5	852.3	780.9
2	D	0	21.1	15.0	737.3	703.1	708.9	688.2
2	D	0	24.5	17.1	662.5	642.5	609.8	601.2
2	D	0	28.0	19.0	594.8	589.6	564.8	547.0
2	D	0	30.8	20.8	558.2	549.0	531.4	525.8
3	A	80	0.0	0.0	2088.1	2078.6	1961.9	1911.5
3	A	80	2.1	0.9	1952.0	1892.8	1781.1	1757.6
3	A	80	4.0	1.6	1794.6	1783.3	1644.6	1607.1
3	A	80	6.0	2.1	1632.8	1635.5	1522.7	1455.7
3	A	80	13.7	4.7	1144.6	1156.8	1076.7	1104.1
3	A	80	17.2	5.7	1003.8	981.5	910.0	940.0
3	A	80	20.6	6.7	868.3	862.1	788.1	810.6
3	A	80	24.0	7.6	760.0	748.2	695.2	700.1
3	A	80	27.9	8.2	675.6	645.7	613.3	618.2
3	A	80	30.3	8.8	635.0	595.1	571.0	573.6
3	A	80	37.7	10.4	566.1	517.0	507.0	499.8
3	B	90	0.0	0.0	2022.0	1980.4	1953.3	1891.6
3	B	90	2.2	0.9	1851.7	1775.4	1751.2	1705.4
3	B	90	4.0	1.7	1695.6	1638.1	1591.3	1549.5
3	B	90	6.1	2.3	1536.6	1482.9	1445.7	1387.3
3	B	90	13.8	4.1	1067.2	1040.0	1015.6	1002.4
3	B	90	17.3	4.9	905.9	893.8	870.8	860.8
3	B	90	20.7	5.7	792.6	784.0	747.8	740.7
3	B	90	24.1	6.6	686.4	689.4	651.6	641.4
3	B	90	28.0	7.3	602.7	607.9	577.6	568.6

Table B-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
3	B	90	30.4	7.8	565.1	569.0	544.6	534.1
3	B	90	37.7	9.0	500.1	507.2	*	*
3	C	0	0.0	0.0	2059.7	1933.0	1944.8	1906.9
3	C	0	2.2	1.4	1826.0	1705.7	1754.6	1727.6
3	C	0	4.1	2.8	1673.4	1565.7	1610.3	1574.7
3	C	0	6.2	4.1	1527.9	1434.4	1461.5	1426.9
3	C	0	13.9	8.8	1105.2	1051.2	1058.2	1005.6
3	C	0	17.3	10.9	955.9	910.0	923.8	877.3
3	C	0	20.7	13.1	845.5	798.2	795.3	776.0
3	C	0	24.1	15.0	758.0	716.3	695.8	686.9
3	C	0	28.0	16.5	670.0	636.5	617.6	608.9
3	C	0	30.5	17.8	626.5	593.7	577.3	572.4
3	C	0	37.7	21.7	548.7	515.6	495.6	507.3
3	D	70	0.0	0.0	2096.1	2023.6	2065.3	1892.9
3	D	70	2.3	1.3	1812.4	1758.4	1862.3	1712.4
3	D	70	4.1	2.1	1669.3	1574.4	1667.5	1556.9
3	D	70	6.2	3.1	1516.9	1439.5	1469.2	1370.1
3	D	70	13.9	6.0	998.4	1008.3	1058.3	903.3
3	D	70	17.4	7.4	844.6	850.0	907.1	785.9
3	D	70	20.8	8.6	750.3	731.6	766.1	686.3
3	D	70	24.2	9.9	667.8	658.4	653.9	595.8
3	D	70	28.0	11.1	594.1	593.1	587.6	535.6
3	D	70	30.5	11.9	564.2	559.2	551.7	513.2
4	A	70	0.0	0.0	2067.9	2037.8	2027.9	2061.6
4	A	70	2.0	0.9	1934.6	1849.2	1846.2	1890.5
4	A	70	4.0	2.0	1694.5	1652.4	1604.4	1626.9
4	A	70	6.1	2.6	1543.7	1514.5	1482.4	1487.4
4	A	70	13.8	5.2	1132.7	1098.3	1093.6	1155.1
4	A	70	17.1	6.0	1016.0	965.7	972.4	1025.8
4	A	70	20.7	6.7	885.5	846.2	859.8	886.2
4	A	70	24.1	7.5	774.4	742.6	768.4	774.6
4	A	70	27.7	8.3	695.3	654.7	698.5	699.2
4	A	70	30.0	8.6	651.8	609.7	654.5	655.4
4	A	70	39.3	10.7	552.7	511.0	555.5	542.1
4	B	0	0.0	0.0	2040.3	2109.1	2006.5	2104.5

Table B-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
4	B	0	2.0	1.6	1852.5	1892.1	1800.3	1924.6
4	B	0	4.1	3.1	1702.9	1717.7	1607.7	1730.4
4	B	0	6.1	4.3	1564.1	1584.8	1466.6	1562.1
4	B	0	13.9	9.7	1094.2	1144.9	1112.6	1145.3
4	B	0	17.2	12.0	946.6	999.7	985.5	1026.4
4	B	0	20.8	14.2	832.6	867.1	843.4	896.9
4	B	0	24.4	16.4	727.5	775.2	741.1	778.2
4	B	0	27.7	18.5	647.4	694.3	676.5	704.3
4	B	0	30.1	20.2	603.7	642.7	633.7	667.2
4	B	0	39.4	26.4	520.7	533.1	529.2	564.3
4	C	90	0.0	0.0	2030.7	2070.7	2063.5	2067.9
4	C	90	2.2	0.9	1876.3	1903.8	1909.1	1907.3
4	C	90	4.2	1.5	1690.4	1746.4	1744.3	1755.6
4	C	90	6.2	2.1	1557.4	1618.6	1611.6	1609.4
4	C	90	14.0	3.5	1156.9	1220.8	1143.5	1211.3
4	C	90	17.2	4.4	1003.7	1074.7	1004.0	1060.1
4	C	90	20.8	5.1	874.3	946.5	868.0	930.8
4	C	90	24.4	5.7	765.3	826.9	761.7	806.3
4	C	90	27.8	6.5	684.9	742.6	681.7	725.4
4	C	90	30.1	6.7	638.0	690.7	635.5	669.6
4	C	90	39.4	8.6	527.9	570.9	528.5	538.8
4	D	80	0.0	0.0	2060.2	2125.2	2037.9	2044.1
4	D	80	2.2	1.0	1812.4	1897.1	1871.4	1908.3
4	D	80	4.3	1.7	1648.7	1686.2	1663.0	1735.3
4	D	80	6.3	2.4	1514.7	1556.1	1484.3	1550.6
4	D	80	14.0	4.9	980.8	1120.0	1083.8	1017.6
4	D	80	17.3	5.9	820.5	975.8	950.7	897.9
4	D	80	20.9	6.9	708.5	831.0	802.9	777.4
4	D	80	24.5	7.9	620.6	737.1	691.7	671.2
4	D	80	27.8	8.8	558.1	667.2	627.8	603.5
4	D	80	30.2	9.7	528.0	623.3	588.5	572.7
4	D	80	39.5	11.0	*	540.3	*	*

* tray removed prior to this time.

APPENDIX C

Fixed-Rate Drying of Red Haven Peaches

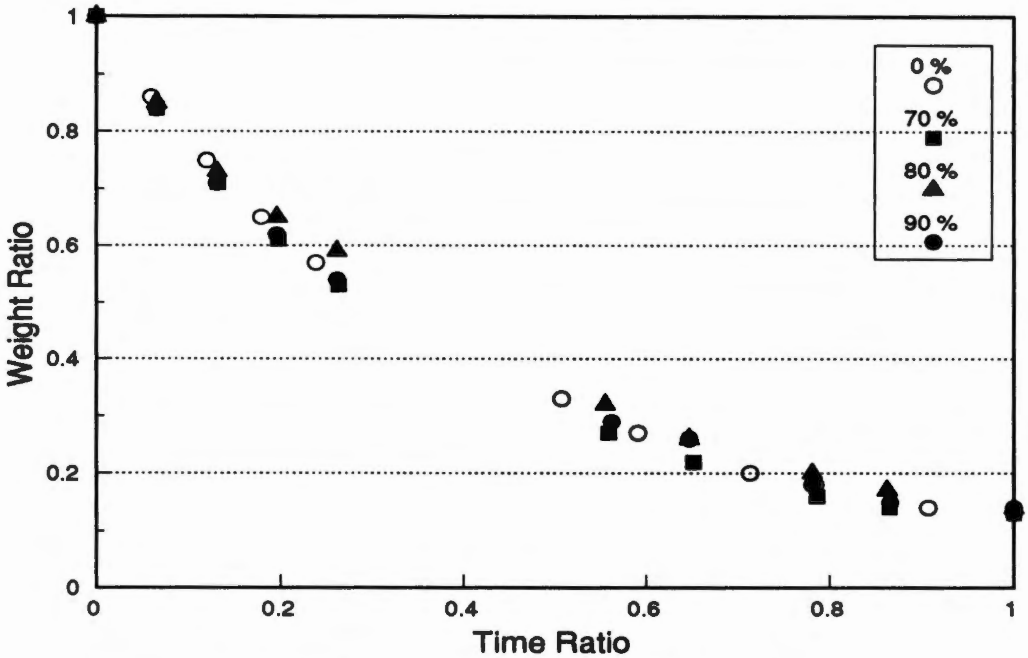


Figure C-1. Effect of recirculated air on the moisture removal for Red Haven peaches (test 1).

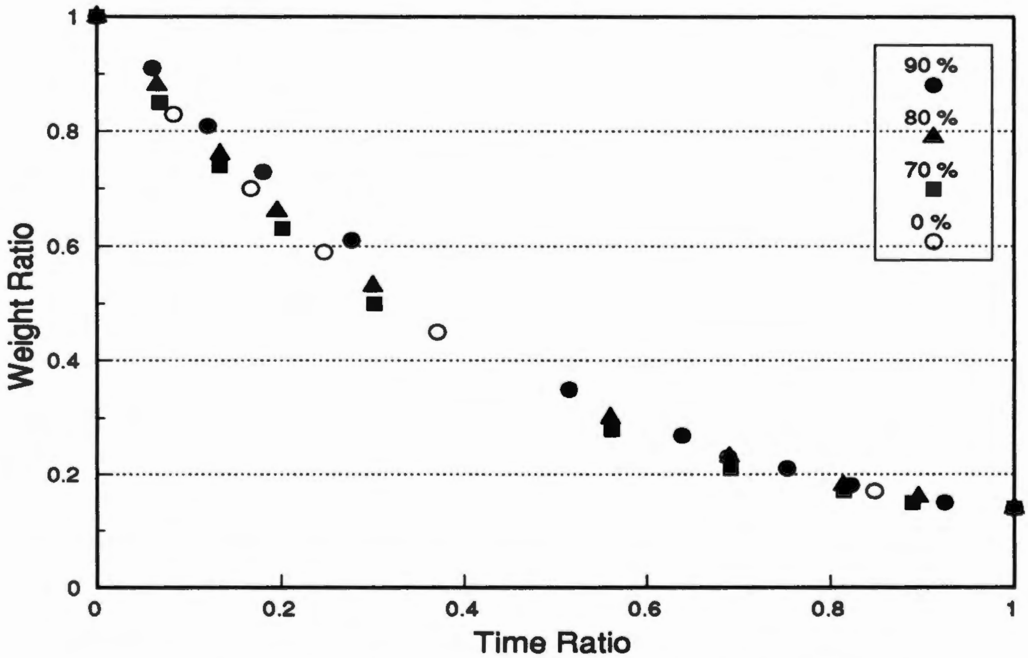


Figure C-2. Effect of recirculated air on the moisture removal for Red Haven peaches (test 2).

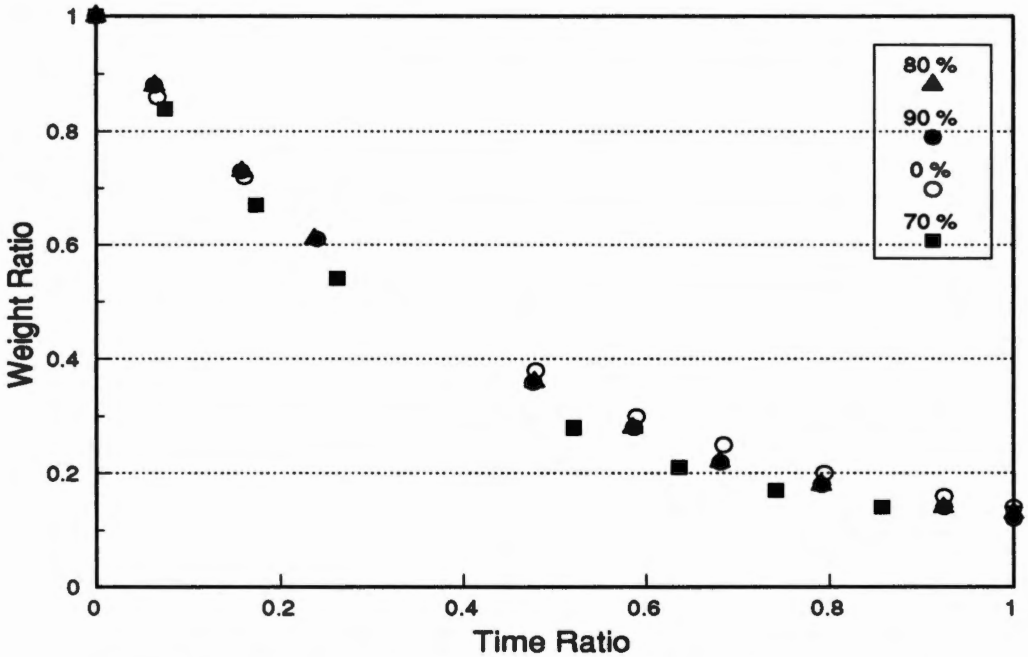


Figure C-3. Effect of recirculated air on the moisture removal for Red Haven peaches (test 3).

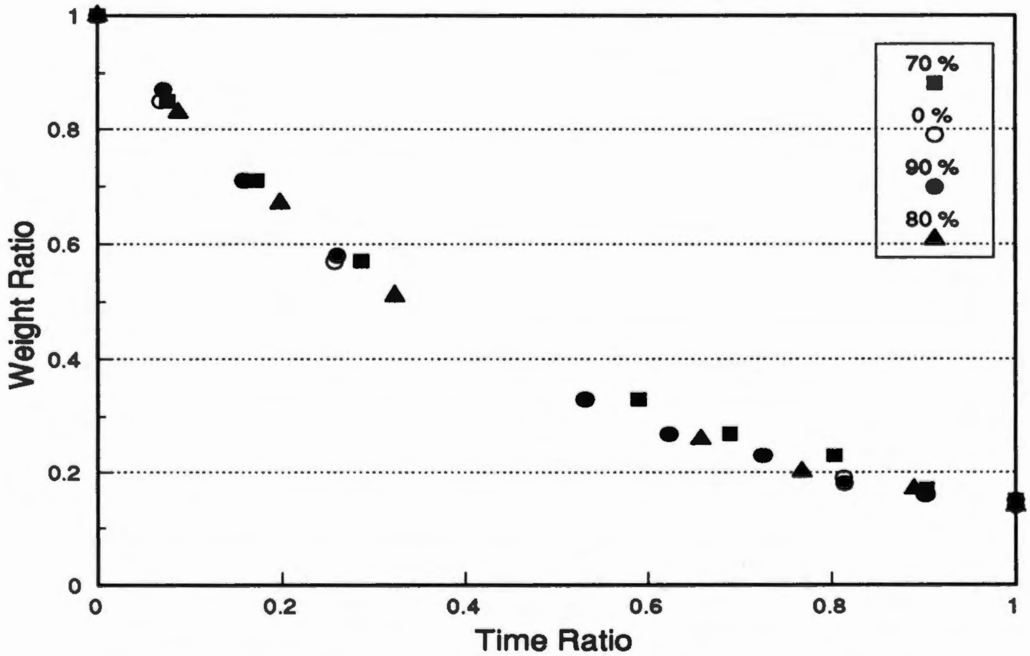


Figure C-4. Effect of recirculated air on the moisture removal for Red Haven peaches (test 4).

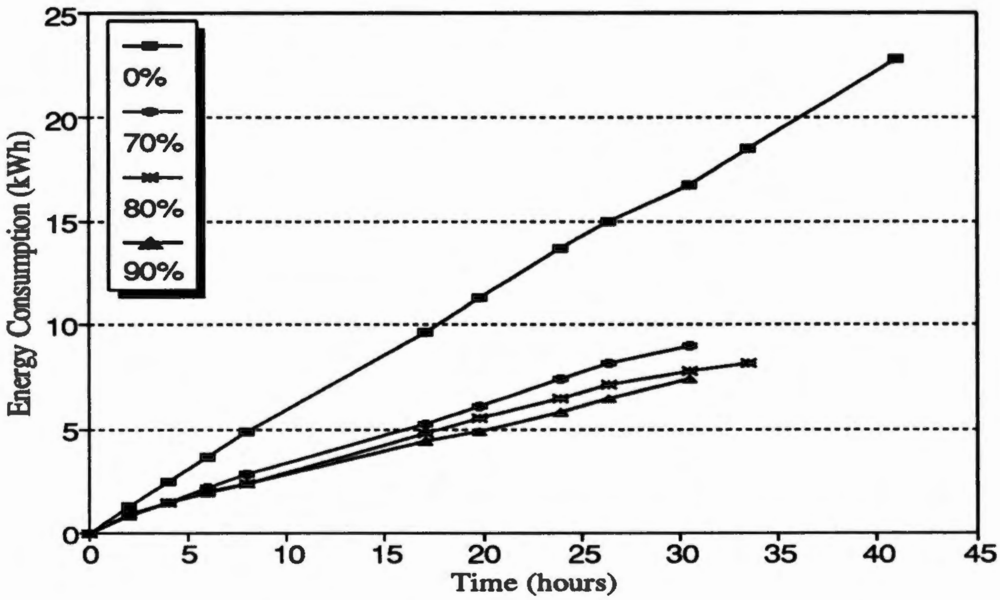


Figure C-5. The experimental data of cumulative energy consumption versus time for dried Red Haven peaches (test 1).

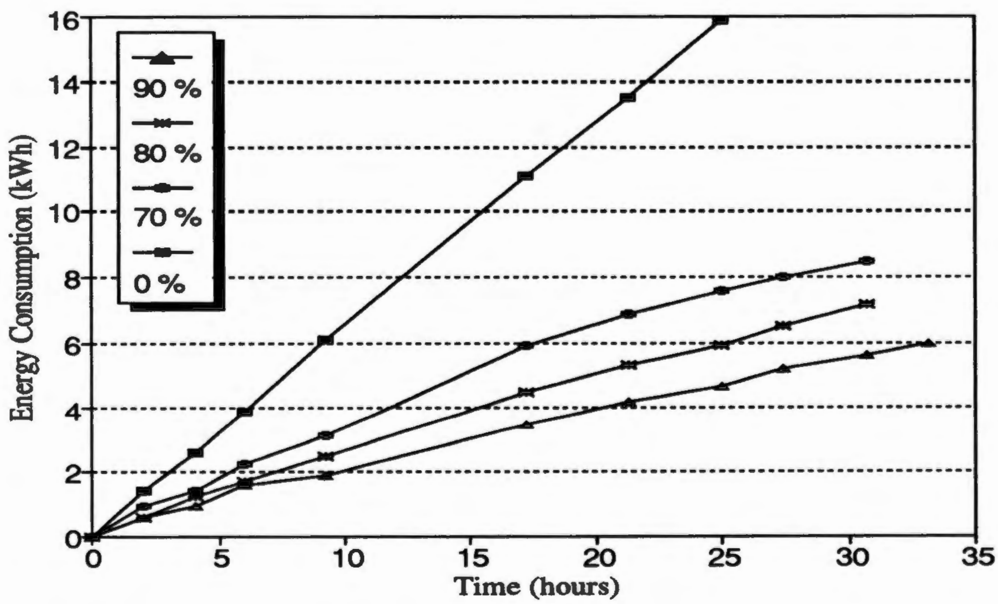


Figure C-6. The experimental data of cumulative energy consumption versus time for dried Red Haven peaches (test 2).

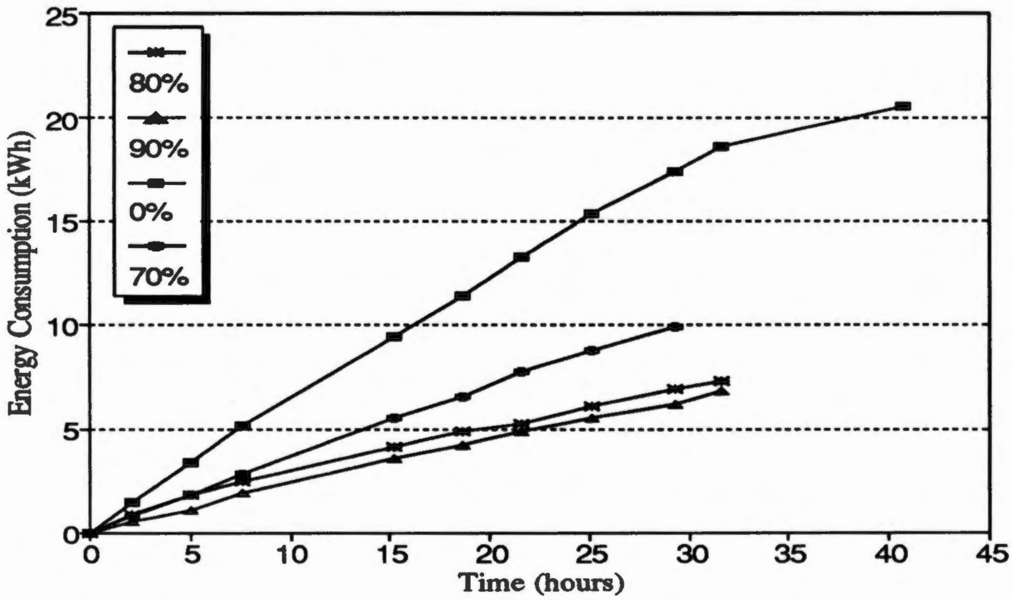


Figure C-7. The experimental data of cumulative energy consumption versus time for dried Red Haven peaches (test 3).

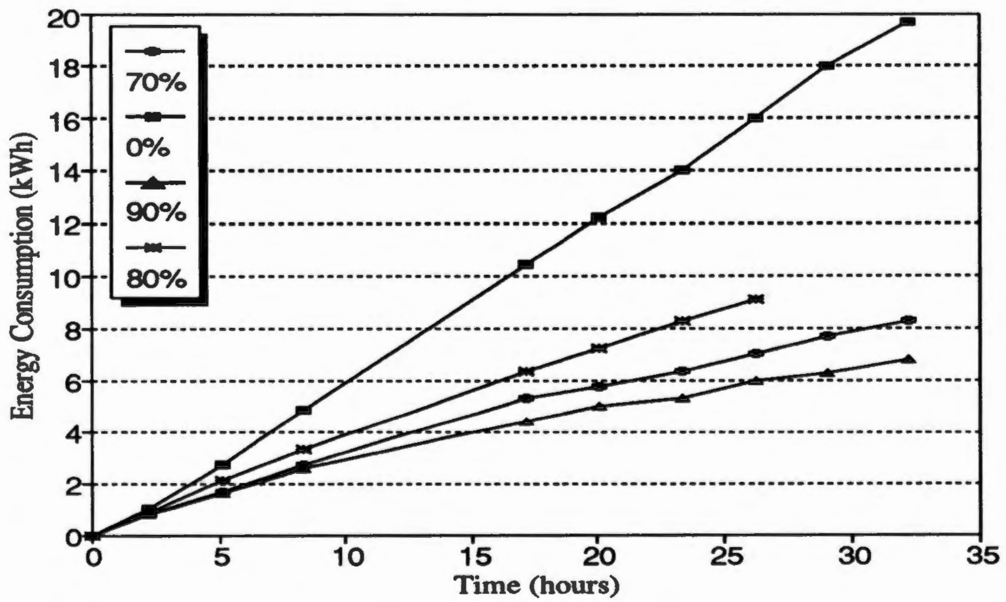


Figure C-8. The experimental data of cumulative energy consumption versus time for dried Red Haven peaches (test 4).

Table C-1. Time, energy consumption, and total fruit weights for Run Haven peach tests.

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
1	A	0	0.0	0.0	1487.4	1447.0	1225.2	1363.3
1	A	0	2.0	1.3	1335.4	1276.0	1072.8	1228.2
1	A	0	4.0	2.5	1207.6	1126.0	951.3	1118.7
1	A	0	6.0	3.7	1098.9	1013.0	847.6	1001.9
1	A	0	8.0	4.9	998.3	924.0	770.5	914.7
1	A	0	17.0	9.6	727.7	600.9	514.4	648.3
1	A	0	19.8	11.3	659.8	531.5	460.7	579.4
1	A	0	23.9	13.7	568.7	466.7	408.2	487.4
1	A	0	26.3	15.0	532.6	435.5	390.1	457.8
1	A	0	30.4	16.8	485.1	400.1	365.8	420.3
1	A	0	33.5	18.5	434.8	*	*	400.7
1	B	70	0.0	0.0	1218.7	1359.9	1219.1	1357.0
1	B	70	2.0	0.8	1076.9	1186.2	1044.1	1194.8
1	B	70	4.0	1.4	955.2	1032.9	901.7	1069.8
1	B	70	6.0	2.2	851.1	930.1	805.2	946.5
1	B	70	8.0	2.8	758.5	837.4	721.9	861.8
1	B	70	17.0	5.3	527.3	568.1	475.4	548.0
1	B	70	19.8	6.1	466.8	488.4	424.4	498.1
1	B	70	23.9	7.4	410.9	430.1	382.5	433.0
1	B	70	26.3	8.1	389.3	406.3	369.4	411.6
1	B	70	30.5	9.0	368.5	381.8	*	387.9
1	C	80	0.0	0.0	1280.1	1367.5	1242.2	1544.2
1	C	80	2.0	0.9	1113.8	1195.3	1109.0	1369.6
1	C	80	4.0	1.4	979.6	1066.7	988.3	1206.9
1	C	80	6.0	2.0	894.3	968.0	903.3	1107.1
1	C	80	8.0	2.4	830.8	899.9	837.3	1022.3
1	C	80	17.1	4.8	550.3	598.3	566.8	689.9
1	C	80	19.8	5.5	493.1	531.9	504.9	609.7
1	C	80	23.9	6.5	434.6	463.3	436.9	521.7
1	C	80	26.4	7.1	411.2	437.6	411.2	483.6
1	C	80	30.6	7.8	385.5	406.2	379.7	440.9
1	C	80	33.6	8.1	*	*	*	419.6
1	D	90	0.0	0.0	1439.8	1287.2	1167.3	1578.4
1	D	90	2.0	0.8	1198.0	1104.1	1043.0	1415.1

Table C-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
1	D	90	4.0	1.4	1063.0	996.4	912.1	1213.8
1	D	90	6.0	1.9	965.8	903.8	818.1	1084.8
1	D	90	8.0	2.4	856.8	822.6	743.7	977.0
1	D	90	17.2	4.4	571.4	526.3	515.5	691.4
1	D	90	19.8	4.9	511.6	470.6	555.5	611.1
1	D	90	23.9	5.8	455.0	422.9	408.6	522.0
1	D	90	26.5	6.5	421.6	394.3	381.2	472.2
1	D	90	30.6	7.4	392.2	*	*	425.6
2	A	90	0.0	0.0	1389.2	1418.7	1278.0	1295.5
2	A	90	2.0	0.6	1288.2	1305.0	1184.3	1083.2
2	A	90	4.0	0.9	1191.8	1202.2	1083.2	1005.6
2	A	90	6.0	1.6	1092.4	1098.3	1005.6	861.2
2	A	90	9.2	1.9	950.4	954.2	861.2	580.9
2	A	90	17.1	3.5	705.6	650.5	580.9	490.6
2	A	90	21.2	4.2	598.7	559.4	490.6	436.2
2	A	90	25.0	4.7	521.4	490.3	436.2	410.2
2	A	90	27.3	5.2	486.8	454.6	410.2	386.2
2	A	90	30.7	5.6	455.3	421.3	386.2	*
2	A	90	33.2	6.0	439.3	405.2	*	*
2	B	80	0.0	0.0	1278.3	1444.5	1356.7	1296.7
2	B	80	2.0	0.6	1161.7	1289.3	1215.1	1162.7
2	B	80	4.1	1.2	1030.6	1170.1	1091.5	1036.7
2	B	80	6.0	1.7	914.6	1044.3	995.4	918.9
2	B	80	9.2	2.5	788.6	882.7	857.6	798.8
2	B	80	17.2	4.5	572.7	586.5	584.3	550.6
2	B	80	21.2	5.3	496.2	502.5	500.9	465.1
2	B	80	25.0	5.9	443.8	447.7	448.7	418.3
2	B	80	27.5	6.5	420.7	423.3	425.3	398.6
2	B	80	30.7	7.2	399.2	*	399.9	*
2	C	70	0.0	0.0	1292.5	1388.5	1368.3	1304.6
2	C	70	2.1	0.9	1104.1	1237.0	1212.9	1160.0
2	C	70	4.1	1.4	990.3	1096.6	1089.9	1032.8
2	C	70	6.2	2.2	886.7	973.6	960.5	921.6
2	C	70	9.3	4.1	752.2	829.0	820.5	773.5

Table C-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
2	C	70	17.3	5.9	537.5	561.0	569.1	537.6
2	C	70	21.3	6.9	466.2	480.4	488.0	465.9
2	C	70	25.1	7.6	422.5	432.3	437.6	420.2
2	C	70	27.4	8.0	402.1	412.1	417.7	400.9
2	C	70	30.8	8.5	*	*	396.3	*
2	D	0	0.0	0.0	1429.3	1309.1	1368.8	1356.3
2	D	0	2.1	1.4	1220.7	1098.4	1187.5	1210.5
2	D	0	4.2	2.6	1092.1	951.5	1020.0	1060.4
2	D	0	6.2	3.9	970.4	859.4	882.4	909.3
2	D	0	9.3	6.1	771.5	733.6	767.4	728.2
2	D	0	17.3	11.1	444.0	466.4	528.4	525.3
2	D	0	21.3	13.5	409.2	388.2	447.8	449.6
2	D	0	25.1	15.9	*	*	*	401.2
3	A	80	0.0	0.0	1452.1	1498.6	1521.3	1426.9
3	A	80	2.0	0.9	1323.8	1358.4	1379.6	1307.7
3	A	80	5.0	1.8	1115.1	1203.4	1185.3	1116.1
3	A	80	7.5	2.5	977.5	1051.7	1062.3	961.8
3	A	80	15.1	4.1	663.4	715.1	744.1	691.9
3	A	80	18.5	4.9	583.0	603.8	628.6	590.3
3	A	80	21.5	5.3	524.2	540.3	553.7	517.7
3	A	80	25.0	6.1	469.6	479.2	489.5	455.1
3	A	80	29.2	6.9	436.5	431.6	439.5	419.7
3	A	80	31.6	7.3	*	414.1	417.7	*
3	B	90	0.0	0.0	1488.8	1487.7	1356.1	1349.1
3	B	90	2.0	0.5	1339.0	1352.6	1223.6	1213.5
3	B	90	5.0	1.1	1147.8	1191.4	1055.0	1032.0
3	B	90	7.6	1.9	992.8	1043.1	934.6	894.8
3	B	90	15.1	3.6	679.0	699.7	653.7	640.8
3	B	90	18.6	4.2	587.8	592.2	555.6	552.6
3	B	90	21.6	4.9	519.6	523.4	495.5	487.1
3	B	90	25.1	5.6	456.4	462.8	442.8	436.0
3	B	90	29.3	6.2	415.1	413.3	405.1	401.6
3	B	90	31.7	6.8	*	*	389.9	*
3	C	0	0.0	0.0	1474.4	1351.4	1473.8	1392.2

Table C-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
3	C	0	2.1	1.4	1288.2	1201.4	1311.8	1241.6
3	C	0	5.1	3.4	1124.2	1032.3	1128.9	1082.8
3	C	0	7.6	5.2	1011.4	921.8	984.3	946.2
3	C	0	15.2	9.4	701.5	672.1	738.2	661.2
3	C	0	18.7	11.4	610.5	576.6	645.0	580.0
3	C	0	21.7	13.3	554.1	510.6	573.9	523.2
3	C	0	25.2	15.4	500.6	464.3	505.1	464.1
3	C	0	29.3	17.4	447.6	425.4	459.4	418.1
3	C	0	31.7	18.6	425.9	405.2	435.8	402.6
3	C	0	32.5	19.2	421.2	*	429.2	*
3	D	70	0.0	0.0	1451.7	1488.2	1410.0	1307.4
3	D	70	2.2	0.8	1215.0	1282.3	1249.5	1177.5
3	D	70	5.1	1.8	1042.2	1055.8	1019.8	977.6
3	D	70	7.7	2.8	898.3	923.6	867.2	821.1
3	D	70	15.3	5.6	557.3	629.8	607.1	516.5
3	D	70	18.7	6.6	474.5	526.2	521.8	455.3
3	D	70	21.8	6.8	432.6	470.5	460.1	413.0
3	D	70	25.2	8.8	401.5	432.4	421.3	384.1
3	D	70	29.4	9.9	*	405.9	*	*
4	A	70	0.0	0.0	1454.2	1359.3	1359.3	1479.6
4	A	70	2.2	0.8	1324.4	1193.5	1308.1	1308.1
4	A	70	5.0	1.7	1125.4	1051.9	1117.4	1054.0
4	A	70	8.3	2.7	962.4	890.6	969.9	889.0
4	A	70	17.1	5.3	642.5	609.7	669.0	597.9
4	A	70	20.0	5.8	578.1	532.7	586.0	532.5
4	A	70	23.3	6.4	528.2	487.1	530.3	483.4
4	A	70	26.2	7.0	472.2	436.8	478.5	435.5
4	A	70	29.0	7.7	442.9	406.7	449.2	*
4	A	70	32.2	8.3	*	*	426.5	*
4	B	0	0.0	0.0	1459.2	1358.3	1453.4	1411.2
4	B	0	2.2	1.0	1296.0	1181.0	1266.0	1237.4
4	B	0	5.1	2.7	1124.6	1030.1	1076.4	1070.4
4	B	0	8.3	4.9	960.2	894.1	927.6	890.1
4	B	0	17.1	10.4	650.7	598.8	652.3	623.4

Table C-1. continued

Test	Dryer	Rate (%)	Time (hrs)	Cum_Eng (kWh)	Weight (g) tray 1	Weight (g) tray 2	Weight (g) tray 3	Weight (g) tray 4
4	B	0	20.1	12.2	581.7	528.1	580.7	563.8
4	B	0	23.4	14.0	537.8	484.0	527.2	515.2
4	B	0	26.2	16.0	481.1	442.6	474.0	458.7
4	B	0	29.1	18.0	449.5	415.5	446.2	431.8
4	B	0	32.2	19.7	428.2	*	424.4	*
4	C	90	0.0	0.0	1444.8	1414.7	1409.7	1395.2
4	C	90	2.3	0.8	1289.3	1253.4	1262.6	1236.6
4	C	90	5.2	1.6	1096.9	1070.9	1085.4	1075.2
4	C	90	8.4	2.6	946.9	912.3	920.8	919.0
4	C	90	17.2	4.4	637.4	628.3	610.5	633.6
4	C	90	20.1	5.0	565.2	560.6	546.1	565.4
4	C	90	23.4	5.3	515.1	511.2	498.6	518.1
4	C	90	26.3	6.0	435.3	464.8	450.9	466.5
4	C	90	29.1	6.3	*	*	424.6	435.5
4	C	90	32.3	6.8	*	*	*	415.6
4	D	80	0.0	0.0	1451.0	1386.4	1396.2	1482.9
4	D	80	2.3	0.9	1229.4	1159.3	1220.2	1314.1
4	D	80	5.2	2.1	1059.8	959.8	1002.3	1118.5
4	D	80	8.5	3.3	882.9	812.1	815.7	897.9
4	D	80	17.3	6.4	533.4	538.3	559.1	561.6
4	D	80	20.2	7.3	470.8	472.5	497.0	504.8
4	D	80	23.4	8.3	438.4	435.3	451.0	464.5
4	D	80	26.3	9.1	406.7	408.6	415.7	424.4

* tray removed prior to this time.

APPENDIX D

Variable-Rate Drying of Apples

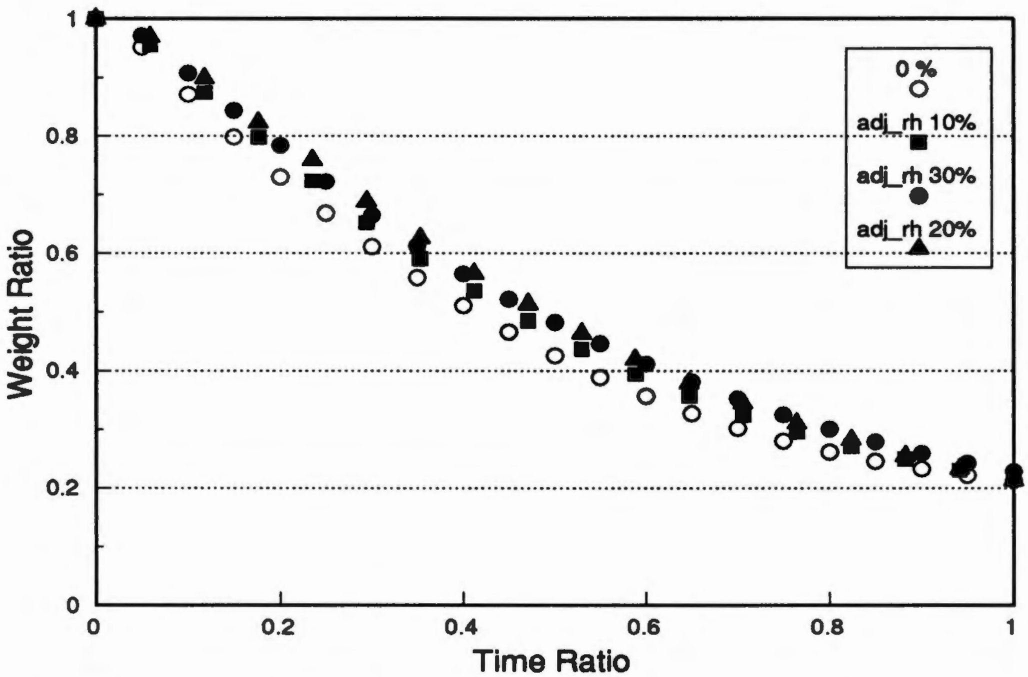


Figure D-1. Effect of variable recirculation rates on drying rates (test 1).

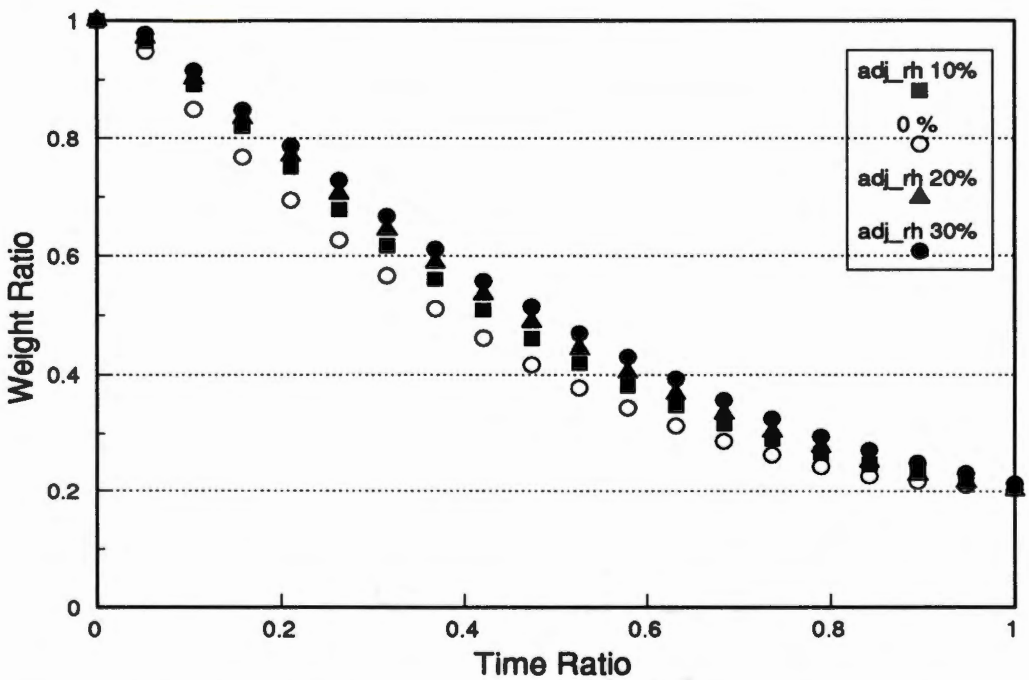


Figure D-2. Effect of variable recirculation rates on drying rates (test 2).

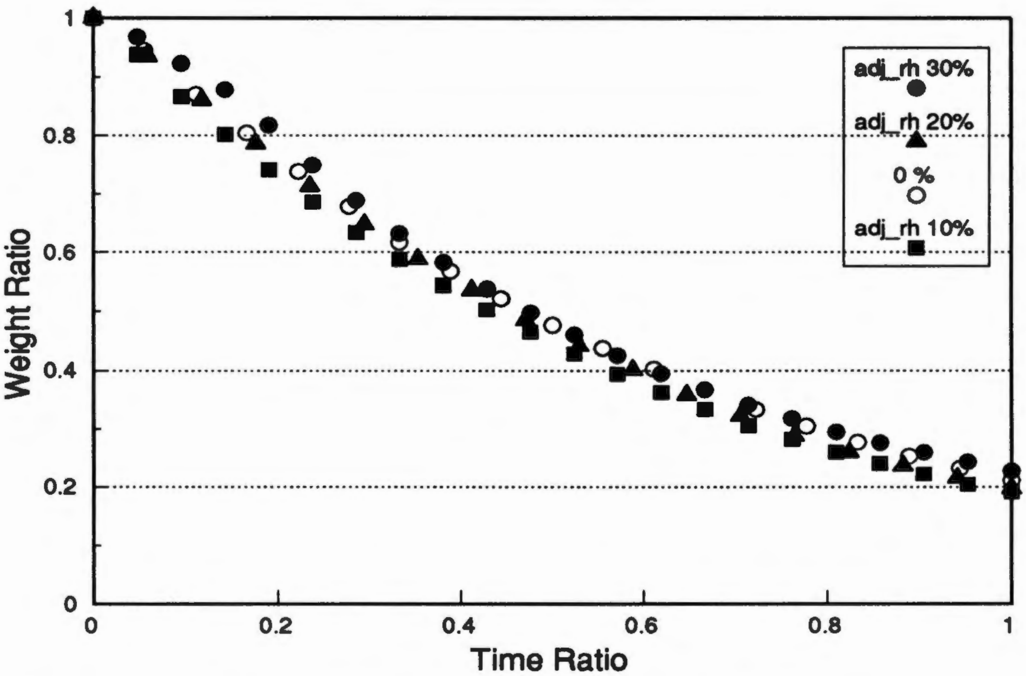


Figure D-3. Effect of variable recirculation rates on drying rates (test 3).

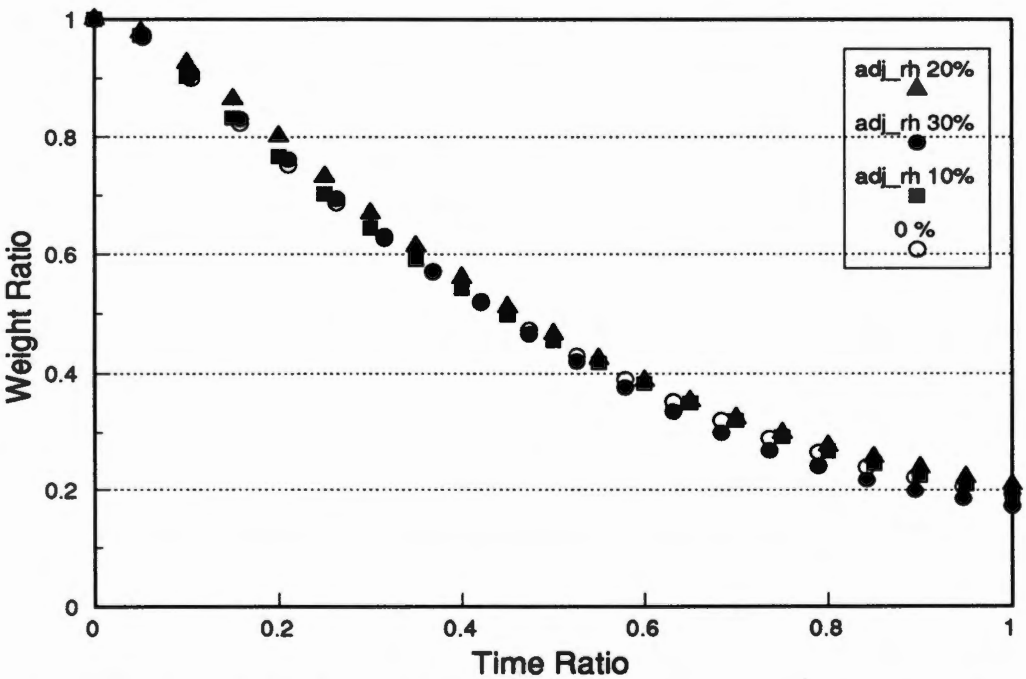


Figure D-4. Effect of variable recirculation rates on drying rates (test 4).

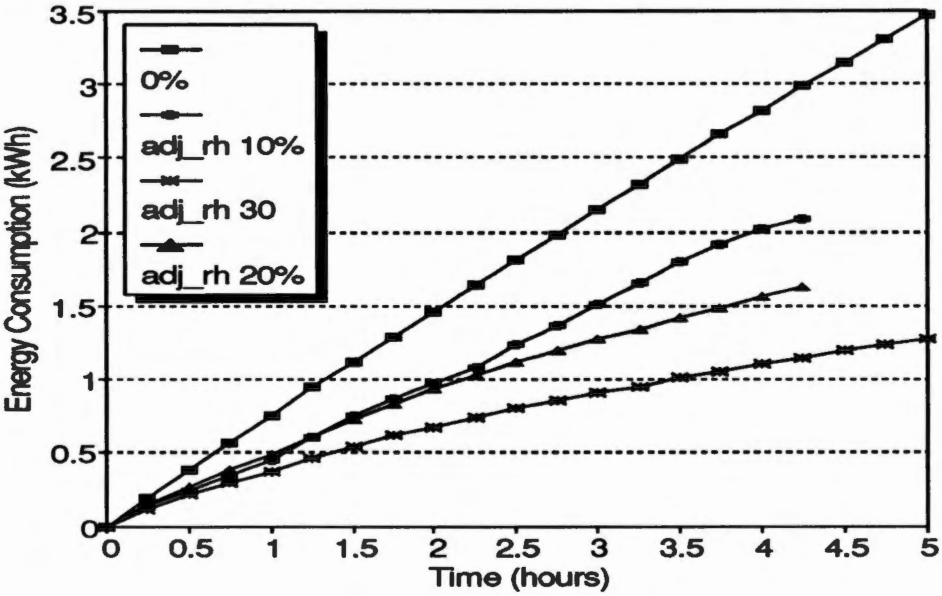


Figure D-5. The experimental data of cumulative energy consumption versus time for variable-rate apple drying (test 1).

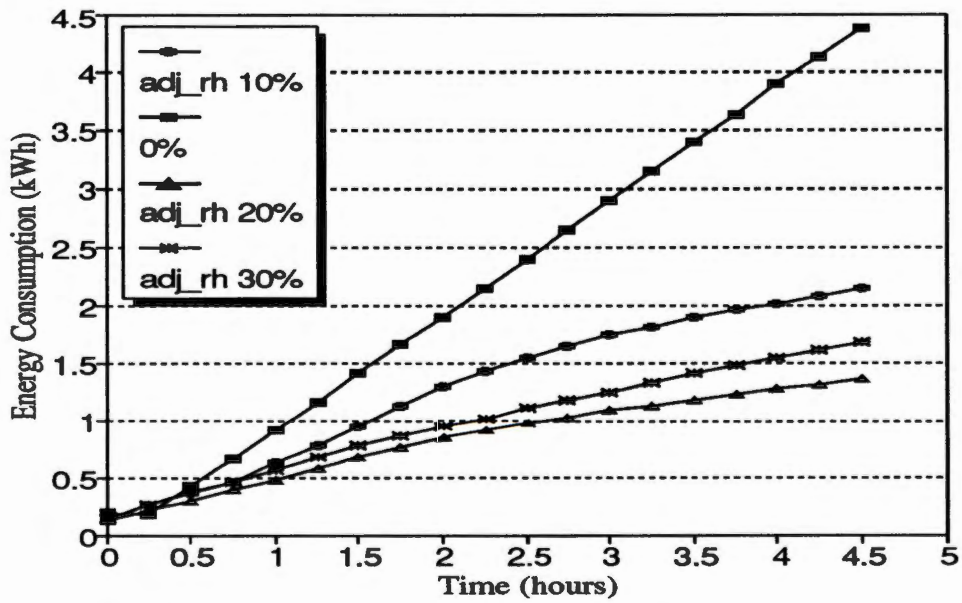


Figure D-6. The experimental data of cumulative energy consumption versus time for variable-rate apple drying (test 2).

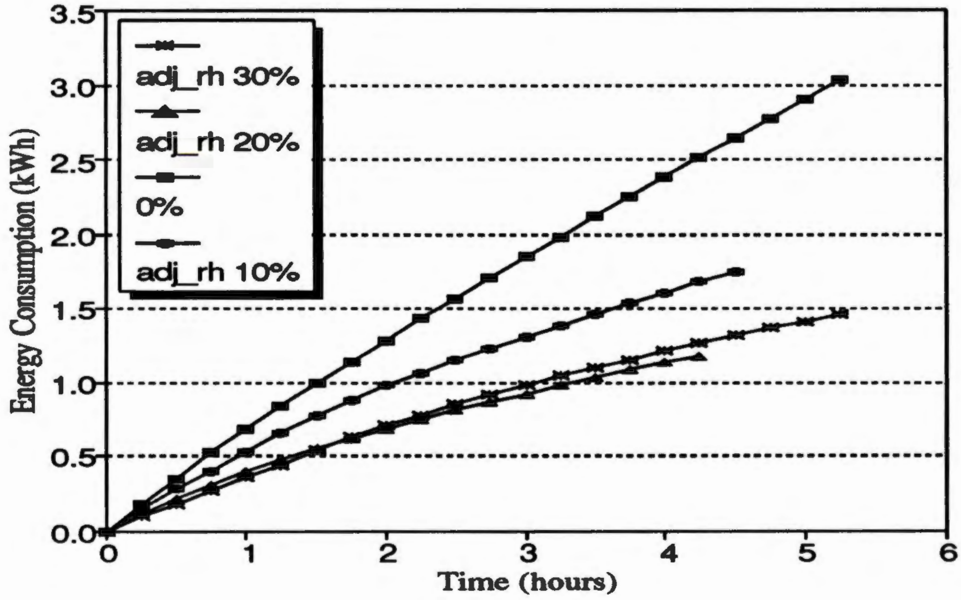


Figure D-7. The experimental data of cumulative energy consumption versus time for variable-rate apple drying (test 3).

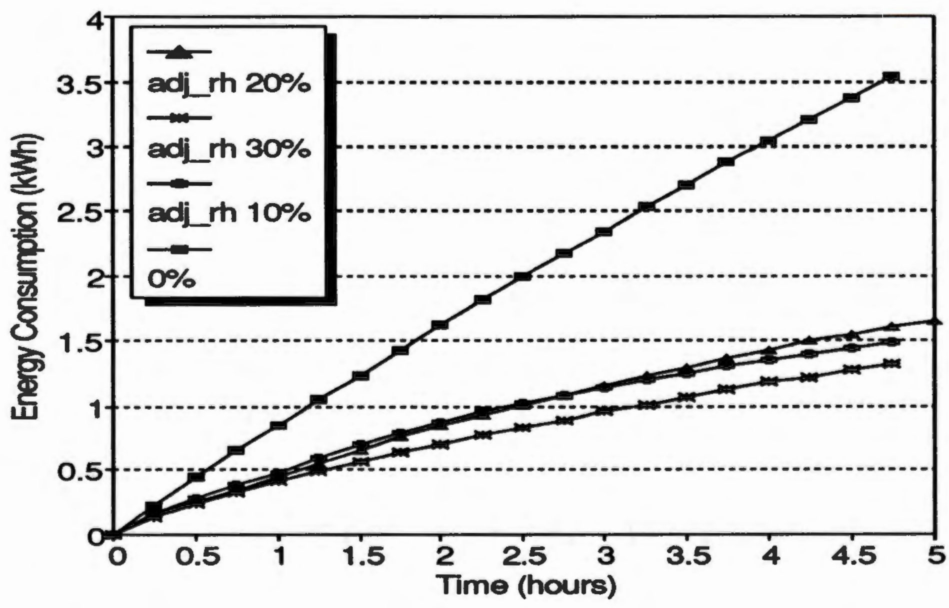


Figure D-8. The experimental data of cumulative energy consumption versus time for variable-rate apple drying (test 4).

Table D-1. Time, energy consumption, total fruit weights, and weight ratio for variable-rate apple tests.

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	A	0	0	0	0	1004.4	1
1	A	0	0.25	108	0.1944	956.06	0.95187
1	A	0	0.5	213	0.3834	875.85	0.87201
1	A	0	0.75	319	0.5742	801.46	0.79795
1	A	0	1	422	0.7596	733.36	0.73015
1	A	0	1.25	523	0.9414	671.05	0.66811
1	A	0	1.5	618	1.1124	613.61	0.61092
1	A	0	1.75	715	1.2870	561.47	0.55901
1	A	0	2	815	1.4670	513.67	0.51142
1	A	0	2.25	914	1.6452	468.69	0.46664
1	A	0	2.5	1008	1.8144	427.47	0.42560
1	A	0	2.75	1103	1.9854	390.46	0.38875
1	A	0	3	1194	2.1492	358.07	0.35650
1	A	0	3.25	1290	2.3220	328.97	0.32753
1	A	0	3.5	1385	2.4930	303.36	0.30203
1	A	0	3.75	1478	2.6604	281.45	0.28022
1	A	0	4	1566	2.8188	262.83	0.26168
1	A	0	4.25	1659	2.9862	247.08	0.24600
1	A	0	4.5	1749	3.1482	233.79	0.23277
1	B	70	0	0	0	1028.9	1
1	B	70	0.25	73	0.1314	982.92	0.95531
1	B	70	0.5	135	0.2430	900.34	0.87505
1	B	70	0.75	192	0.3456	820.36	0.79732
1	B	70	1	252	0.4536	744.28	0.72337
1	B	70	1.25	338	0.6084	670.87	0.65203
1	B	70	1.5	414	0.7452	608.51	0.59142
1	B	70	1.75	486	0.8748	552	0.53650
1	B	70	2	539	0.9702	499.54	0.48551
1	B	70	2.25	602.5	1.0845	449.89	0.43725
1	B	70	2.5	683	1.2294	405.38	0.39399
1	B	70	2.75	759	1.3662	367.35	0.35703
1	B	70	3	841.5	1.5147	333.81	0.32443
1	B	70	3.25	920.5	1.6569	304.3	0.29575
1	B	70	3.5	997.5	1.7955	279.09	0.27125
1	B	70	3.75	1067	1.9206	256.95	0.24973
1	B	70	4	1122	2.0196	237	0.23034

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	B	70	4.25	1159	2.0862	219.95	0.21377
1	C	90	0	0	0	970.28	1
1	C	90	0.25	64	0.1152	942.97	0.97185
1	C	90	0.5	116	0.2088	880.79	0.90777
1	C	90	0.25	161	0.2898	818.98	0.84407
1	C	90	0.5	207	0.3726	760.27	0.78356
1	C	90	0.75	257	0.4626	700.4	0.72185
1	C	90	1	302	0.5436	645.12	0.66488
1	C	90	1.25	343	0.6174	594.46	0.61267
1	C	90	1.5	378	0.6804	548.88	0.56569
1	C	90	1.75	411	0.7398	506.87	0.52240
1	C	90	2	446	0.8028	468.63	0.48298
1	C	90	2.25	474	0.8532	433.27	0.44654
1	C	90	2.5	503	0.9054	399.81	0.41206
1	C	90	2.75	532	0.9576	369.75	0.38108
1	C	90	3	562	1.0116	341.63	0.35209
1	C	90	3.25	588	1.0584	314.72	0.32436
1	C	90	3.5	615	1.1070	291.43	0.30036
1	C	90	3.75	639	1.1502	270.17	0.27845
1	C	90	4	662	1.1916	251.39	0.25909
1	D	80	0	0	0	906.06	1
1	D	80	0.25	84	0.1512	878.36	0.96943
1	D	80	0.5	152	0.2736	814.34	0.89877
1	D	80	0.75	215	0.3870	746.05	0.82340
1	D	80	1	276	0.4968	687.09	0.75833
1	D	80	1.25	339	0.6102	623.59	0.68824
1	D	80	1.5	403	0.7254	566.92	0.62570
1	D	80	1.75	460	0.8280	512.03	0.56512
1	D	80	2	517	0.9306	465.76	0.51405
1	D	80	2.25	571	1.0278	420.41	0.46400
1	D	80	2.5	621	1.1178	379.96	0.41935
1	D	80	2.75	666	1.1988	343.32	0.37892
1	D	80	3	707	1.2726	311.98	0.34433
1	D	80	3.25	747	1.3446	281.59	0.31079
1	D	80	3.5	785	1.4130	255.61	0.28211
1	D	80	3.75	827	1.4886	230.23	0.25410

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
1	D	80	4	867	1.5606	210.86	0.23272
1	D	80	4.25	901	1.6218	192.36	0.21230
2	A	70	0	0	0	994.59	1.00000
2	A	70	0.25	75	0.1350	959.14	0.96436
2	A	70	0.5	141	0.2538	886.35	0.89117
2	A	70	0.75	200	0.3600	814.76	0.81919
2	A	70	1	259	0.4662	746.55	0.75061
2	A	70	1.25	345	0.6210	674.77	0.67844
2	A	70	1.5	437	0.7866	613.84	0.61718
2	A	70	1.75	530	0.9540	557.55	0.56058
2	A	70	2	629	1.1322	506.11	0.50886
2	A	70	2.25	719	1.2942	458.97	0.46147
2	A	70	2.5	797	1.4346	417.04	0.41931
2	A	70	2.75	863	1.5534	378.7	0.38076
2	A	70	3	920	1.6560	345.95	0.34783
2	A	70	3.25	969	1.7442	314.84	0.31655
2	A	70	3.5	1011	1.8198	289.21	0.29078
2	A	70	3.75	1055	1.8990	265.09	0.26653
2	A	70	4	1092	1.9656	246.37	0.24771
2	A	70	4.25	1123	2.0214	232.17	0.23343
2	A	70	4.5	1155	2.0790	214.65	0.21582
2	A	70	4.75	1192	2.1456	202.76	0.20386
2	B	0	0	0	0	976.59	1
2	B	0	0.25	107	0.1926	925.44	0.94762
2	B	0	0.5	209	0.3762	829.5	0.84938
2	B	0	0.75	307	0.5526	749.66	0.76763
2	B	0	1	403	0.7254	677.79	0.69404
2	B	0	1.25	497	0.8946	611.71	0.62637
2	B	0	1.5	590	1.0620	553.12	0.56638
2	B	0	1.75	681	1.2258	499.38	0.51135
2	B	0	2	772	1.3896	451.09	0.46190
2	B	0	2.25	860	1.5480	407.52	0.41729
2	B	0	2.5	947.5	1.7055	369.2	0.37805
2	B	0	2.75	1033	1.8594	335.27	0.34331
2	B	0	3	1118	2.0124	305.23	0.31255
2	B	0	3.25	1202	2.1636	279.88	0.28659

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
2	B	0	3.5	1285	2.3130	257.76	0.26394
2	B	0	3.75	1367	2.4606	238.71	0.24443
2	B	0	4	1448	2.6064	222.58	0.22792
2	B	0	4.25	1530	2.7540	212.06	0.21714
2	B	0	4.5	1611	2.8998	204.86	0.20977
2	B	0	4.75	1692	3.0456	198.43	0.20319
2	C	80	0	0	0	940.24	1
2	C	80	0.25	68	0.1224	912.08	0.97005
2	C	80	0.5	120	0.2160	847.52	0.90139
2	C	80	0.75	169	0.3042	783.3	0.83309
2	C	80	1	218	0.3924	724.04	0.77006
2	C	80	1.25	268	0.4824	663.55	0.70572
2	C	80	1.5	322	0.5796	605.91	0.64442
2	C	80	1.75	374	0.6732	553	0.58815
2	C	80	2	422	0.7596	503.62	0.53563
2	C	80	2.25	470	0.8460	459.89	0.48912
2	C	80	2.5	512	0.9216	417.35	0.44388
2	C	80	2.75	545	0.9810	379.51	0.40363
2	C	80	3	578	1.0404	345.67	0.36764
2	C	80	3.25	606	1.0908	314.18	0.33415
2	C	80	3.5	633	1.1394	284.8	0.30290
2	C	80	3.75	659	1.1862	260.26	0.27680
2	C	80	4	686	1.2348	236.91	0.25197
2	C	80	4.25	709	1.2762	215.43	0.22912
2	C	80	4.5	733	1.3194	203.06	0.21597
2	C	80	4.75	757	1.3626	189.28	0.20131
2	D	90	0	0	0	1008.7	1
2	D	90	0.25	82	0.1476	986.42	0.97791
2	D	90	0.5	147	0.2646	922.58	0.91462
2	D	90	0.75	207	0.3726	855.05	0.84768
2	D	90	1	260	0.4680	793.71	0.78686
2	D	90	1.25	316	0.5688	735.35	0.72901
2	D	90	1.5	379	0.6822	672.97	0.66717
2	D	90	1.75	432	0.7776	616.24	0.61092
2	D	90	2	482	0.8676	562.56	0.55771
2	D	90	2.25	528	0.9504	519.39	0.51491

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
2	D	90	2.5	569	1.0242	473.87	0.46978
2	D	90	2.75	617	1.1106	434.21	0.43046
2	D	90	3	657	1.1826	395.99	0.39257
2	D	90	3.25	697	1.2546	359.93	0.35683
2	D	90	3.5	741	1.3338	327.92	0.32509
2	D	90	3.75	783	1.4094	297.23	0.29467
2	D	90	4	822	1.4796	273.66	0.27130
2	D	90	4.25	858	1.5444	251.99	0.24982
2	D	90	4.5	895	1.6110	233.65	0.23163
2	D	90	4.75	931	1.6758	216.53	0.21466
3	A	90	0	0	0	1000.3	1
3	A	90	0.25	56	0.1008	968.5	0.96821
3	A	90	0.5	100	0.1800	923.69	0.92341
3	A	90	0.75	146	0.2628	878.69	0.87843
3	A	90	1	197	0.3546	817.76	0.81751
3	A	90	1.25	245	0.4410	750.43	0.75020
3	A	90	1.5	300	0.5400	689.64	0.68943
3	A	90	1.75	351	0.6318	632.95	0.63276
3	A	90	2	394	0.7092	582.5	0.58233
3	A	90	2.25	434	0.7812	538.41	0.53825
3	A	90	2.5	475	0.8550	497.88	0.49773
3	A	90	2.75	511	0.9198	459.98	0.45984
3	A	90	3	548	0.9864	424.99	0.42486
3	A	90	3.25	580	1.0440	394.12	0.39400
3	A	90	3.5	609	1.0962	366.93	0.36682
3	A	90	3.75	640	1.1520	340.7	0.34060
3	A	90	4	676	1.2168	316.84	0.31674
3	A	90	4.25	707	1.2726	294.64	0.29455
3	A	90	4.5	734	1.3212	275.57	0.27549
3	A	90	4.75	761	1.3698	258.4	0.25832
3	A	90	5	786	1.4148	242.68	0.24261
3	A	90	5.25	813	1.4634	227.67	0.22760
3	B	80	0	0	0	959.19	1
3	B	80	0.25	64	0.1152	897.59	0.93578
3	B	80	0.5	120	0.2160	825.54	0.86066
3	B	80	0.75	171	0.3078	753.48	0.78554

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
3	B	80	1	220	0.3960	684.85	0.71399
3	B	80	1.25	265	0.4770	620.7	0.64711
3	B	80	1.5	306	0.5508	564.1	0.58810
3	B	80	1.75	344	0.6192	513.72	0.53558
3	B	80	2	381	0.6858	465.32	0.48512
3	B	80	2.25	416	0.7488	423.62	0.44164
3	B	80	2.5	450	0.8100	383.58	0.39990
3	B	80	2.75	483	0.8694	343.53	0.35815
3	B	80	3	514	0.9252	308.4	0.32152
3	B	80	3.25	545	0.9810	275.28	0.28699
3	B	80	3.5	574	1.0332	248.59	0.25917
3	B	80	3.75	603	1.0854	226.17	0.23579
3	B	80	4	630	1.1340	206.3	0.21508
3	B	80	4.25	657	1.1826	189.84	0.19792
3	C	0	0	0	0	964.74	1
3	C	0	0.25	100	0.1800	905.21	0.93829
3	C	0	0.5	196	0.3528	836.07	0.86663
3	C	0	0.75	291	0.5238	773.31	0.80157
3	C	0	1	381	0.6858	714.99	0.74112
3	C	0	1.25	470	0.8460	661.99	0.68618
3	C	0	1.5	552	0.9936	611.78	0.63414
3	C	0	1.75	634	1.1412	566.67	0.58738
3	C	0	2	716	1.2888	524.84	0.54402
3	C	0	2.25	796	1.4328	485.05	0.50278
3	C	0	2.5	875	1.5750	448.12	0.46450
3	C	0	2.75	953	1.7154	412.63	0.42771
3	C	0	3	1030	1.8540	379.81	0.39369
3	C	0	3.25	1105	1.9890	349.26	0.36203
3	C	0	3.5	1178	2.1204	320.97	0.33270
3	C	0	3.75	1252	2.2536	294.31	0.30507
3	C	0	4	1325	2.3850	271.63	0.28156
3	C	0	4.25	1396	2.5128	250.09	0.25923
3	C	0	4.5	1469	2.6442	230.97	0.23941
3	C	0	4.75	1542	2.7756	213.44	0.22124
3	C	0	5	1614	2.9052	196.76	0.20395
3	C	0	5.25	1685	3.0330	184.06	0.19079

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
3	D	70	0	0	0	1010.7	1
3	D	70	0.25	83	0.1494	955.38	0.94527
3	D	70	0.5	155	0.2790	879.83	0.87052
3	D	70	0.75	222	0.3996	813.19	0.80458
3	D	70	1	295	0.5310	746.78	0.73887
3	D	70	1.25	367	0.6606	685.14	0.67789
3	D	70	1.5	428	0.7704	624	0.61739
3	D	70	1.75	489	0.8802	573.61	0.56754
3	D	70	2	545	0.9810	526.48	0.52091
3	D	70	2.25	591	1.0638	480.89	0.47580
3	D	70	2.5	640	1.1520	441.12	0.43645
3	D	70	2.75	683	1.2294	405.5	0.40121
3	D	70	3	729	1.3122	370.28	0.36636
3	D	70	3.25	772	1.3896	335.61	0.33206
3	D	70	3.5	811	1.4598	307.26	0.30401
3	D	70	3.75	855	1.5390	279.8	0.27684
3	D	70	4	896	1.6128	255.29	0.25259
3	D	70	4.25	937	1.6866	234.03	0.23155
3	D	70	4.5	974	1.7532	213.45	0.21119
4	A	80	0	0	0	1033	1
4	A	80	0.25	75	0.1350	1010.6	0.97832
4	A	80	0.5	134	0.2412	955.85	0.92531
4	A	80	0.75	189	0.3402	892.71	0.86419
4	A	80	1	243	0.4374	827.25	0.80082
4	A	80	1.25	302	0.5436	755.94	0.73179
4	A	80	1.5	361	0.6498	691.49	0.66940
4	A	80	1.75	415	0.7470	633.02	0.61280
4	A	80	2	468	0.8424	579.18	0.56068
4	A	80	2.25	517	0.9306	528.49	0.51161
4	A	80	2.5	563	1.0134	482.24	0.46683
4	A	80	2.75	603	1.0854	439.01	0.42499
4	A	80	3	643	1.1574	399.94	0.38716
4	A	80	3.25	685	1.2330	365.4	0.35373
4	A	80	3.5	719	1.2942	335.03	0.32433
4	A	80	3.75	757	1.3626	308.71	0.29885
4	A	80	4	793	1.4274	285.62	0.27650

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
4	A	80	4.25	832	1.4976	264.78	0.25632
4	A	80	4.5	865	1.5570	246.79	0.23891
4	A	80	4.75	894	1.6092	230.61	0.22324
4	A	80	5	921	1.6578	216.21	0.20930
4	B	90	0	0	0	1035.1	1
4	B	90	0.25	73	0.1314	1003.2	0.96918
4	B	90	0.5	129	0.2322	939.92	0.90805
4	B	90	0.75	178	0.3204	859.6	0.83045
4	B	90	1	224	0.4032	788.12	0.76140
4	B	90	1.25	269	0.4842	718.51	0.69415
4	B	90	1.5	311	0.5598	652.62	0.63049
4	B	90	1.75	350	0.6300	590.91	0.57087
4	B	90	2	389	0.7002	537.76	0.51952
4	B	90	2.25	427	0.7686	483.16	0.46678
4	B	90	2.5	463	0.8334	434.7	0.41996
4	B	90	2.75	498	0.8964	389.71	0.37650
4	B	90	3	532	0.9576	348.04	0.33624
4	B	90	3.25	565	1.0170	310.8	0.30026
4	B	90	3.5	596	1.0728	278.67	0.26922
4	B	90	3.75	626	1.1268	251.04	0.24253
4	B	90	4	655	1.1790	226.75	0.21906
4	B	90	4.25	682	1.2276	206.38	0.19938
4	B	90	4.5	709	1.2762	191.08	0.18460
4	B	90	4.75	735	1.3230	177.23	0.17122
4	C	70	0	0	0	1028.4	1
4	C	70	0.25	86	0.1548	1000.7	0.97306
4	C	70	0.5	151	0.2718	928.42	0.90278
4	C	70	0.75	207	0.3726	855.44	0.83182
4	C	70	1	264	0.4752	788.1	0.76634
4	C	70	1.25	326	0.5868	722.23	0.70229
4	C	70	1.5	385	0.6930	662.81	0.64451
4	C	70	1.75	438	0.7884	608.37	0.59157
4	C	70	2	490	0.8820	558.31	0.54289
4	C	70	2.25	531	0.9558	512.02	0.49788
4	C	70	2.5	571	1.0278	468.66	0.45572
4	C	70	2.75	606	1.0908	429.66	0.41779

Table D-1. continued

Test	Dryer	Rate-start (%)	Time (hrs)	Counts	Cum_Eng (kWh)	Weight (g)	Weight_ratio (%)
4	C	70	3	639	1.1502	393.95	0.38307
4	C	70	3.25	669	1.2042	360.11	0.35017
4	C	70	3.5	695	1.2510	329.43	0.32033
4	C	70	3.75	724	1.3032	300.87	0.29256
4	C	70	4	751	1.3518	275.13	0.26753
4	C	70	4.25	774	1.3932	252.83	0.24585
4	C	70	4.5	801	1.4418	232.27	0.22586
4	C	70	4.75	823	1.4814	214.66	0.20873
4	C	70	5	846	1.5228	198.62	0.19313
4	D	0	0	0	0	1050.4	1
4	D	0	0.25	124	0.2232	1023.4	0.97430
4	D	0	0.5	242	0.4356	944.27	0.89896
4	D	0	0.75	356	0.6408	864.04	0.82258
4	D	0	1	468	0.8424	789.67	0.75178
4	D	0	1.25	581	1.0458	721.1	0.68650
4	D	0	1.5	690	1.2420	658.35	0.62676
4	D	0	1.75	799	1.4382	600.68	0.57186
4	D	0	2	904	1.6272	547.02	0.52077
4	D	0	2.25	1008	1.8144	496.71	0.47288
4	D	0	2.5	1108	1.9944	451.23	0.42958
4	D	0	2.75	1206	2.1708	408.91	0.38929
4	D	0	3	1304	2.3472	370.09	0.35233
4	D	0	3.25	1404	2.5272	336.42	0.32028
4	D	0	3.5	1503	2.7054	305.07	0.29043
4	D	0	3.75	1599	2.8782	279.01	0.26562
4	D	0	4	1693	3.0474	252.66	0.24054
4	D	0	4.25	1787	3.2166	234.06	0.22283
4	D	0	4.5	1877	3.3786	215.71	0.20536
4	D	0	4.75	1964	3.5352	201.81	0.19213

Cum_Eng = (Counts x 1.8)/1000

VITA

Xia Liu was born in Chongqing city, P. R. China, on January 29, 1960. She received the Bachelor of Science degree in Agricultural Engineering in August 1982 from Southwestern Agricultural University, Chongqing, P. R. China. She was then employed by that university and taught in the Agricultural Engineering Department for five years.

Supported by a Chinese government scholarship and a research assistantship from the Agricultural Engineering Department, The University of Tennessee, she received her Master of Science degree in Agricultural Engineering from the University of Tennessee, Knoxville in May 1991. She accepted a research assistantship and continued study toward the Doctor of Philosophy degree in Agricultural Engineering at The University of Tennessee. She received the Doctor of Philosophy degree with a major in Agricultural Engineering in May, 1994.

She is a member of Gamma Sigma Delta honor society. She also is a member of the American Society of Agricultural Engineers and the Institute of Food Technologists.