EFFECTS OF POST-HARVEST CHLORINE TREATMENT ON BLUEBERRY QUALITY

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EFFECTS OF POST-HARVEST CHLORINE

TREATMENT ON BLUEBERRY

QUALITY

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A	Cross sectional area of the dryer, m^2
a	Subscript for air properties
a_o	Pre-exponential factor in Ahrrenius-type equation, s^{-1}
a_v	Specific area of the solid, m^{-1}
a_1	Constant in Ahrrenius-type equation, K
Cp_a	Specific heat of air, J-kg^{-1}-C^{-1}
Cp_s	Specific heat of solid, J-kg^{-1}-C^{-1}
C_1	Coefficient in energy and mass balance equations of air, s^{-1}
C_2	Coefficient in mass balance equation of air
C_3	Coefficient in energy balance equation of air, C^{-1}-s^{-1}
C_4	Coefficient in energy balance equation of air, kg-J^{-1}
C_5	Coefficient in energy balance equation of solid, C^{-1}-s^{-1}
C_6	Coefficient in energy balance equation of solid, kg-J^{-1}
D	Diameter of the solid particle, m
H	Enthalpy, J
$\bar{H}$	Normalized value of enthalpy
ΔH^{vap}	Enthalpy of vaporization of water, J-kg^{-1}
h	Heat transfer coefficient of air, J-m^{-2}-s^{-1}-C^{-1}
j	Node or tray number in the deep bed

k	Drying constant, s^{-1}
L	Height of the deep bed, m
liq	Superscript for properties of liquid water
M	Moisture content of drying solid, $kg\text{-}kg^{-1}$
M_e	Equilibrium moisture content, $kg\text{-}kg^{-1}$
$\bar{M}$	Normalized value of moisture
$\dot{M}$	Mass flow rate, $kg\text{-}s^{-1}$
o	Subscript for initial conditions
P	Pressure, Pa
P^{sat}	Saturation Pressure, Pa
RH	Air relative humidity
s	Subscript for properties of solid
T	Air temperature, C
T_r	Reference temperature, C
t	Time, s
V	Volume, m^3
v	Air velocity, $m\text{-}s^{-1}$
W	Specific humidity of air, $kg\text{-}kg^{-1}$
$\bar{W}$	Normalized value of Specific humidity of air
w	Subscript for water properties
Y_w	Ratio of molecular weight of water to molecular weight of air
z	Spatial vertical coordinate
γ	Generic function

Δ	Differential increment
ε	Bed porosity
θ	Particle temperature
ρ	Density, kg-m^3

CHAPTER I

INTRODUCTION

Several varieties of blueberry are well adapted to growing conditions in many regions of the United States. Supplies are usually available during the summer months, and can be stored only for a short period after harvesting. Therefore, blueberries have become prime candidates for dehydration, canning or freezing (Kim, 1987).

In recent years, consumer preference for fresh, non-processed products has increased significantly, and blueberries are considered one of the commodities that can offer higher margins of profits, since they are used as a main ingredient in a number of specialty foods.

Intact, sound blueberries are characterized by a firm, smooth appearance, and by the presence of a white, wax-like material on the surface, known as bloom. As the fruit deteriorates, the skin becomes softer, and with excessive handling the loss of the bloom becomes more apparent.

Several researchers have studied different techniques to extend the shelf-life of blueberries, however, efforts to increase the life of the fresh fruit under refrigeration have not been entirely successful. Carefully selected berries can be held in marketable conditions for two weeks, if stored in film-capped baskets at 0 C. After that period, there is significant loss in quality, mainly softening of the tissues and development of off-flavors (Salunkhe and Desai, 1986).

Research in blueberry fruit set and development has been directed at three principal areas: (1) to increase the fruit set to obtain higher yields, (2) to concentrate the ripening period to facilitate machine harvesting, and (3) to develop a post-harvest treatment that will lead to improved shelf life of the fresh fruit (Eck, 1986). Besides increasing the availability of blueberries in domestic markets, higher production combined with lower harvesting costs and effective control of decay can enhance significantly the possibility to export to distant markets which is one of the major goals of the producers.

Microbial decay, a problem that affects this fruit, results from the action of yeast and mold, which is favored by storage conditions of high relative humidity. A number of spoilage inhibitors are cited in the literature (Jay, 1986), and weak solutions of sodium hypochlorite in water (100 ppm) are mentioned as possible inhibitors of microbial growth (Maness, 1991).

The ratio of soluble solids to titrable acidity of the juice has been traditionally used to indicate the degree of maturity of fruits and, consequently, also denotes the degree of deterioration. In this work, maturity ratio is one of the variables considered for study.

Besides having a positive effect on quality, by retarding or reducing microbial invasion, the application of chlorine treatment also causes changes in external appearance. Texture and bloom are particularly affected by handling during the application of the chlorine dip, and exposure to the drying air at high temperature or low relative humidity can cause dehydration with irreversible damage to the fruit.

The main purpose of this study was to evaluate the effects of using sodium hypochlorite as a rinse and of removing the surface moisture, on quality attributes of color and storability of Bluecrop blueberries. Specifically, changes that occur in acidity and sugar content of the juice, appearance of microorganisms, and modifications in texture and skin color of the fruit were evaluated.

Another objective of this research was to develop a mathematical model to simulate the removal of the surface moisture, which can be used to predict if irreversible damage by dehydration of the fruits occurs under specific air conditions. This model was developed in a general way, and can be used to simulate deep-bed and tray drying of other agricultural products.

CHAPTER II

LITERATURE REVIEW

Growing blueberries has become an important commercial activity in the United States. Michigan, Maine and New Jersey lead in production, and Florida and Georgia recently increased contribution to domestic supply.

The cultivated blueberry was obtained by selective breeding of the best strains of wild blueberries, and comprise three major species of *Vaccinum*, including *V. corymbosum* (highbush), *V. ashei* (rabbiteye) and *V. angustifolium* (lowbush) (Eck, 1986). Today, Bluecrop is the major commercial variety, followed by Jersey, Rubel, Blue Ray, Bluetta and Elliots (Anonymous, 1987).

Currently, the annual crop is approximately 140 million pounds, with an 18 percent increase in five years. It is estimated that by the year 2000 the production will increase to 185 million pounds (Anonymous, 1991a).

Fruit Characteristics

During maturation, blueberries undergo a number of changes in their chemical and physical state and attain their full size and maximum edible quality. These changes are due to several synthetic and degradative processes that occur sequentially or concurrently within the fruit.

Color changes from green, typical of the initial stages of maturation, to blue-red, and ultimately to 100 percent blue in the fully ripe berries. This is due to the loss of chlorophyll and the synthesis of anthocyanins, which gives the fruit its characteristic color. This pigment is mainly concentrated in the skin, although in some cultivars the pigment may extend through the entire fleshy pericarp. After reaching its permanent color, the blueberry develops a waxy coating that gives it a light blue bloom which is highly prized for the commercial market (Eck, 1986).

The final part of maturation is marked also by the onset of ripening, characterized by a rapid increase in the rate of respiration. Fruit acidity decreases but soluble solids increase. There is a positive linear relationship between the sugar/acidity ratio of the fruit and progress of ripening. As the ratio increases, the shelf life of the berry decreases. The predominant sugars in the blueberry are glucose and fructose, and citric acid the major organic acid (Kushman and Ballinger, 1967).

The aroma of a fruit is an important quality criterion and as fruits ripen there is an increase in the rate of synthesis of the compounds that impart this property. The predominant volatiles emitted by ripening blueberries are ethylene, acetaldehyde, methyl acetate, methyl alcohol and ethyl alcohol (Eck, 1986).

There are also significant textural changes that occur during ripening of fleshy fruits. These changes represent an irreversible process once it is initiated. In blueberries, softening is due mainly to hydrolysis of pectin molecules present in the cell wall. Softening and weight loss which are more prevalent in the late stages of ripening, are due to the loss of tissue during respiration, since substrate is consumed from the fruit and carbon dioxide, water and energy are produced.

Following fruit development, growth ceases and senescence occurs. This stage is characterized by an increase in fruit pH and decrease in soluble solids and titratable acidity.

Harvesting and Storage

Blueberries have a brief harvest season (95% of the annual crop is harvested between June and August). The period time from full bloom to harvest is difficult to apply as an index of ripeness of berries, since the blossoming period lasts 2 to 5 weeks for most cultivars; therefore, picking is necessary every 6 to 8 days. Blueberries can be stored only for a short time after harvesting, so, they are prime candidates for preservation methods of dehydration, canning or freezing. Thirty five percent of the United States crop is sold in the fresh form, about 30% is frozen, 20% is canned, and the rest is used for pie filling (Kim, 1987).

Harvesting and sorting are tedious and expensive, since they traditionally have been done by hand. More recently, blueberries are also mechanically harvested, and automatic systems of inspection are starting to be implemented (Anonymous, 1992a).

There is one grade, U.S. No. 1, which applies to selected and hybrid varieties of the highbush blueberry. General specifications require product to be clean, well-colored and not overripe, wet or affected by decay.

Kushman and Ballinger (1971) proposed a set of standards to be used as a sorting criteria when using mechanical harvesting methods. Fruits that fall in this category would be considered suitable for the fresh market, and should be free of unripe, excessively soft and small berries; the content of soluble solids (sugar) should be at least ten percent, and the pH of the fruit should be higher than 3.25.

Fresh harvested, sound blueberries can be held as long as two weeks under optimum storage conditions. Recommended temperature and relative humidity are 1 to 3 C, and 90 percent, respectively. However, although high humidity atmospheres help to maintain smooth skin, it also promotes the growth of yeast and molds. A variety of these microorganisms often bring about spoilage of blueberries.

Among the signs of decay are: softness of the skin, appearance of bruises and loss of sugar content (Jay, 1986). Usually, loss of quality is caused by pathogens that infect blueberries through wounds and other weakened sites. The predominant fungi isolated from fruits of the highbush blueberry are: *Glomerella cingulata*, *Botrytis cinerea* and *Alternaria tenuis* (Capellini et al., 1972).

Preservation Methods

Since only the best berries are selected for the market, and because of the short storage time, the price of fresh blueberries can be extremely high, even shortly after the harvest season is over. Therefore, devising ways to extend the storage time has become a matter of primary importance.

Many efforts have been made to preserve blueberries. Among the methods that are widely used in industry are: freezing (dry or syrup packs), canning and dehydration.

Initial research to dry blueberries included air blast dehydration (Friar and Mrak, 1943), which provided a product with good color retention, but it is unable to regain the original plumpness during reconstitution. The explosion puffing process (Eisenhardt et al., 1964) was developed later, and was applied to pieces of fruits and vegetables. Blueberries were dried to a final moisture content of 6 percent and were suitable for use in bakery products. Later, Sullivan et al. (1982) developed a more practical, less labor extensive method. The principle is similar to the original batch explosion puffing, but it allows drying the product continuously.

Jayaraman et al. (1980) found that blueberries dried in a fluidized bed show similar properties to those processed by explosion puffing or freeze-drying, with the advantage that the technique involved simpler equipment, thus with a lower capital investment. Later (1982), the same researchers introduced the high temperature, short-time fluidized bed treatment, which resulted in a product with good rehydration characteristics.

Kim (1987) used high temperature, fluidized bed method to obtain product that had less bulk density, larger diameter, and faster rehydration time compared to those produced using conventional drying and explosion puffing. The technique was also used to process blueberries that had been previously dehydrated by osmosis with a sucrose solution. The final product had properties similar to raisins, and was suitable for consumption in the dried state.

Another method used successfully to dry blueberries is tunnel drying. First, the berries are sweetened with fructose, then dried to a final moisture content of 12 percent. Sunflower oil is added as a processing aid. The shelf life is one year, if the product is packed in vacuum-sealed foil bags and stored in a cool, dry area. The product is used as a specialty snack food and as an ingredient in several baked goods

(Anonymous, 1991).

The use of the processing methods described above has resulted in a number of products commercially available today, which are suitable for specific industrial applications. However, consumer preference for fresh, non-processed products has increased considerably, and fresh blueberries are one of the commodities that can offer higher margins of profits.

There are a number of characteristics that are unique to the fresh fruit, and that are lost or significantly changed with processing. For example, during canning there is an irreversible loss of color intensity, a property that gives excellent eye appeal to finished products without the use of artificial colorants.

The berries also impart a variety of desirable flavors and texture commonly sought in baked and dairy foods (Anonymous, 1992).

The natural, intensely sweet flavor of cultivated blueberries reduces the need for additional sugar in food products, also their use contribute water-soluble fiber while functioning as a low-calorie filler.

Blueberries flow freely, which allows for easy dispersion and continuous mixing of dairy desserts and baked goods. Their plump appearance enhances aesthetic appeal and improves the healthy image of the foods (Anonymous, 1992).

The need to preserve the quality attributes of fresh blueberries has been recognized by a number of researchers. Low temperature storage, use of controlled atmospheres and use of chemicals to prevent microbial spoilage are, currently, the main areas of study.

Ceponis and Capellini (1985) concluded that CO_2 enriched atmospheres can reduce post-harvest decay development during and after cold storage, but because a 20 percent enrichment caused off-flavors, they suggested that no more than 15 percent should be utilized.

Smittle and Miller (1988) found that storage in atmospheres containing 20 percent CO_2 and 5 percent oxygen resulted in greater percentages of marketable and firm fruit, and better sensory ratings than blueberries stored in air.

The use of chlorine dips was first suggested by Capellini and Ceponis (1977). In their tests, samples of blueberries with and without stem were immersed for 30 seconds in either tap water or a 0.025 percent sodium hypochlorite solution. Excess moisture was drained from the samples but not dried. Their results indicated that wetting the berries increased the incidence of decay, which was not controlled effectively by dipping in the chlorine solution. Besides reducing microbial action and delaying biochemical reactions that lead to decay, any method should also prevent damages to the visual appearance of the fruits, and in this case special attention should be placed on the preservation of the bloom.

Experience has shown that even moderate handling, like packing by hand in pint boxes, reduces significantly the amount of original bloom present (Ballinger et al., 1973). The same detrimental effect was observed in a study designed to determine the effects of precooling on fruit decay, when moisture condensed on the surface of cold blueberries exposed to warm air (Hudson and Tietjen, 1981).

Use of Machine Vision Techniques

Spectral properties of fruits and vegetables have been used with success to detect defects and other surface characteristics without destroying the samples (Howarth et al., 1990). There are two ways of quantifying the spectral properties of an object: (1) measure the reflectance at specific wavelengths, and (2) measure the amount of each primary color, and its attributes of hue, saturation and intensity.

Spectrophotometers can provide useful information in terms of amount of light reflected, transmitted or absorbed by an object. Reflectance is most widely used in the determination of color of agricultural commodities. The spectral reflectance curve shows "peaks" that characterize a specific feature of a surface, then it is possible to compare objects handled under any specified set of conditions.

Color machine-vision systems provide information about the color of objects. Typically, a system like this gives distribution, usually histograms with mean values and standard deviation, of the three primary colors reflected by an object. Machine-vision systems also measure properties like hue, saturation and intensity. Hue corresponds to the color, such as green that predominates in the object. Intensity refers to the brightness and saturation indicates how dark or light the color is (Anonymous, 1991b).

Reflectance spectra can give very useful information about the wavelengths where some specific features appear. For the purpose of this study, it is possible to know which bands or arithmetic combinations are useful to identify changes in the appearance of the bloom, that occur during processing.

Similar principles have been used with success for plant classification

(Shropshire, 1991), for the detection of defects of fresh-market carrots (Howarth et al., 1990), and for the identification of defective peanut kernels (Kranzler and Rigney, 1990; Dowell, 1991).

Mathematical Modeling of Moisture Removal

Dehydration and water evaporation are important operations found frequently in food manufacturing, and both refer to the removal of moisture from a product.

In general, the terms dehydration and drying refer to the methods of food preservation by which water activity is decreased to a level where microbial activity and deteriorative biochemical reaction rates are reduced to a minimum (Toledo, 1991).

Evaporation is essentially an operation in which heat is transferred by conduction, convection and radiation from gases to the liquid surface from which vapor is transferred by diffusion and convection back to the gas stream. This principle occurs in transfer from droplets, found in spray drying, crystallization, dissolution, transfer in fluidized beds, and in any other operation where transfer occurs between a continuous phase and spherical particles (Ranz and Marshall, 1952).

The widespread use of computers has promoted the use of modeling and simulation as tools to understand and predict the performance of a variety of unit operations found frequently in the food industry.

Normally, processes are represented as sequences of units, in which there is a continuous flow of materials and energy from one process unit to the next. These are known as "flowsheet models", and are applied mainly to process design and plant operation. Input consists of information contained in the process flowsheet, and the output is a complete representation of the performance of the system, including composition, flow and properties of all intermediate and product streams.

Models can be used to determine changes in operating conditions needed to accommodate changes in feed streams, changes in product requirements, and in environmental conditions.

There are several process simulators currently available in the market. Based on the mode of operation they can be either Dynamic or Steady-State packages. One example of a continuous simulator is Aspen Plus (Aspen Technology, Inc.), which allows modeling systems with solids and complex materials, as well as electrolytes.

Other programs, like Speedup (Aspen Technology, Inc.), can solve also dynamic processes, where the operation is represented by a set of equations in space and time. The advantage of this simulator is that it allows prediction of the performance of the system under non-steady conditions, and produce input for automatic-control software.

There are also simulation packages designed to represent the operation of biological processes. Examples of this type of simulators are: BioPro Designer (Intelligen, Inc.) and BioProcess Simulator (Aspen Technology, Inc.). Simulation of systems that process biological materials have been limited, however, to situations where only pure components are handled. Examples of well studied systems are: batch and continuous reactors, membrane separators, crystallizers, and heat sterilizers.

In these cases, although the principle of operation can be fully described mathematically, the applicability of the models is limited to situations in which the physical properties of the materials are known, and where factors that affect the final quality of the product, and that can not be represented by the model, are not significant.

These limitations can be overcome through more experimentation in the areas of physical properties, and a better understanding of the factors that affect them.

Drying Models

A number of theoretical, semi-theoretical and empirical approaches have been used to represent the drying behavior of agricultural products.

The diffusion equation, which assumes that all resistance to mass transfer occurs at the outer surface of the drying material, and that all the flow within the kernel occurs by diffusion, has been extensively used to predict the drying behavior of cereal grains (Fortes and Okos, 1981; Brooker et al., 1978).

The assumption of a diffusion coefficient and thermal conductivity that do not depend on the moisture content of the kernel, made analytical solutions possible. However, numerical methods are required if this properties are not constant or if the particle has irregular shape (Brooker et al., 1978).

In view of the difficulties found when using the diffusion equation, several empirical and semi-empirical approaches were followed to describe thin-layer drying.

Thompson et al. (1968) proposed a drying equation for corn over the range of 60 to 150 C. Ross and White (1972) combined a logarithmic method and an Arrhenius-type equation to describe the thin-bed drying characteristics of white corn, and Misra and Brooker (1980) developed a model to describe drying of shelled yellow corn, using air temperature, air humidity and velocity as independent variables.

Since the analysis of deep-bed drying is based on thin-layer models, more sophisticated models have been developed that can represent more realistically the process of moisture movement in kernels.

Fortes and Okos (1981) proposed a model that involves a non-equilibrium approach, and the internal gradient of relative humidity was considered the driving force for mass transfer.

Deep-bed drying models usually fall into two broad categories: the Heat and Mass Balance Models and the Differential Equation Models.

The first group is valid only for low air flow and low temperature conditions. It is assumed that under this regime, equilibrium is reached at each layer at each time period. The advantage of their use is that a thin-layer equation is not necessary, but they are not realistic, since equilibrium is not reached even at low air flow.

The second group uses a theoretical approach based on the laws of simultaneous heat and mass transfer. As a result, a set of four partial differential equations is obtained, which represents the temperature and moisture conditions of air and particles in the system at a given time (Morey et al., 1978).

The main assumptions are: the volume shrinkage is negligible during the drying process; the temperature gradient within the particles is also negligible; the particle to particle conduction is not significant; the air flow is plug type; the system is adiabatic; the heat capacities of air and particle are known and constant, and an accurate thin-layer equation is known (Brooker et al., 1978).

Models of this type have been successfully used to represent the operation of fixed-bed dryers.

Brooker et al. (1978) reported results of their simulation of corn drying. Chhinnan and Young (1978) used a similar approach to simulate deep-bed drying of peanuts, and Stone (1982) modeled the drying of hops.

The validation of all these models is usually complex since measuring the moisture content of the particles during a test without influencing the results of the experiments is a particularly difficult problem (Morey et al., 1978).

Although the exact prediction of drying performance is practically impossible, experience has proven that the use of these models and their simulation has contributed significantly to understand and to develop the science of drying.

Studies on Evaporation

The process of evaporation includes simultaneous heat and mass transfer between two phases in contact. The transport proceeds usually with a continuously changing particle size and is therefore transient in nature (Brian and Hales, 1969).

Usually, researchers have concentrated their attention on the development of correlations that permit the evaluation of dimensionless numbers. This has allowed determination of heat transfer coefficients from Nusselt number equations, and mass transfer coefficients from Sherwood number correlations.

Dimensional analysis has been applied to a number of situations, particularly spheres immersed in fluid streams.

In their study, Ranz and Marshall (1952) investigated the factors that influence the rate of evaporation of pure liquid drops, and the rate of evaporation of water drops containing suspended solids. Their findings have been extensively used in spray drying situations, especially in the determination of drying time of aqueous solutions.

Steinberger and Treybal (1960) proposed an equation that correlate heat and mass transfer data for single spheres immersed in streams of gases and liquids, for Reynolds numbers ranging from 1 to 30,000 and values of Schmidt number between 0.6 and 3,000.

An expression relating mass transfer, due to forced convection, to hydrodynamic conditions over the entire surface of a sphere was obtained by Grafton (1963). By analogy, predictions for heat transfer, that were in good agreement with experimental data, were also obtained from the same correlation.

There are many situations where the particles undergoing transfer are not spherical, which adds to the complexity of the problem. In an attempt to predict the effect of shape on transfer, Lochiel and Calderbank (1964) developed equations to describe mass transfer around solid spheres, spheroids and spherical caps. Their correlations are applicable only when the Schmidt number is large in value, and are valid for transfer in creeping flow (Reynolds number lower than 1) and boundary layer flow (Reynolds number values higher than 1).

All these studies have provided invaluable information for the development of processing techniques used in the industry today. However, fundamental investigation is still needed in areas of heat and mass transfer that involve non-uniform geometries like those found in agricultural products.

CHAPTER III

EXPERIMENTAL METHODS

Bluecrop blueberries were obtained from the Oklahoma Vegetable Research Station in Bixby, Oklahoma.

Four separate replicates were conducted during the summer months of 1991 and 1992. All the berries were hand harvested, cleaned and selected for uniform ripeness, firmness and color. They were transported under refrigeration to the Agricultural Engineering Laboratory were they were maintained at 2 C and 85% relative humidity until time for analysis.

The experiments were conducted within 24 hours of harvesting, and for all four replicates, the handling of the samples was the same.

The experimental methods applied in this study can be classified into: (1) Procedures involved in the storage study, and (2) Collection of data required for modeling.

Storage Study

The purpose of this section of the project was to determine the effect of sodium hypochlorite rinse on the quality attributes of blueberries after a specified period of storage under refrigeration.

The experiment was arranged as a factorial, with three levels of rinse: water only, sodium hypochlorite and no-rinse; and three levels of storage time: one, two and three weeks.

Twenty four pints of blueberries were divided into two equal lots. One lot was dipped into a water bath at 2 C, the other into a 100-ppm sodium hypochlorite solution, for 30 minutes. The liquid was drained, and the berries were blot-dried allowing them to roll over paper towels. Then, samples of approximately one pint each were placed on trays, labeled and randomly assigned to the laboratory dryers.

The berries were exposed to the drying air at room temperature and relative humidity conditions for 30 minutes and until all the surface moisture had been removed. A diagram of a section of the dryer is presented in Figure 1, and the operation conditions of these runs are summarized in Appendix E.

Once the excess moisture was evaporated, the berries were placed on fiberboard baskets, and covered with plastic film secured with a rubber band. Samples were weighed, labeled and stored in a refrigerator during the specified times at 2 C and 85% relative humidity. For each treatment combination, the experiments were done in triplicate.

After the specified storage times, samples from each rinse-storage combination were weighed to determine weight loss (percent) during storage. Also, each berry from these samples was rated for firmness, shriveling, leakage and microbial growth.

Firmness was determined subjectively, by applying light finger pressure while rotating the berry, similar to the tests of Smittle and Miller (1988).

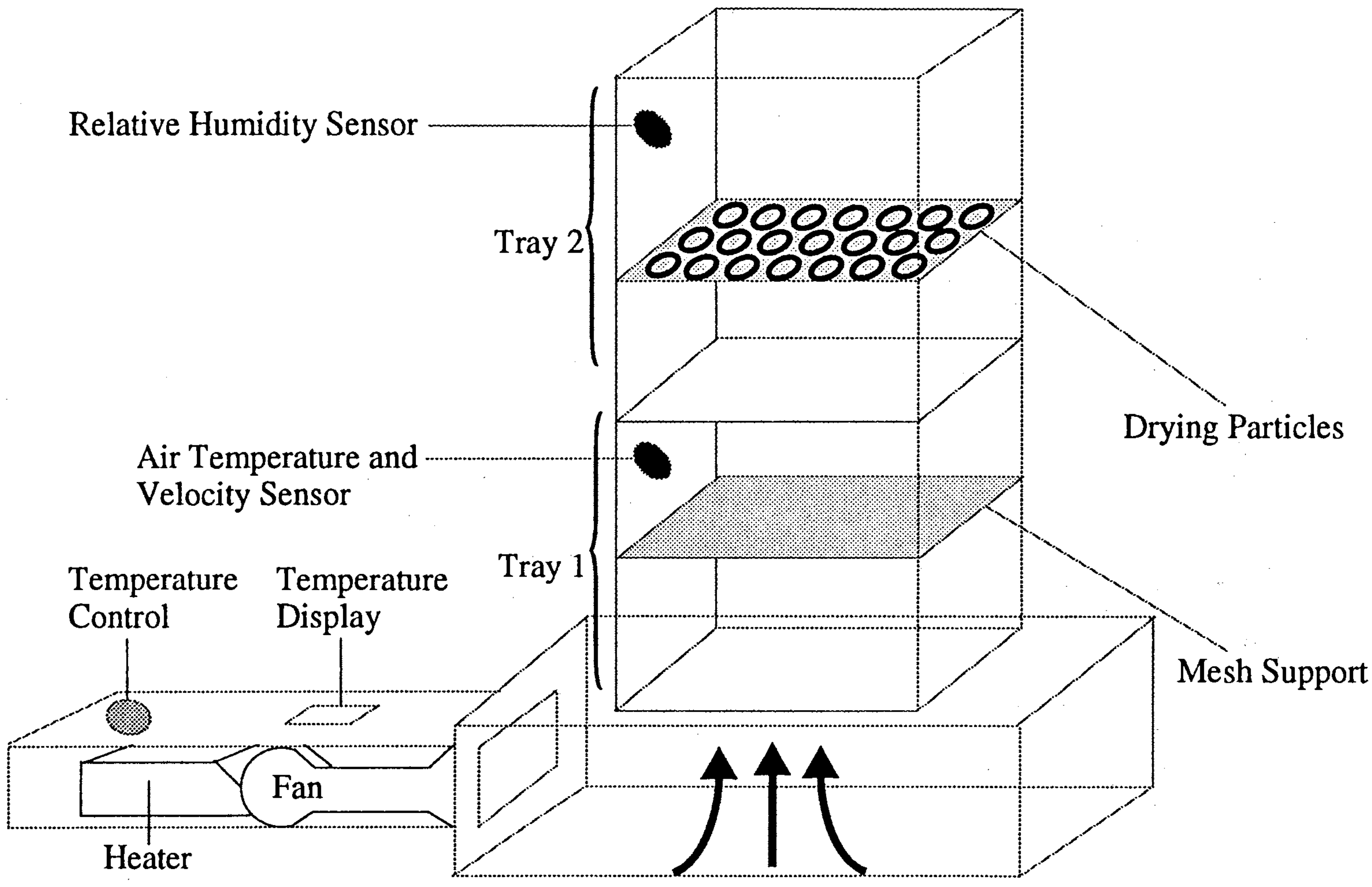

Figure 1. Diagram of the Tray Dryer

Post-Storage Analysis

In addition to the treatment combinations described before, four controls were prepared. These were samples that did not undergo any treatment, but were checked for quality changes after one, two and three weeks of refrigeration storage. The fourth control was a "zero sample", which was frozen immediately after harvesting. These controls were also prepared in triplicate. Blueberries that showed good overall quality were frozen, and used later for chemical analysis.

Part of the frozen sample (50.0 ± 0.5 g) was homogenized (Omni Mixer, Model 17105, OMNI) at 45 percent of the maximum speed for 30 seconds. The blend was strained to separate the juice from the seeds and skin, using a double-layer cheese cloth.

The juice was used for the determination of pH, and soluble solids by the refractometer method (AOAC, 1984). Also, 5.00 ± 0.05 g of the pure juice were mixed with 45 ml of distilled water, and used for the determination of pH and acidity, which was measured by titration with 0.01 N sodium hydroxide solution. The end point of titration was considered when the pH of the solution reached the value of 7.00 ± 0.05 (pH meter Accumet, Model 910, Fisher Scientific).

For each sample these analyses were done in duplicate. The ratio of soluble solids to titrable acidity is used in this work as an indicator of degree of ripeness.

Machine-Vision Analysis

Two sets of experiments were done using machine-vision techniques. The first part consisted of the determination of the reflectance properties of blueberry skin samples, the second considered acquisition and processing of blueberry images.

Reflectance Properties. The purpose of these experiments was to determine the appearance of specific features in the reflectance spectra of blueberry skin samples, having different amounts of bloom.

The system used is from the Physics Department at Oklahoma State University. First, it was necessary to determine the suitability of the spectrophotometer (IBM Model 9430, UV-Visible range), to be used in this application.

The reflectance of three carrot-skin samples was measured in the 300 to 900 nm wavelength region, and the spectra obtained were compared to reflectance plots of fresh-market carrots (Howarth et al., 1990).

In both cases, refection plots showed similar characteristics, and it was decided that the equipment was suitable for the purpose of this study. It was used for the determination of reflectance properties in the remainder of the project.

The spectrophotometer is equipped with a 60 mm integrating-sphere reflection attachment. The internal surface of the sphere is coated with barium sulfate, which concentrates the light in the interior of the chamber. Readings were taken at 2 nm intervals. Scan speed was 100 nm/min.

A piece of fruit skin (1 x 0.25 cm) was fitted in the interior of a mounting disk, covering the area exposed to light in the spectrophotometer chamber. Reflectance percent was measured against an aluminum oxide standard, in the range of 200 to 900 nm.

Since blueberries were not always available, samples of plum skin were used to determine spectral features that could relate to the amount of bloom present. A similar procedure was used when blueberries were obtained.

Four types of samples were used in the reflectance study: fresh- with bloom, and fresh- without bloom (both from the same berry); chlorine- rinsed, and water-rinsed.

Half of the skin of fresh blueberries was carefully removed, trying to maintain the original appearance of the bloom. The other half of the peel was cleaned, rubbing the sample with paper towel until the appearance was shiny. Then, each skin sample was fitted in the center of a mounting disk and placed in the sample holder for analysis.

Water and chlorine-rinsed skin samples were obtained from fresh blueberries prepared as explained in the storage study, and used for the determination of reflectance properties immediately after the removal of surface moisture.

Results from this section were used to determine the best equipment configuration to be used in the acquisition and processing of blueberry images.

Image Processing. The experimental design for this section was similar to that of the storage study. The effects of type of rinse (water only, sodium hypochlorite and no-rinse) and storage time (zero, one, two and three weeks) were determined on color properties of blueberry skin samples.

The response variables in this experiment were amount of red, blue and green color present (RGB), as well as hue, saturation and intensity (HSI).

Values of standard deviation of each of the color properties were also considered variables in the study, and were regarded as indicators of the distribution of these characteristics over the surface of the berry.

Twenty blueberries from each treatment combination were selected for study. The equipment used in this experiment is from the Agricultural Engineering Laboratory at Oklahoma State University, and a diagram of the configuration is presented in Figure 2.

A camera (Sony, Model XC-711) with a 180 mm Tamron lens was used. A chamber was installed to diffuse the light and avoid excessive reflectance especially along the edges of the berries. It consisted of a section of plastic pipe (dia. approx. 40 cm), and was illuminated from each side by two 75 W incandescent bulbs. The camera was placed at the top of the chamber. Distance to the object was 40 cm.

Before deciding on the final setting of the equipment, it was necessary to test for variations in the values of color properties that might be caused by the position of the camera with respect to the object.

For this purpose, a preliminary study was done using plum samples with and with-out bloom. From this analysis it was concluded that the readings of color properties did not depend on the position of the camera with respect to the object.

Blueberries were analyzed at the end of the storage periods. To ensure that the setting of the equipment was the same, readings of RGB and HSI were taken for a standard (barium sulfate). Then, before starting new measurements, the distance to the camera and lens opening were adjusted until the same values of the color properties were obtained for the standard.

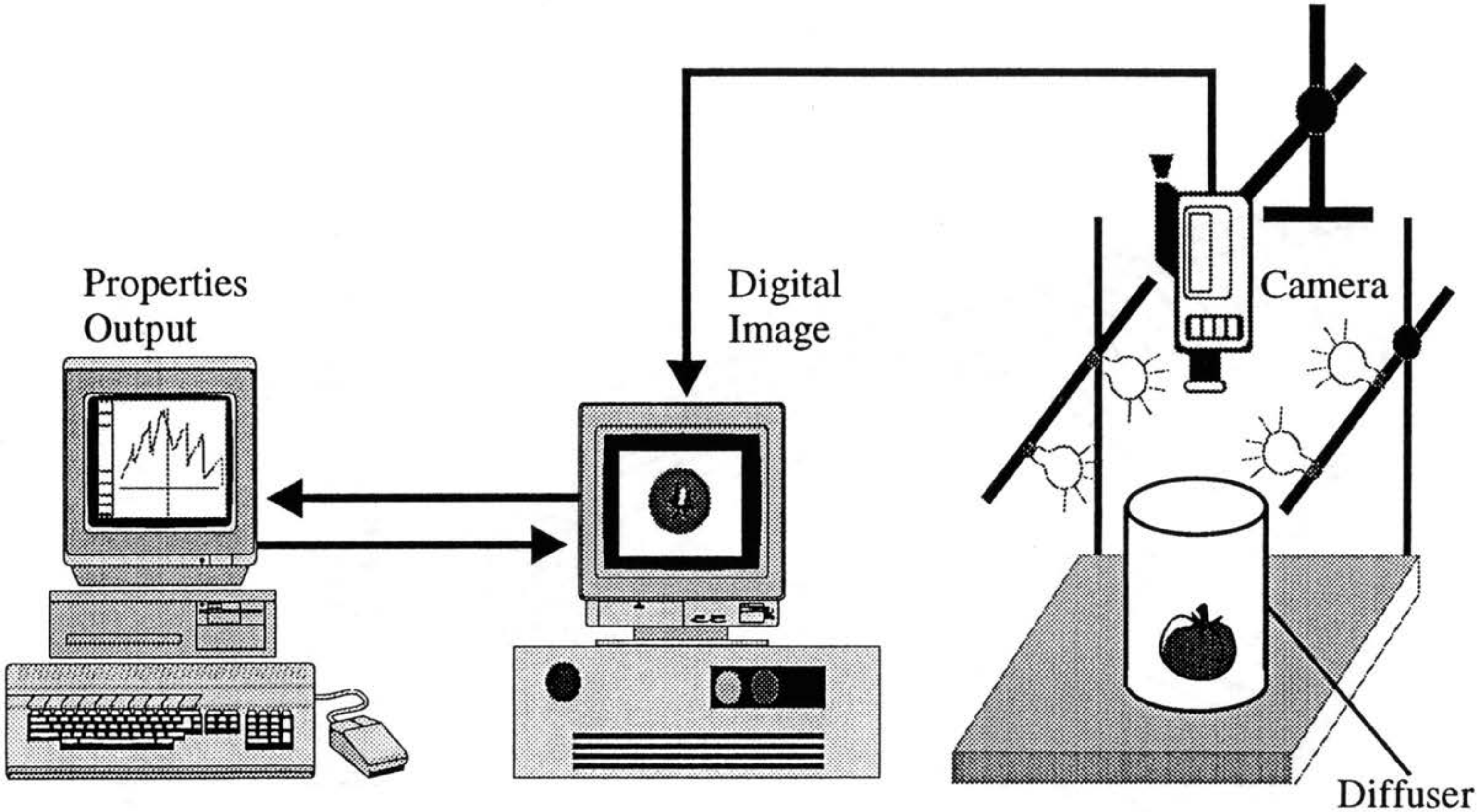

Figure 2. Equipment Configuration for Image Processing

Blueberry images were recorded by a microcomputer equipped with a digitizer and image processing boards (Data Translation, Model DT2871). The digitized image was displayed on a color monitor (Sony, Model PVM-1342 Q) from which values of color properties and standard deviations were obtained.

Data Required for Modeling

The purpose of the experiments described in this section was to evaluate several blueberry properties and parameters related to the configuration of the drying equipment, and that have to be considered in the mathematical models described later in this study.

Drying Curves

Data from this section were used to describe the rate of surface-moisture removal from blueberries that were rinsed in either water or sodium hypochlorite solution.

After the dip, samples of approximately 30 g were weighed and placed on trays in the dryers. One by one, the baskets were removed from the dryer at 30 seconds intervals during the first 3 minutes, and every 5 minutes until the drying time was 30 minutes. The weight was recorded immediately after each basket was removed from the dryer.

Temperature, air velocity and relative humidity were recorded. Data of this section were used to obtain the curves of rate of moisture removal for a thin layer.

Physical Properties

Density. This was evaluated by measuring the displacement of a volume of water after adding a known weight of blueberries. The procedure followed is described by Kim (1987).

Moisture Content. The total moisture content of the blueberries was measured according to the procedures of AOAC (1984). For each replicate, the determination was done in triplicate. The values of moisture, as a percent of the total sample weight, were later used for the estimation of thermal conductivity, using the correlations given by Toledo (1991).

Size. Diameter and projected area of thirty-six fresh blueberries were obtained through machine-vision techniques. The software used for this purpose allowed reading of pixel values of area and diameter of the berries directly. These readings were converted to metric units and used in the mathematical model, in equations where the geometry of the system had to be considered.

Temperature and Velocity of Air. These properties were measured with a digital velocity meter (Velocicheck, Model 8330, TSI). This instrument has a telescoping probe, that allows readings of air velocity and temperature between trays, as well as at the entrance and exit of the dryer.

Relative Humidity of Air. Values of relative humidity were obtained using a transmitter (NYAD, Model 85). The sensor was connected to a power supply (DC), and the readings of electric current were converted to percent relative humidity values using a calibration curve.

CHAPTER IV

EXPERIMENTAL RESULTS

In this chapter, the main findings from the statistical analysis are described and compared to results from other studies. Special considerations are made about the statistical significance of the Rinse and Storage Time treatments and their interactions.

The first part of this discussion refers to data obtained during the post-harvest analysis of blueberry samples. The second section explains the main findings of the reflectance and image processing studies.

Storage Study

These experiments were arranged as a factorial, with three levels of Rinse (No-Rinse, Water, and Chlorine), and 3 levels of Storage time (One, Two and Three weeks). Samples from each harvest were considered a block. Four blocks (replicates) were obtained, and each treatment combination was applied in triplicate, so each mean is the average of twelve readings.

The Analysis of Variance used in this case is presented in Table I. The model includes Block, Treatment and Block x Treatment effects.

Treatment effects contain Rinse, Storage and the Rinse x Storage interactions. There were a total of 108 data points.

This analysis was used to determine the effects of the treatment combinations on water loss, mold development, and softening of the tissue (as percent of initial sample weight).

TABLE I

ANALYSIS OF VARIANCE OF
STORAGE STUDY

Source	Degrees of Freedom
Model	35
Block	3
Treatment	8
Rinse	2
Storage	2
Rinse x Storage	4
Block x Treatment	4
Error	2
Total	107

The hypothesis under test was that means of the chlorine treatments represent better quality than means of the other rinse treatments, at the same storage level.

A summary of the main findings after the statistical analysis is presented in Table II. In all cases, a significance probability-level of 5% is considered. Comparisons were based on the error term expressed as Block x Treatment interaction.

The GLM procedure of SAS (SAS Institute, NC) was used for the analysis. Similar results would be obtained with the ANOVA procedure, since in this case there are no missing values. GLM was used because it has the LSD (Least Significant Difference) which was also of interest in this study.

Block effects were significant, indicating that the response to the treatment combinations depended on the harvest.

Results of the storage study are summarized in Table II. All variables in this table were calculated as percent of initial sample weight.

TABLE II

SUMMARY OF RESULTS OF THE
STORAGE STUDY

Property	Rinse	Storage	Rinse x Storage
Water loss (%)	n.s.	**	n.s.
Soft (%)	**	n.s.	*
Mold (%)	*	*	n.s.
Good (%)	n.s.	*	n.s.

n.s.: not significant at the 0.05 p-level; **: significant at the 0.01 p-level; *: significant at the 0.05 p-level.

Mean values of these properties are presented in Appendix A.

Sample weight loss (expressed as water loss), is presented graphically in Figure 3. This property was not significantly affected by the type of rinse applied, but the effect of storage time was highly significant. Water loss increased from 3.9% in the first week, to 10.6% at the end of the third week of storage.

Blueberries that were chlorine-rinsed showed significantly less mold growth than samples of the control (no-rinse) or water-rinse groups. Although the amount of

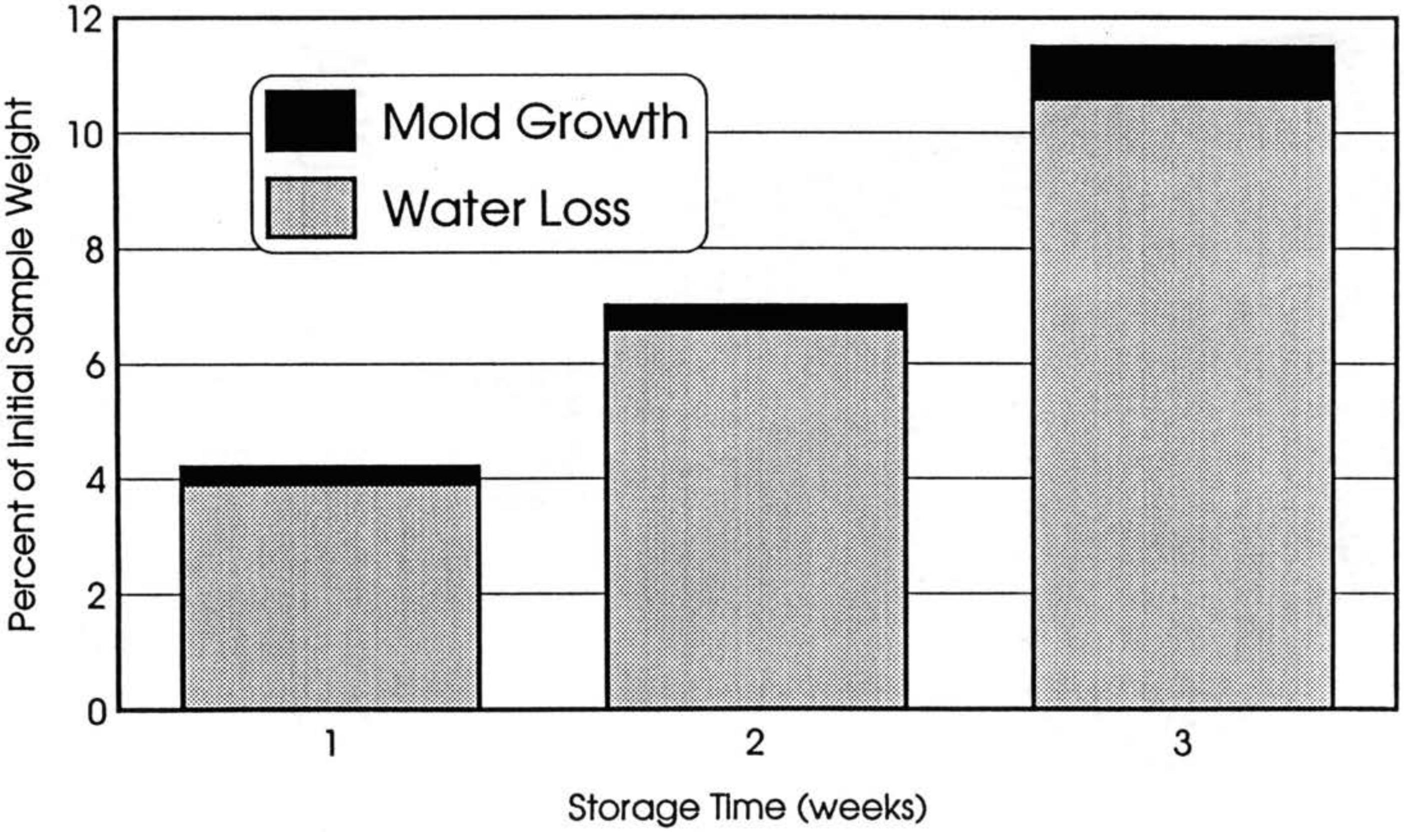

Figure 3. Water Loss and Mold Appearance During Refrigeration Storage

sample that developed mold was less than 1% for each of the treatments, it was possible to determine that the application of the chlorine rinse reduces the appearance of molds.

Weight of soft blueberries increased with storage time, and depended also on the type of rinse applied. After one week of storage, samples of the chlorine and water treatments showed higher percentages of soft berries than controls. This can be attributed to damage to the fruits caused by handling during the application of the dip and removal of the excess moisture. Weight of soft berries of the control group increased with time, however this tendency was not observed in the other rinse treatments (Figure 4).

Overall good quality was not significantly affected by type of rinse, but depended on storage time. After one week, the average amount of berries that showed good quality was 84.5%, significantly higher than the percent soft after three weeks (77.4%).

Titratable acidity, pH of the juice, percent of soluble solids, and the ratio of soluble solids to titratable acidity have been considered indicators of degree of ripeness and quality indexes, and their variation with storage time has been discussed by a number of researchers (Smittle and Miller, 1988; Eck, 1986; Galletta et al., 1971; Ballinger and Kushman, 1970).

Earlier studies show that the amount of decay that develops in any set of samples shows considerable variation from replicate to replicate making it difficult to measure decay accurately and consistently (Galletta et al.,1971).

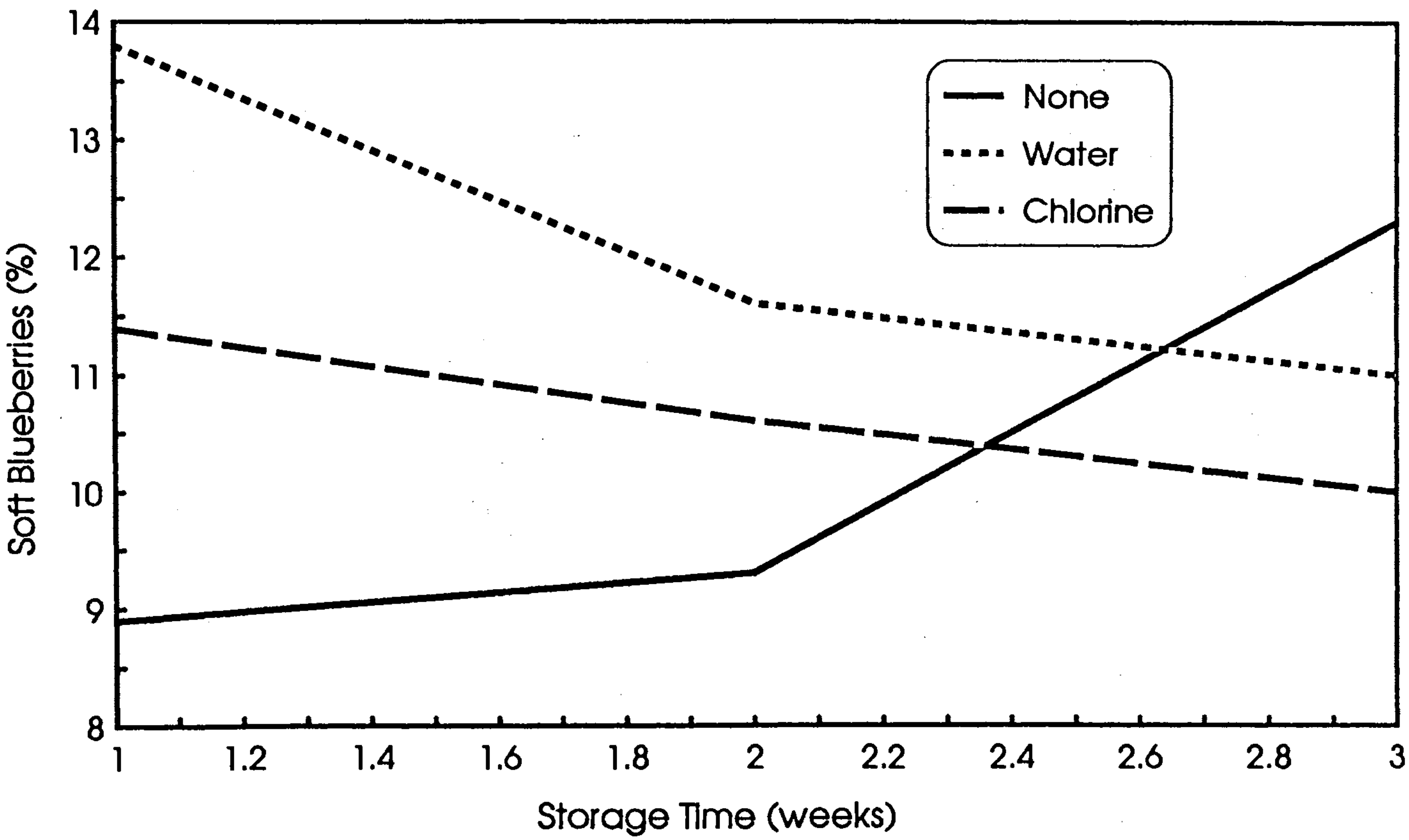

Figure 4. Weight of Soft Blueberries as Percent of Initial Sample

Soluble solids, pH and acidity determinations are more consistent in variation and more objectively determined, and also reflect culinary quality of the fruits.

Results of the post-storage study are presented in Appendix B, and the analysis of variance applied in this case is shown in Table III.

In this analysis, controls were blueberries that were frozen immediately after harvest (did not undergo any of the rinse treatments).

TABLE III

ANALYSIS OF VARIANCE OF
POST-STORAGE ANALYSIS

Source	Degree of Freedom
Model	47
Block	3
Treatments	11
Rinse	2
Storage	3
Rinse x Storage	6
Block x Treatment	33
Error	240
Total	287

Block x Treatment interaction was the error term used for determination of effect significance, and as in the previous analysis, it was found that block effects were significant, verifying that grouping samples by harvest date was a good practice in these experiments.

A summary of the statistical analysis is presented in the next table.

TABLE IV

SUMMARY OF RESULTS OF THE POST-STORAGE STUDY

Property	Rinse	Storage	Rinse x Storage
pH	n.s.	*	n.s.
S.S.	n.s.	**	n.s.
Acidity (%)	*	*	*
S.S./Acidity	*	*	*

n.s.: not significant at the 0.05 p-level; **: significant at the 0.01 p-level; *:significant at the 0.05 p-level.

pH values were affected significantly by storage time. Variation with time (over all rinse treatments) is shown in Figure 5, and mean values are shown in Table XIII (Appendix B). Means of the control and one-week treatments were significantly lower than means of the two and three week storage times.

Galletta et al. (1971) found that increase in pH values was directly correlated with incidence of decay. Also they found that when pH and acidity were used as predictors of decay, pH appears to contribute more than acidity to the prediction of blueberry deterioration.

Using pH as a predictor of decay, results of this work suggest that detrimental changes would not occur during the first week of storage (compared to the control), but a reduction of quality would be expected after the second and third weeks.

Studies of blueberry properties using controlled atmospheres show that there is no effect of the type of environment on pH value (Smittle and Miller, 1988), and from

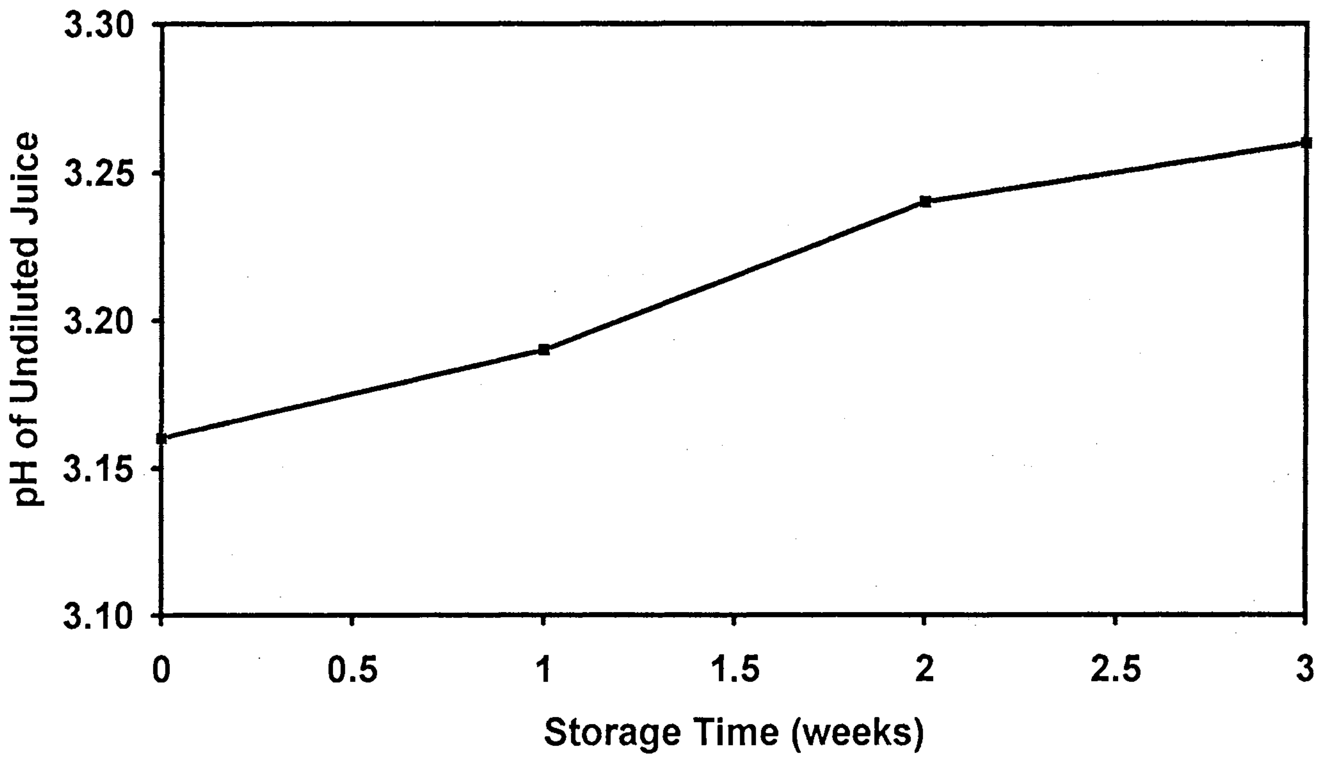

Figure 5. pH Values of Blueberry Juice as Function of Storage Time

this work is evident that type of rinse did not have any significant effect on this property.

The ratio of total soluble solids to titratable acidity is used commonly as an indicator of degree of ripeness and a predictor of decay. From studies conducted to determine the relationship between stage of ripeness and development of decay, it has been found that soluble solids to acidity ratio increases with storage (Ballinger et al., 1978), and that it is a function of holding temperature.

Values of soluble solids were significantly affected only by storage time. Mean values (over all rinse treatments) are presented in Table XIV, Appendix B, and varied from 9.37% for the control, to 11.79% after three weeks of storage.

Type of rinse and storage had significant effects on acidity, which in this work was calculated as percent malic acid. Means are shown in Table XV, Appendix B.

Titratable acidity percent decreased with time for chlorine and water-rinsed samples. For the no-rinse treatment, acidity was not significantly different for samples of the one, two and three weeks storage times, but was lower for the "zero" samples (frozen immediately after harvest).

Means of soluble solids to acidity ratio are presented in Table XVI, and are shown graphically in Figure 6. In all cases, the tendency was to increase with storage time. The rate of change was higher for samples of the rinse treatments than the control.

Ballinger et al. (1978) established several marketing criteria relating the index of ripeness (soluble solids/acidity ratio) to the distance to the final market. In their study they used several varieties of blueberry. Values of titratable acidity were

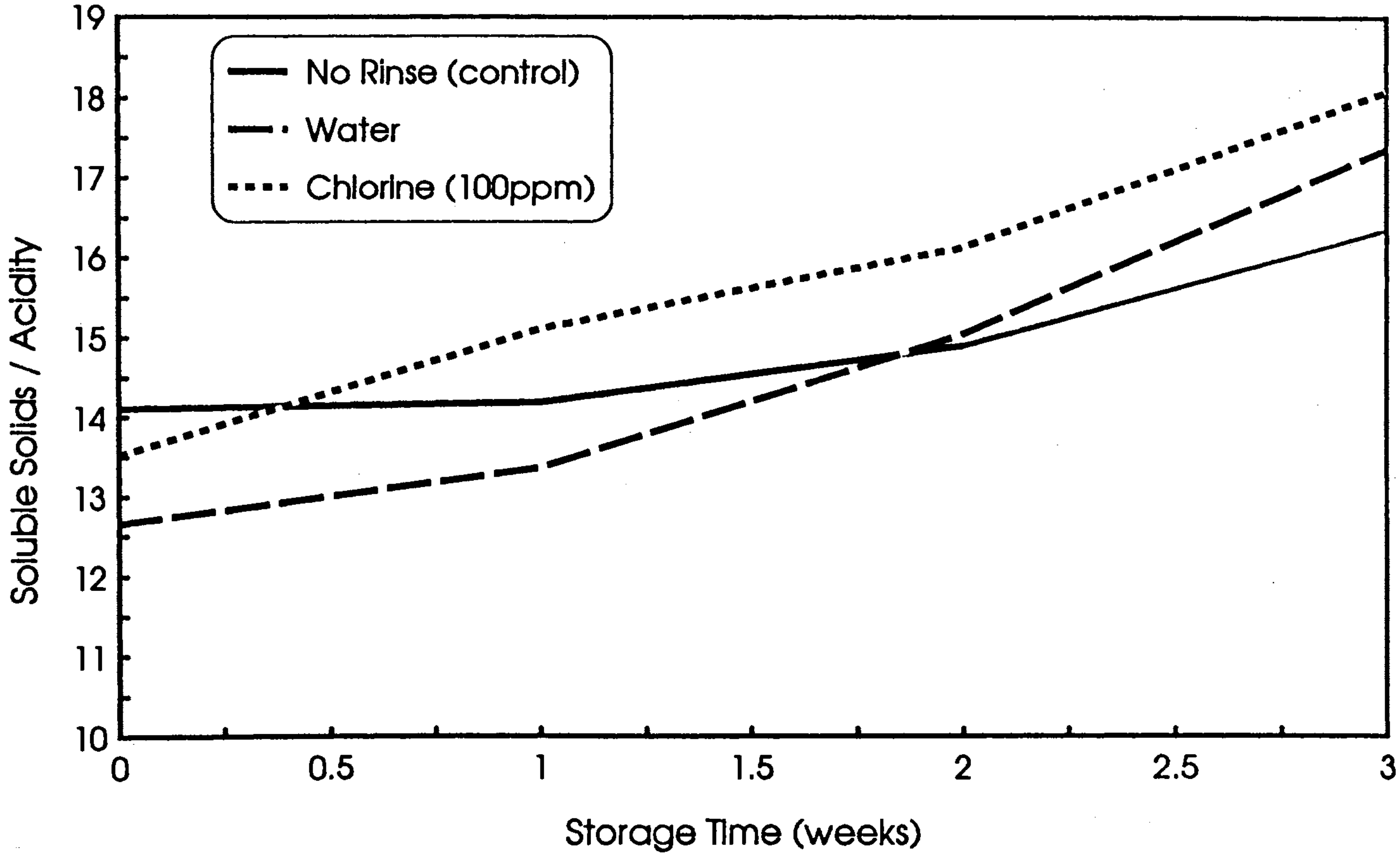

Figure 6. Ratio of Soluble Solids to Titratable Acidity for Each Rinse Treatment

calculated as percent of citric acid, and during forty five days of storage, varied from 1.34 to 0.24 for Jersey, and from 1.32 to 0.49 for the Blueray variety.

They established that blueberries destined for long distance shipment (transoceanic) should have soluble solids to acidity ratio not higher than twenty; those destined for intermediate distance (no more than 4800 km) should have a ratio lower than 27, and blueberries marketed locally can have a ratio of 30 or less.

Since their estimations were based on acidity content measured as percent citric acid, it is not possible to establish a comparison between the results of this study and the published results of Ballinger et al. (1978).

It would be of interest to calculate the values of titratable acidity as percent of citric acid, and to determine whether chlorine-rinsed samples are adequate for the fresh market.

Machine-Vision Analysis

The first set of experiments was used to determine the appearance of specific features in the reflectance spectra of blueberry skin samples.

Figure 7 shows the plots obtained for four types of blueberry samples tested: fresh- with bloom, fresh- without bloom, water-rinsed and chlorine-rinsed. Samples from fresh, non-processed blueberries (with bloom) showed higher reflectance (approx. 20%) in the 200 to 300 nm range than samples from berries that were processed, either with water, or chlorine-rinsed. Lowest reflectance values were found for fresh berries without bloom . Water-rinsed samples had higher

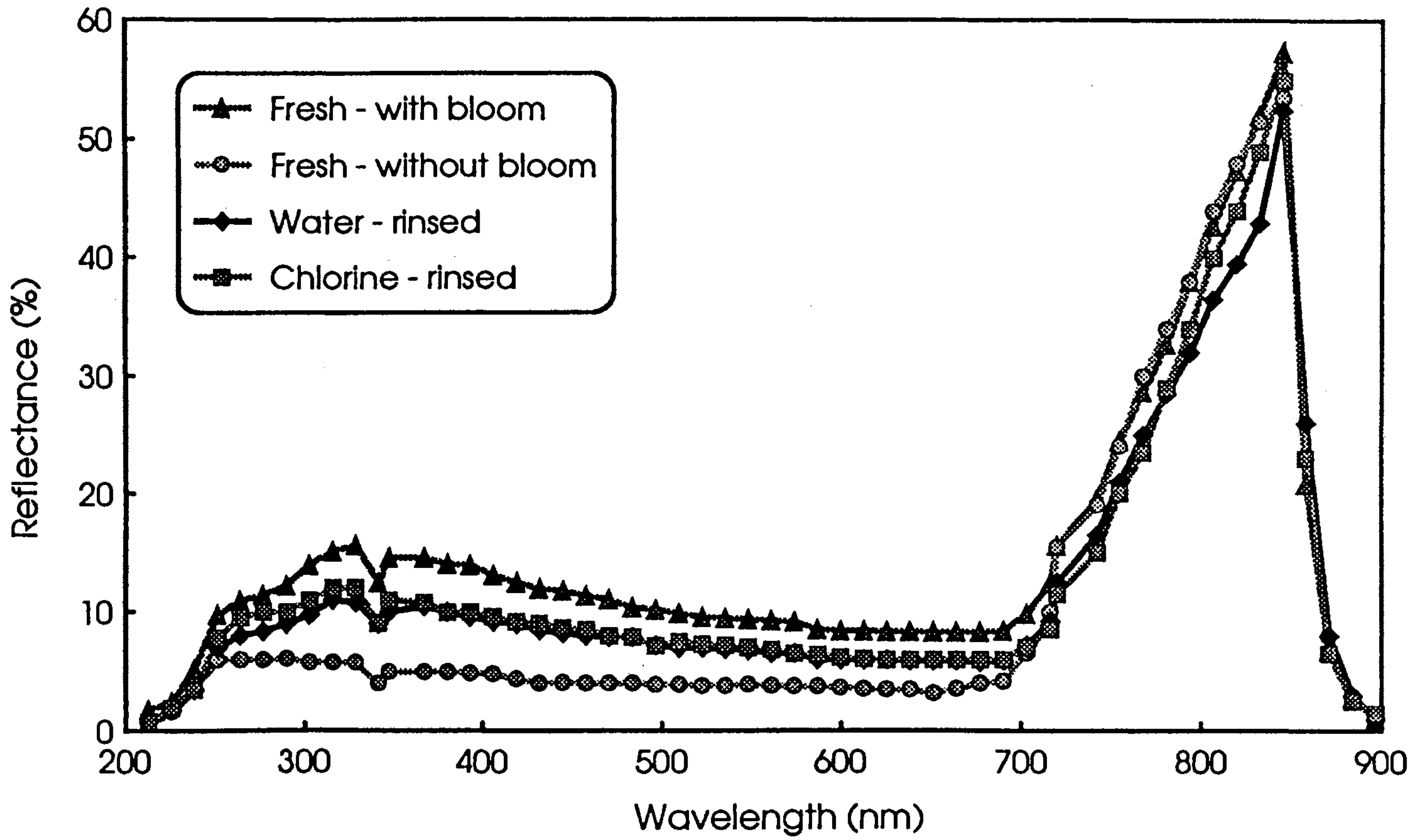

Figure 7. Reflectance Spectra of Blueberry Skin Samples

reflectance in the 680 to 830 nm range than samples that were chlorine-rinsed. Between 400 and 700 nm, there was no noticeable difference between samples of these two rinse treatments.

Image acquisition and processing were done with a lens configuration that allowed detection of differences in the 680 - 830 nm range, in order to determine color differences between rinse treatments.

Image Processing

The red, green, blue (color components), hue, saturation and intensity (color properties) data obtained for blueberry samples having different amounts of bloom, were analyzed for the effects of Type of rinse and Storage time.

The GLM procedure of SAS (SAS Institute, Cary, NC) was used for this purpose. There were no missing data, and mean comparisons were done with the LSD procedure of SAS.

The effects tested were: Type of rinse, Storage and Rinse x Storage Interaction. There were 240 data points for each property (20 for each treatment combination). The model used for the analysis of variance is shown in Table V.

SAS results indicate that at the 5% probability level, there is no significant difference in means due to type of rinse applied, except for the variable Hue. Storage time was significant at the 0.05 p-level for all variables.

The interaction Rinse x Storage was not significant for any of the variables, which indicates that the effects (rinse and storage) act independently. For this reason, means were calculated for each storage time, over all the levels of rinse.

TABLE V

ANALYSIS OF VARIANCE OF
IMAGE PROCESSING

Source	Degrees of Freedom
Model	11
Rinse	2
Storage	3
Rinse x Storage	6
Error	228
Total	239

A summary of mean values of color components is given in the following table.

TABLE VI

MEAN RGB VALUES

Storage Time (Weeks)	Red	Green	Blue
0	174.5^{a}	163.0^{a}	159.3^{a}
1	141.4^{b}	129.1^{b}	121.6^{b}
2	177.6^{a}	164.7^{a}	163.6^{a}
3	183.0^{c}	170.7^{c}	170.6^{c}

^{a,b,c}: Means with the same superscript are not significantly different ($p>0.05$).

Results show that samples from the 2-week and 0-week storage times are not significantly different from each other (at the 0.05 p-level), but are different from samples of the one and three week treatment.

Mean values of Red, Green and Blue for samples of the 3-week storage level were significantly higher (0.01 p-level) than means for all the other storage periods. Mean values of the 1-week storage study are significantly lower (0.01 p-level) than the means for the other storage periods.

Figure 8 shows the Red, Green and Blue values relative to Intensity. Means of these variables are shown in Table XVII (Appendix C).

For R/I and G/I, the tendency is to decrease as storage time increases, except for samples of the 1-week storage time. Similarly, for B/I values, these samples also depart from the trend, which in this case is to increase with storage time.

Values of R/I, G/I and B/I represent the contribution of each color component to intensity, and can vary between 0 and 1.73. A value closer to the upper bound represents then, a higher contribution to intensity.

From this study was found that the contribution of Blue color to Intensity increases with storage time, while Red and Green contributions decrease.

Samples of the one-week storage study were obtained from a different supplier, and this may be the reason why these samples exhibit different behavior than the rest.

Standard deviation values of Red, Green and Blue were considered indexes of color distribution over the blueberry surface, and were also analyzed for Rinse and Storage time effects. Results of this analysis are presented in Table VII.

Excluding the readings obtained from samples of the 1-week storage study, the distribution of color components did not change during the first two weeks, and significantly decreased after the third week.

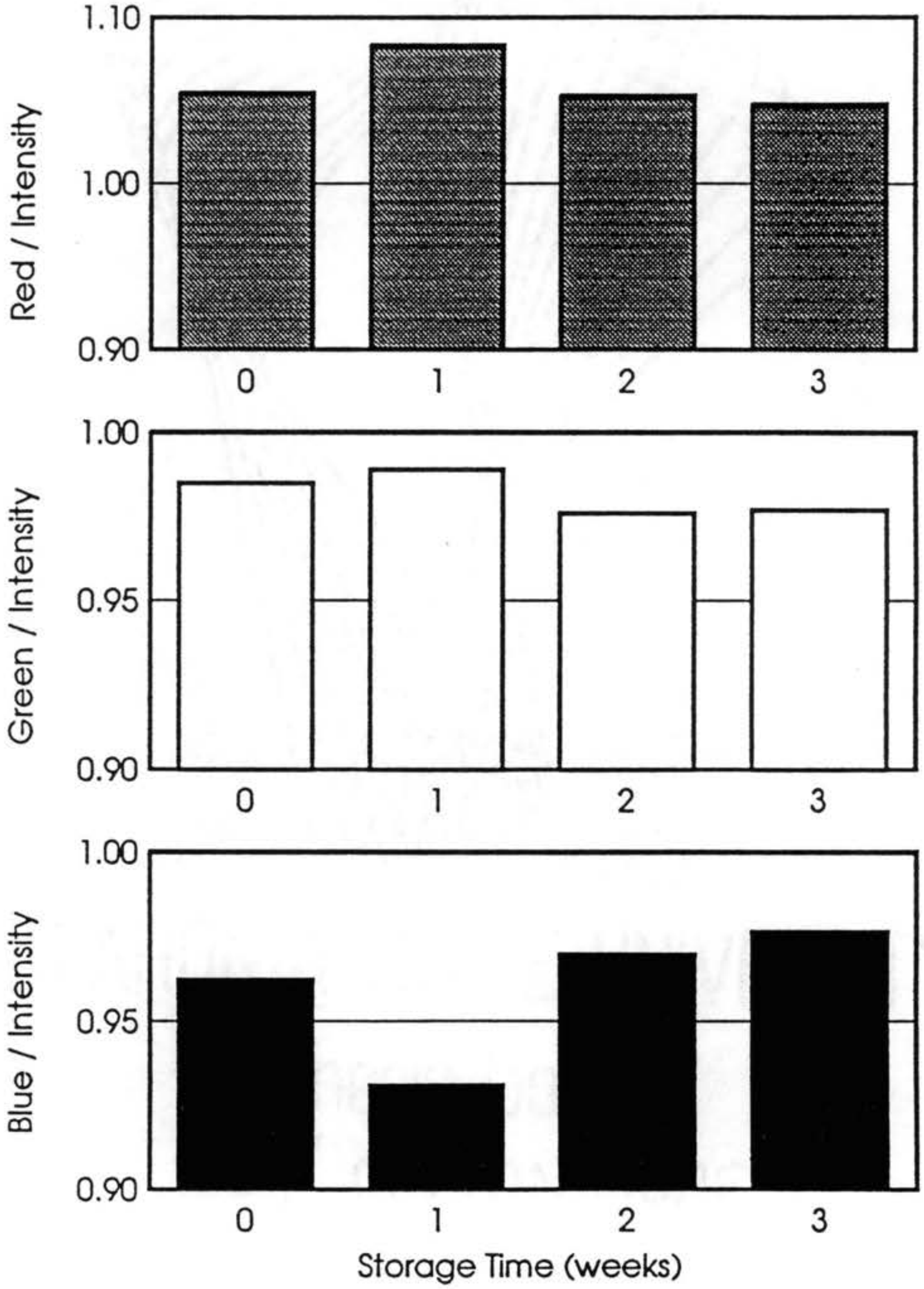

Figure 8. Contribution of Color Components to Intensity

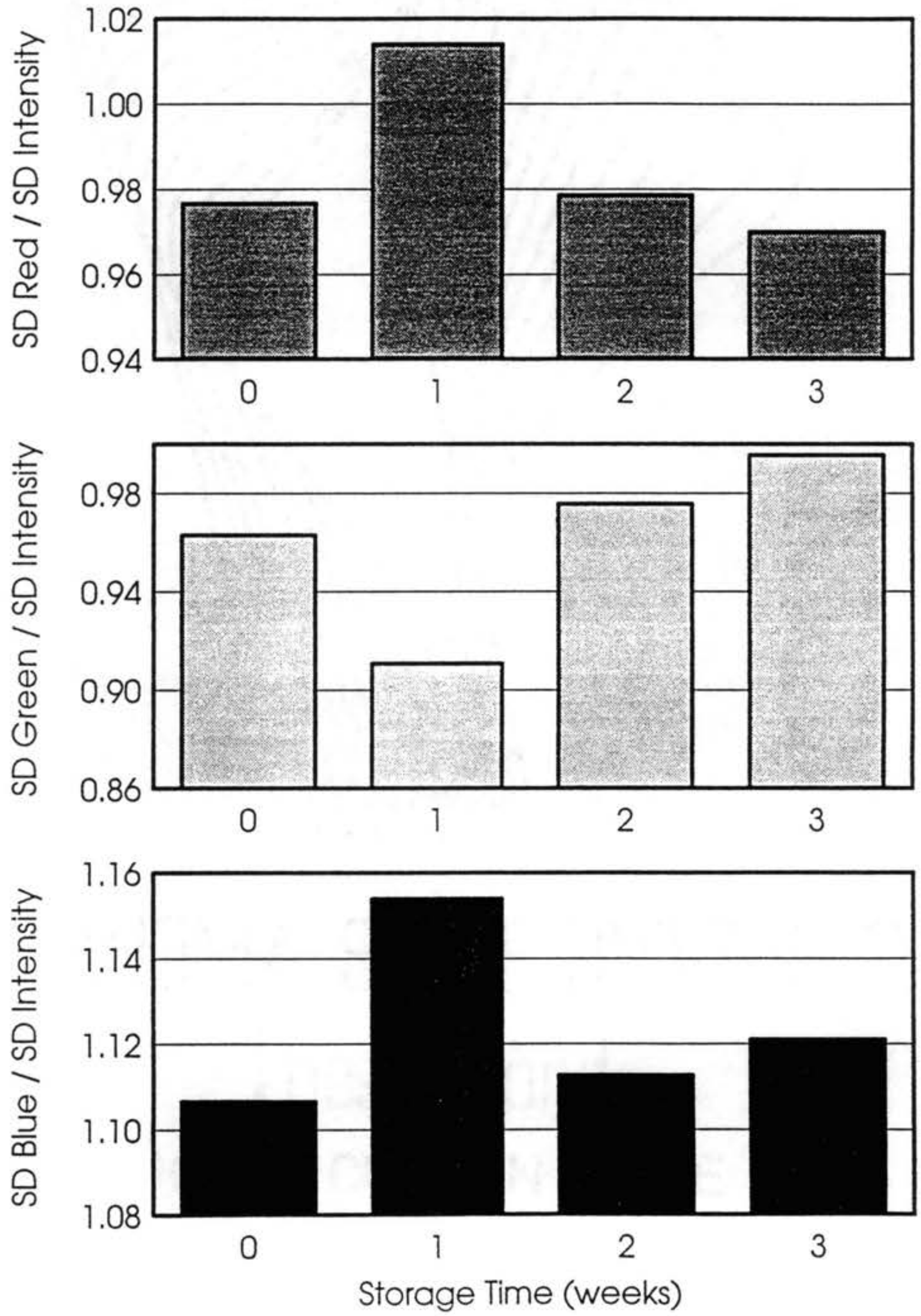

Figure 9. Distribution of Color Components Relative to Distribution of Intensity

The distribution of each color component relative to distribution of Intensity is shown graphically in Figure 9. Green and Blue showed an increase in dispersion with time. Distribution of Red relative to distribution of intensity decreased with storage time (considering only controls, and samples for the two and three weeks treatments).

TABLE VII
MEAN STANDARD DEVIATION
VALUES OF RGB

Storage Time (Weeks)	SD Red	SD Green	SD Blue
0	17.22[a]	16.98[a]	19.51[a]
1	15.14[b]	13.60[b]	17.23[b]
2	17.02[a]	16.97[a]	19.35[a]
3	14.90[b]	15.29[c]	17.22[b]

[a,b,c]: Means with the same superscript are not significantly different ($p>0.05$).

Mean values of Hue, Saturation and Intensity are summarized in Table VIII, and are presented graphically in Figure 10.

TABLE VIII

MEAN HSI VALUES

Storage Time (Weeks)	Hue	Saturation	Intensity
0	76.4[a]	11.7[a]	165.5[a]
1	53.3[b]	19.9[b]	130.6[b]
2	108.5[c]	12.0[a]	168.7[a]
3	117.3[c]	10.5[c]	174.7[c]

[a,b,c]: Means with the same superscript are not significantly different ($p>0.05$).

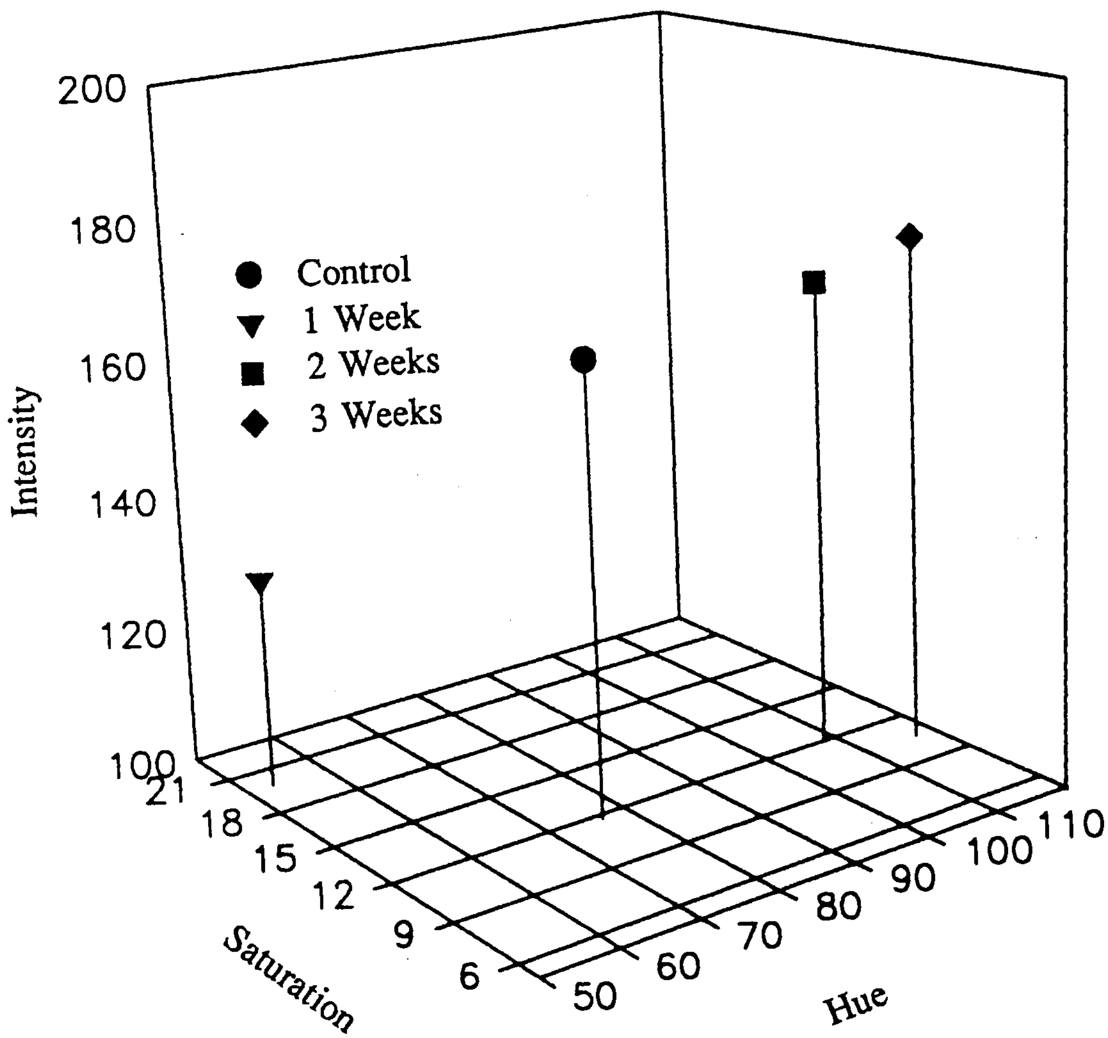

Figure 10. Values of Color Properties for Each Rinse Treatment

In this analysis, samples of the one-week storage group also depart from the trend showed by the other samples.

From Figure 10 it can be seen that (ignoring samples of the one-week group), Intensity values increase with Storage time, indicating that the brightness of the blueberries is higher, which can be seen as loss of bloom.

Hue values increased for samples of the two and three week Storage groups compared to the control. Saturation decreased after three weeks of storage (versus control), but did not change from the second to the third week of storage.

Standard Deviation values of Hue, Saturation and Intensity were also considered as variables and analyzed for variations with storage time.

Mean values are summarized in Table XVIII (Appendix C), and graphically in Figure 11.

TABLE IX

MEAN STANDARD DEVIATION
VALUES OF HSI

Storage Time (Weeks)	SD Hue	SD Saturation	SD Intensity
0	95.29^{a}	5.35^{a}	17.63^{a}
1	76.37^{b}	8.80^{b}	14.93^{b}
2	106.94^{c}	5.69^{a}	17.39^{a}
3	106.22^{c}	4.77^{c}	15.36^{b}

^{a,b,c}: Means with the same superscript are not significantly different ($p>0.05$).

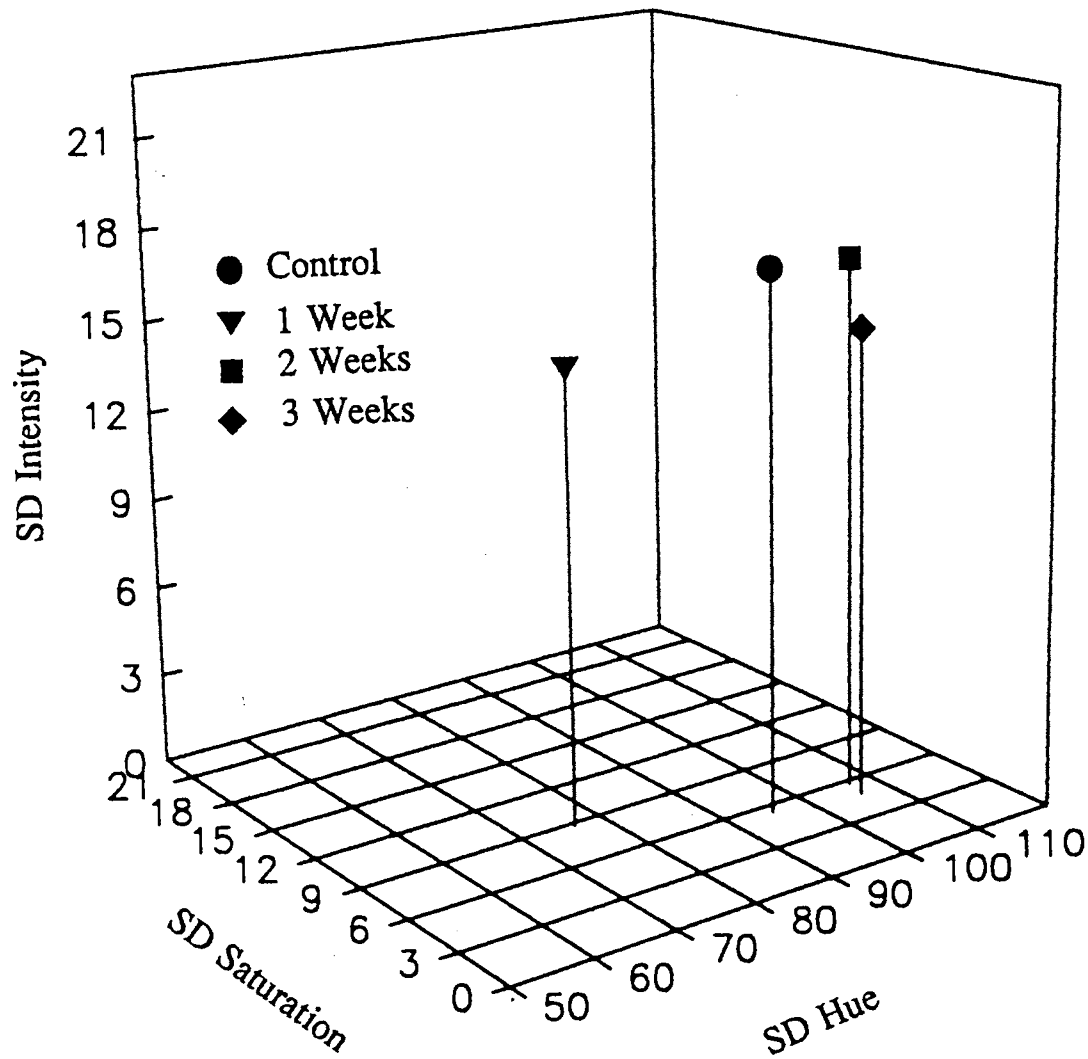

Figure 11. Distribution of Color Properties for Each Rinse Treatment

Samples of the two and three storage times showed higher variation in the distribution of Hue than the control, although no significant change was determined between those two means. Figure 11 shows that variations in the standard deviation values of saturation were not significantly altered from beginning of storage (zero weeks) to the second week, but decreased after three weeks in refrigeration.

As mentioned before, Hue was the only variable that was significantly affected by Type of rinse. Mean value of Hue of Chlorine-rinsed samples (for all storage times) was 95.2, significantly higher (at the 5% probability-level) than the control (No-rinse), which was 81.9, but was not significantly different than the mean of Water-rinsed samples.

CHAPTER V

MATHEMATICAL MODEL

Throughout the years, a number of mathematical models have been suggested to simulate the operation of drying systems.

Although the types of equations used may differ, all models represent changes that occur in the drying air and in the solid particles, using the principles of conservation of mass, heat and momentum.

Parry (1985), in his review of mathematical modeling and computer simulation of agricultural grain drying, classifies models into three basic types: 1) Logarithmic, 2) Heat and mass transfer models, and 3) Systems of partial differential equations.

Models of the first type are simple and use less computing time, but their application is limited to low temperature and low air flow conditions. Heat and mass transfer models involve determinations of temperature and moisture of grain and air for successive sections of the static bed. A number of assumptions are made to simplify calculations, and the accuracy of predictions and range of applicability depends on the validity of the assumptions for a particular case.

Partial differential equations systems, or P.D.E. models, originated from heat and mass balance models, but represent the changes in the form of differential equations, that when integrated, give the temperature and humidity profiles for the solid particles and air stream.

The model presented in this work belongs to the P.D.E. type, and was developed for two reasons: 1) To simulate the evaporation of excess moisture from blueberry surface, and 2) To predict if dehydration is likely to occur under specified air temperature and humidity conditions.

This process can be represented by a set of equations commonly used to describe deep-bed drying, under the assumption that each tray in the dryer represents a layer of a deep-bed system, and that conditions of the air leaving one stage do not change until it reaches the next tray.

The model considers heat and mass transfer processes that occur in static-bed dryers, thus giving some insight on the changes in temperature and humidity that occur during the drying process, and was developed in a general form, so it can be used to simulate dehydration of other agricultural products.

This chapter includes a description of the equations used in the model, as well as the assumptions and boundary conditions considered in its development. The numerical method of solution is also explained. Model validation and results are presented in the next chapter.

Equations of the Model

Assumptions

The equations are derived from consideration of mass and energy balances taken over an arbitrary differential volume within the particle-air mixture.

In the model development, moist air and moist solid are considered binary mixtures, and it is assumed that the mass flow rate of air is constant. The problem is considered one-dimensional, with negligible conduction and radiation effects (when compared to convective heating).

It is also assumed that variations of volumetric mass of dry air are small, and that no shrinkage of the drying particles occurs (Arnaud and Fohr, 1988; Parry, 1985).

Other considerations are: the dryer walls are adiabatic, the total pressure is constant throughout the bed, and the mass transfer rate from the product to the air can be described by a known drying kinetics equation.

The development of the basic model equations is presented in Appendix D, and a list of symbols is shown in the preliminary pages.

Mass and Energy Balances

The behavior of a deep bed dryer can be described by four variables: 1) W, the moisture content of air, expressed as mass of water per unit mass of dry air; 2) H_a, the air enthalpy; 3) H_s, the enthalpy of the solid, and 4) the moisture content of the particles.

Energy changes in the moist air stream are described by the following equation:

$$\rho_a\left[\epsilon\frac{\partial H_a}{\partial t}+v\frac{\partial H_a}{\partial z}\right]=-ha_v\,(T-\theta)\,-\rho_s\,(1-\epsilon)\,\frac{\partial M}{\partial t}H_w \tag{1}$$

The terms include changes in enthalpy with time and position, heat transfer between air and solids, and energy of the evaporating water.

The rate of change of the mass of water per volume unit in the differential element can be expressed as:

$$-\rho_s(1-\epsilon)\frac{\partial M}{\partial t}=\rho_a v\frac{\partial W}{\partial z}+\rho_a\epsilon\frac{\partial W}{\partial t} \tag{2}$$

The development of equation (2) considers the amount of water that enters the element, the water evaporated from the drying solid, and the water leaving the elemental volume.

The equation that describes changes in enthalpy of the drying solid includes heat transfer due to temperature differences between the particles and the drying air, and the enthalpy of the water present in the solid. It can be written as:

$$ha_v(T_a-\theta)+\rho_s(1-\epsilon)\frac{\partial M}{\partial t}\left[H_w^{vapor}\right] = \rho_s(1-\epsilon)\left[\frac{\partial H_s}{\partial t}\right] \tag{3}$$

Changes in M, the moisture content of the solid is given by an equation of the form:

$$\frac{\partial M}{\partial t}=f\,(M_e, M_o, K, T, v) \tag{4}$$

The value of k is characteristic of the drying material, and can be expressed as a function of temperature as follows:

$$k=a_o\ \exp\left(\frac{-a_1}{T}\right) \tag{5}$$

For the simulation examples discussed later in this work, the drying curve will be specified as each particular case is presented.

Space Discretization

The equations described above represent energy and moisture changes that occur in air and solid particles during drying.

This set of partial differential equations will be solved by discretizing the space derivatives, and thus, transforming the set in a system of ordinary differential equations. This is an initial value problem with four O.D.E.'s per node in the discretization.

Using backward differences, the change in a generic property, γ, over a specified space interval is given by:

$$\gamma = \frac{\gamma_j - \gamma_{j-1}}{\Delta z} \tag{6}$$

Based on this principle, air humidity at any point in the bed can be represented by:

$$W = \frac{W_j - W_{j-1}}{\Delta z} \tag{7}$$

Enthalpy values are given by:

$$H_a = \frac{H_{a,j} - H_{a,j-1}}{\Delta z} \tag{8}$$

where j refers to a specific location (node) in the deep bed, and j-1 represents the previous stage.

After the space discretization, the equations for air can be represented by:

$$\frac{dW_j}{dt} = \frac{-v}{\Delta z \epsilon} W_j + \frac{v}{\epsilon \Delta z} W_{j-1} - \frac{\rho_s}{\rho_a} \frac{(1-\epsilon)}{\epsilon} \frac{dM}{dt} \tag{9}$$

$$\frac{dH_{a,j}}{dt} = \frac{-v}{\epsilon \Delta z} H_{a,j} + \frac{v}{\epsilon \Delta z} H_{a,j-1} - \frac{ha_v}{\rho_a \epsilon} (T_j - \theta_j) - \frac{\rho_s}{\rho_a} \frac{(1-\epsilon)}{\epsilon} \frac{dM}{dt} H_w^{vap} \tag{10}$$

The value of the air enthalpy can be obtained from the contributions of dry air and the water fractions present, and is given by:

$$H_a = Cp_a (T - T_r) + WCp_w^{vap} (T - T_r) \tag{11}$$

Values of air temperature can be obtained as function of the variable of integration H_a:

$$T_j = f(H_{a,j}) \tag{12}$$

In equation (10), the enthalpy of water vapor is given by:

$$H_w^{vap} = C_p^{vap} (T - T_r) \tag{13}$$

The enthalpy of the solid is not explicitly given in terms of the variable z, but can be seen that it will vary with distance as the air temperature changes across the dryer. It is given by:

$$H_s = Cp_s(\theta - T_r) + MH_w^{liq}(\theta) \tag{14}$$

where the value of enthalpy of liquid water can be calculated as:

$$H_w^{liq} = Cp_w^{vap}(T - T_r) - \Delta H_w^{vap} \tag{15}$$

Once the solid enthalpy is known, the temperature of the drying particles can be found as a function:

$$\theta_j = f(H_{s,j}) \tag{16}$$

Normalization of the Variables

Equation systems as the one described above for temperature and enthalpy of air and solid exhibits several characteristics which require additional simplifications and the use of particular methods of solution.

In static bed dryers, at the time of commencement of drying, there are rapid changes in enthalpy and in humidity as the incoming air, usually at high temperatures, reaches the moist solid.

The time derivatives of air properties change almost instantaneously, but the changes in solid moisture content occur at a significantly lower rate.

Systems of this type, where variables change with widely different time scales, present the characteristic of stiffness, that can be overcome with the use of appropriate numerical techniques.

Enthalpy and moisture variables can be represented in normalized form as the ratio of the variable at a given time t and position in the dryer, to its initial value (time when drying started), which is known.

In normalized form, these variables become:

$$\overline{W}=\frac{W}{W_o} \Rightarrow W=\overline{W}\cdot W_o \tag{17}$$

$$\overline{H}_a=\frac{H_a}{H_{a,o}} \Rightarrow H_a=\overline{H}_a\cdot H_{a,o} \tag{18}$$

$$\overline{H}_s=\frac{H_s}{H_{s,o}} \Rightarrow H_s=\overline{H}_s\cdot H_{s,o} \tag{19}$$

$$\overline{M}=\frac{M}{M_o} \Rightarrow M=\overline{M}\cdot M_o \tag{20}$$

The equilibrium moisture content can also be represented by:

$$\overline{M}_e=\frac{M_e}{M_o} \Rightarrow M_e=\overline{M}_e\cdot M_o \tag{21}$$

In normalized form, the set of equations becomes:

$$\frac{d\overline{W}_j}{dt} = \frac{v}{\epsilon \Delta z}\overline{W}_j + \frac{v}{\epsilon \Delta z}\overline{W}_{j-1} - \frac{\rho_s}{\rho_a}\frac{(1-\epsilon)}{\epsilon}\frac{m_o}{W_o}\frac{d\overline{M}_j}{dt} \tag{22}$$

$$\frac{d\overline{H}_a}{dt} = \frac{-v}{\epsilon \Delta z}\overline{H}_{a,j} + \frac{v}{\epsilon \Delta z}\overline{H}_{a,j-1} - \frac{ha_v}{\rho_a \epsilon H_{a,o}}(T-\theta) - \frac{\rho_s}{\rho_a}\frac{(1-\epsilon)}{\epsilon}\frac{M_o}{H_{a,o}}H_w^{vap} \tag{23}$$

$$\frac{d\overline{H}_s}{dt} = \frac{h_{av}}{\rho_s(1-\epsilon)H_{s,o}}(T-\theta) + \frac{M_o}{H_{s,o}}\frac{dM}{dt}H_w^{vap} \tag{24}$$

$$\frac{d\overline{M}}{dt} = k(\overline{M} - \frac{M_e}{M_o}) \tag{25}$$

Enthalpy and moisture expressions can be expressed in simplified form if coefficients are formed as follows:

$$C_1 = \frac{v}{\epsilon \Delta z} \tag{26}$$

$$C_2 = \frac{\rho_s(1-\epsilon)}{\rho_a \epsilon}\frac{M_o}{W_o} \tag{27}$$

$$C_3 = \frac{ha_v}{\rho_a \epsilon H_{a,o}} \tag{28}$$

$$C_4 = \frac{\rho_s(1-\epsilon)}{\rho_a \epsilon}\frac{M_o}{H_{s,o}} \tag{29}$$

$$C_5 = \frac{ha_v}{\rho_s(1-\epsilon)H_{s,o}} \tag{30}$$

$$C_6 = \frac{M_o}{H_{s,o}} \tag{31}$$

Finally, the equation set that describes the dryer performance is defined by:

$$\frac{d\overline{W}}{dt} = -C_1 \overline{W}_{j+1} + C_1 \overline{W}_{j-1} - C_2 \frac{d\overline{M}_j}{dt} \tag{32}$$

$$\frac{d\overline{H}_a}{dt} = -C_1 \overline{H}_{a,j+1} + C_1 \overline{H}_{a,j-1} - C_3 (T-\theta) - C_4 H_w^{vap} \frac{d\overline{M}}{dt} \tag{33}$$

$$\frac{d\overline{H}_s}{dt} = C_5 (T-\theta) + C_6 H_w^{vap} \frac{d\overline{M}}{dt} \tag{34}$$

The rate of change in moisture content of the solid is given, in normalized form, by equation (25), and the required value of k is found using equation (5).

A program in FORTRAN was written and linked to the equation solver system of ASPEN Plus (Aspen Technology, Inc., Cambridge, MA).

The possibility of water vapor condensing during drying has been pointed out by several researchers (Costa and Figueiredo, 1993; Stone, 1982; O'Callaghan et al., 1971; Boyce, 1965).

This situation occurs when air at near saturation conditions passes through the upper layers of the bed, which are at lower temperature at the beginning of the drying process. Relative humidity will raise as air is cooled at constant absolute humidity. When 100% relative humidity is reached, the mass transfer process is reversed, and water is deposited on the material with release of latent heat.

The model developed in this work considers the possibility of saturation, based on calculations of relative humidity using the following equation:

$$RH=\frac{W\left(\frac{P}{P_w^{sat}}\right)}{(Y_w+W)} \tag{35}$$

where P_w^{sat} is the water vapor pressure at the current temperature, and Y_w is the ratio of the molecular weight of water to that of air.

If the relative humidity is greater than 100%, the excess water would condensate, increasing the moisture content of the product. The equation of $\partial M/\partial t$ is given in Appendix D (equation 53).

The program listing is presented in Appendix F, and the method of solution is described in the following pages.

<u>Initial and Boundary Conditions</u>

The solution of the system of differential equations requires the value of the initial conditions of the state variables (enthalpy and moisture content) of solid and air in the dryer, as well as those of the incoming drying air.

For each of the simulation cases, the values of air and particle properties are given in Appendix E.

Method of Solution

Several methods have been suggested for the solution of deep bed dryers. For the simulation of Barley drying, Costa and Figueiredo (1993) reduced the system of equations to a single equation, which could be solved by the Newton-Raphson method.

Results provided useful information about the drying process, but the required computation time was about one-half of the time needed to reproduce the drying process experimentally.

Earlier works used a predictor-corrector technique with mid-point predictor and trapezoidal corrector formulas (Parry, 1985). However, the method was found to be sensitive to small changes in temperature derivatives and a special technique based on a modified Euler method was required to obtain starting values for the first integration step.

To overcome these stability problems, computations were usually carried out on a simplified number of equations, with the assumption that the temperature change in the product was zero at all points in the bed, representing the initial period of drying. This solution to the drying equations did not provide an accurate representation of the process, but was useful for preliminary analysis.

Other usual assumptions include ignoring changes in enthalpy or in temperature of the air, but their use limits the accuracy of the predictions, particularly if high moisture and temperature gradients occur during the drying process.

In this work, a robust O.D.E. solver capable of handling very stiff problems was used. The method is a modified predictor-corrector formulation, which has been succssesfully applied to the simulation of batch distillation problems, and is described in detail by Boston et al. (1980).

The implementation of the method requires an implicit integration formula, and the equations should be in backward difference form.

In this algorithm, the step size (Δt) is not restricted by stiffness or numerical stability criteria, and it may be adjusted every time step to maintain the estimated truncation error within specified limits. As the integration proceeds, history points are maintained at unequally spaced intervals using the Nordsieck array concept (Boston et al., 1980). Therefore, each integration step may have its optimally chosen step size without the expense and possible numerical difficulties associated with equally spaced history points.

Figure 12 shows the interactions between the drying model developed in this work and the equation solver of ASPEN Plus.

Several example cases of barley drying are presented in the next chapter, which illustrate the applicability of this method. Also, it was used for the simulation of moisture evaporation from blueberry surface, and to predict if dehydration is likely to occur.

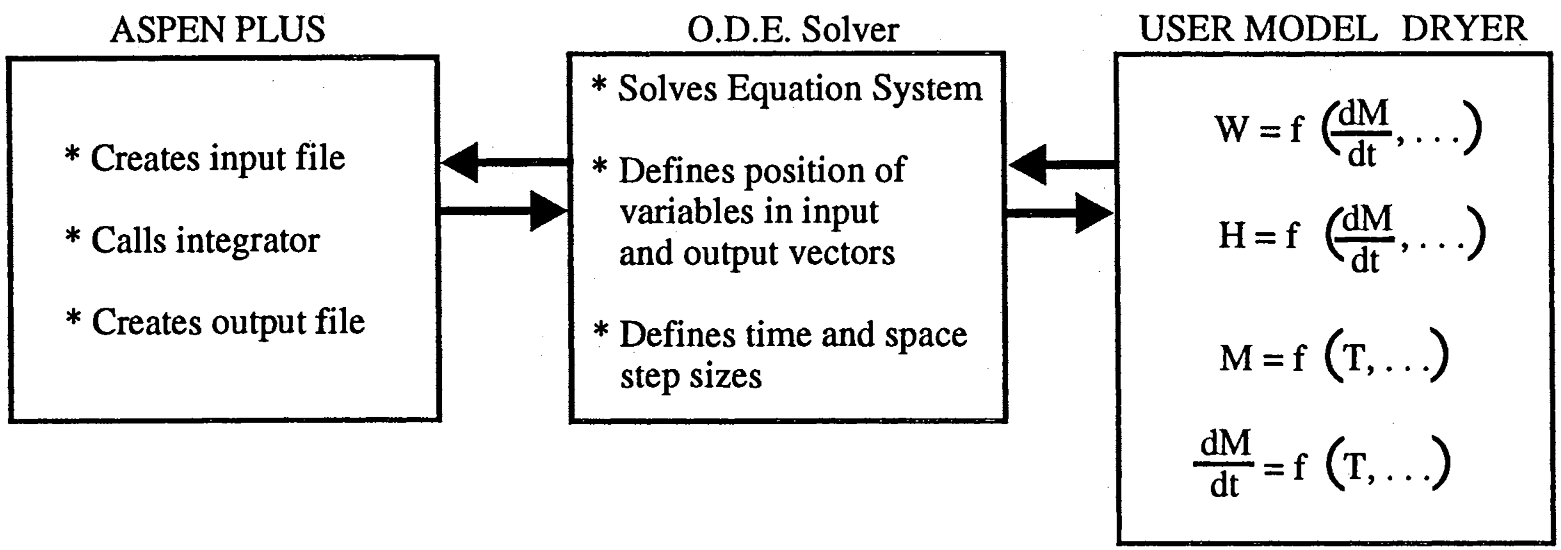

Figure 12. Interaction Between ASPEN PLUS and User Model "Dryer."

CHAPTER VI

SIMULATION RESULTS

The mathematical model described in the previous chapter was tested using published data of barley drying.

In this chapter, the model capabilities and its functionality are discussed, and predictions compared to other simulation results published in the literature. Comparisons against experimental data are also presented.

The last section of this chapter shows the results of the simulation of excess moisture removal and dehydration of blueberries.

Simulation of Deep-Bed Barley Drying

For this simulation run, a deep bed of barley of 0.305 m was used. Initial temperatures of air and barley were 68 C and 18 C, respectively. Physical properties and other air flow conditions are as reported in the works of Costa and Figueiredo (1993), O'Callaghan et al. (1971), and Boyce (1965). They are summarized in Tables XIX and XX (Appendix E).

The first set of results illustrates the model capabilities for a drying time of 250 minutes.

Figure 13 shows the changes in specific humidity of air at several locations in the bed. Air humidity increased significantly during the first 20 minutes of drying, and is evident that the upper layers reached and maintained higher humidity values than the first two stages (nodes at 25 and 75 mm).

Figure 14 presents values of air humidity for the first 20 minutes of the process. The upper three layers show a rapid change between 5 and 15 minutes, the period when condensation occurred. There is a discontinuity in the curve of the layer at 305 mm, which occurs at the point where the model function representing dM/dt changes from drying to condensation.

The air temperature profile and the plot of particle temperature across the bed are presented in Figures 15 and 16, respectively. From the air temperature plot it can be noticed that there is an almost instantaneous increase in temperature in the lower sections of the bed, and after this initial "warm-up" period, the temperature tends to stabilize until it approaches the initial temperature of the drying air.

These rapid changes in air enthalpy in a short time interval may produce instability during the integration process, if the numerical technique used is not capable of handling the stiffness of the system.

To simplify the simulations, several authors assumed that the enthalpy and temperature derivatives with respect to time are negligible (Brooker et al., 1978), but as shown in this work, this is not the case, particularly in the first minutes into the drying process. Throughout the operation, upper layers maintain a lower temperature, which as illustrated in this work, cause saturation of the drying air with the subsequent water condensation over the product surface.

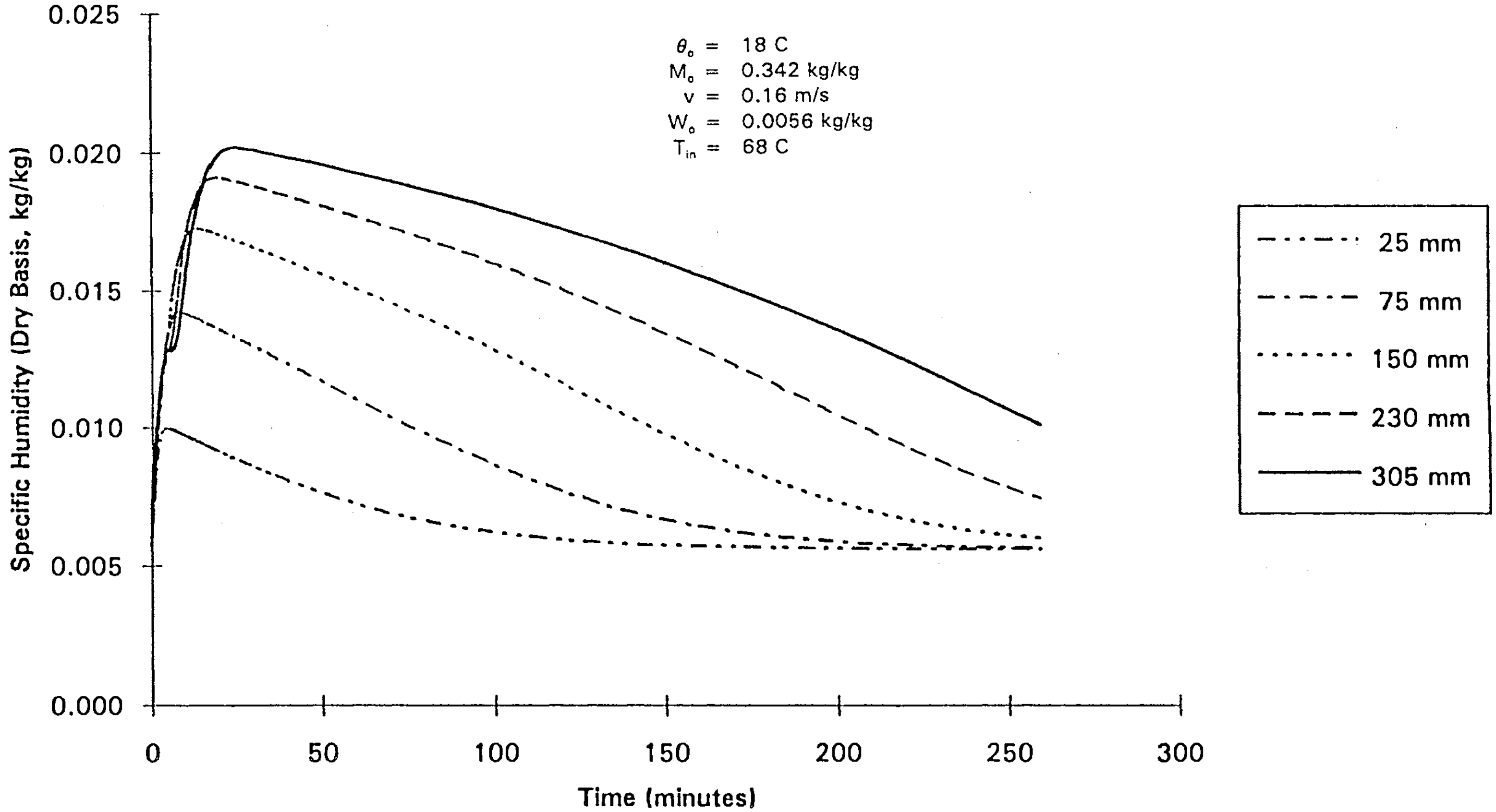

Figure 13. Specific Humidity Profile in Barley Drying

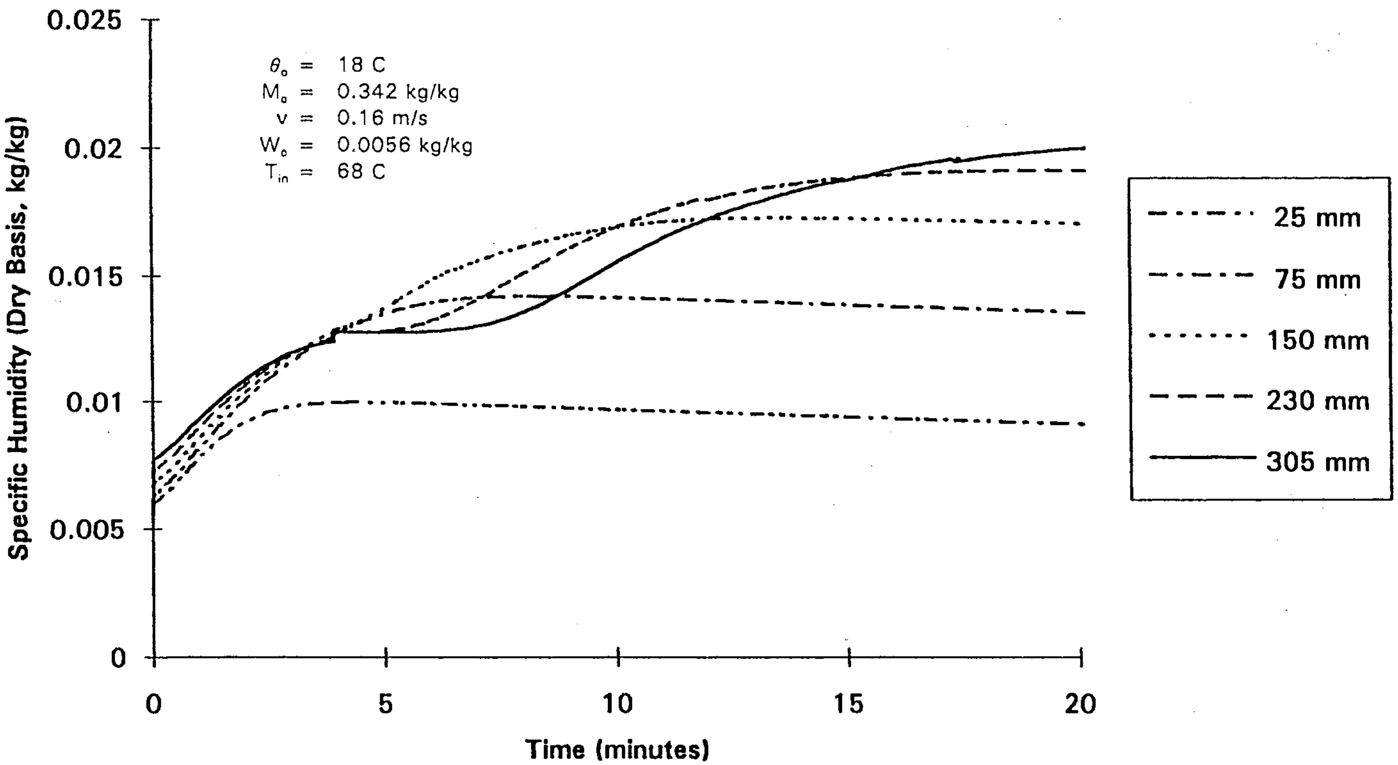

Figure 14. Specific Humidity Profile for the Condensation Interval

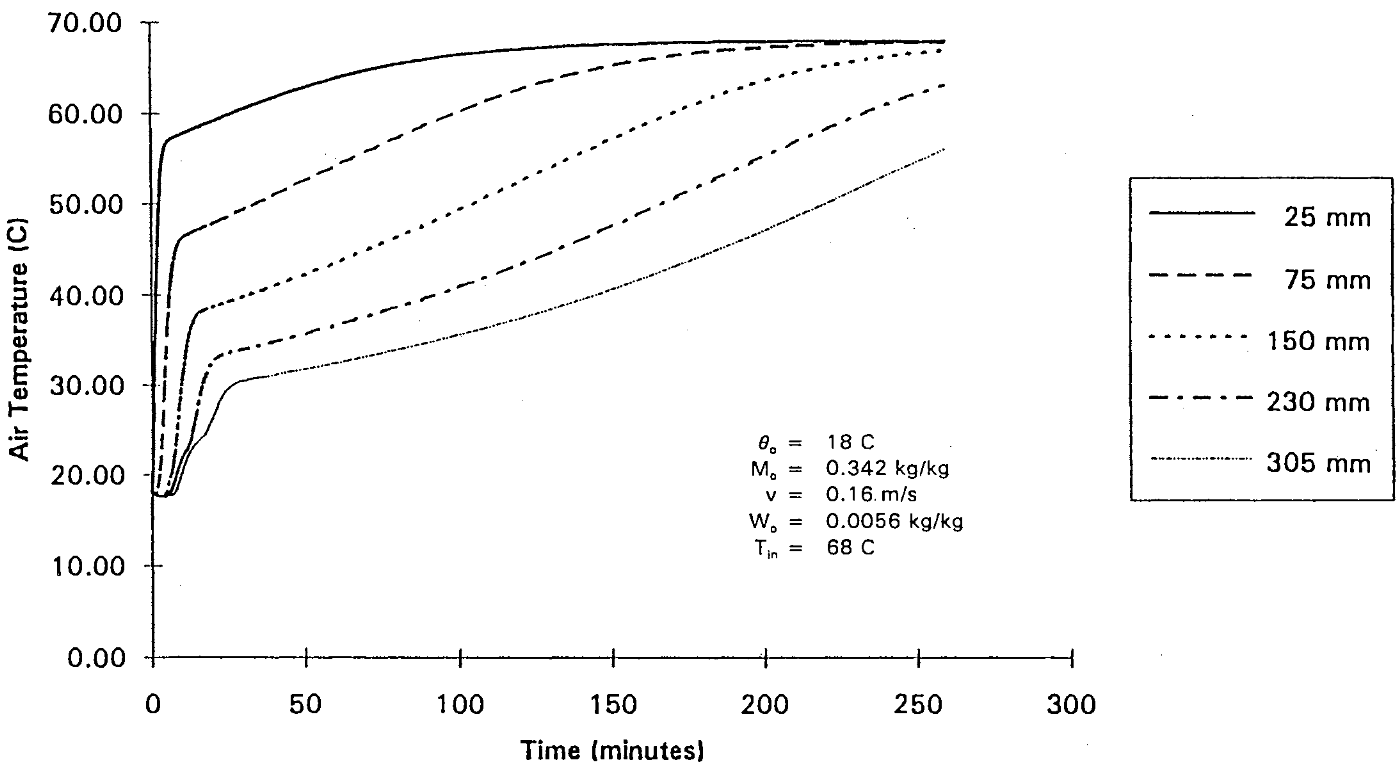

Figure 15. Air Temperature Profile in Barley Drying

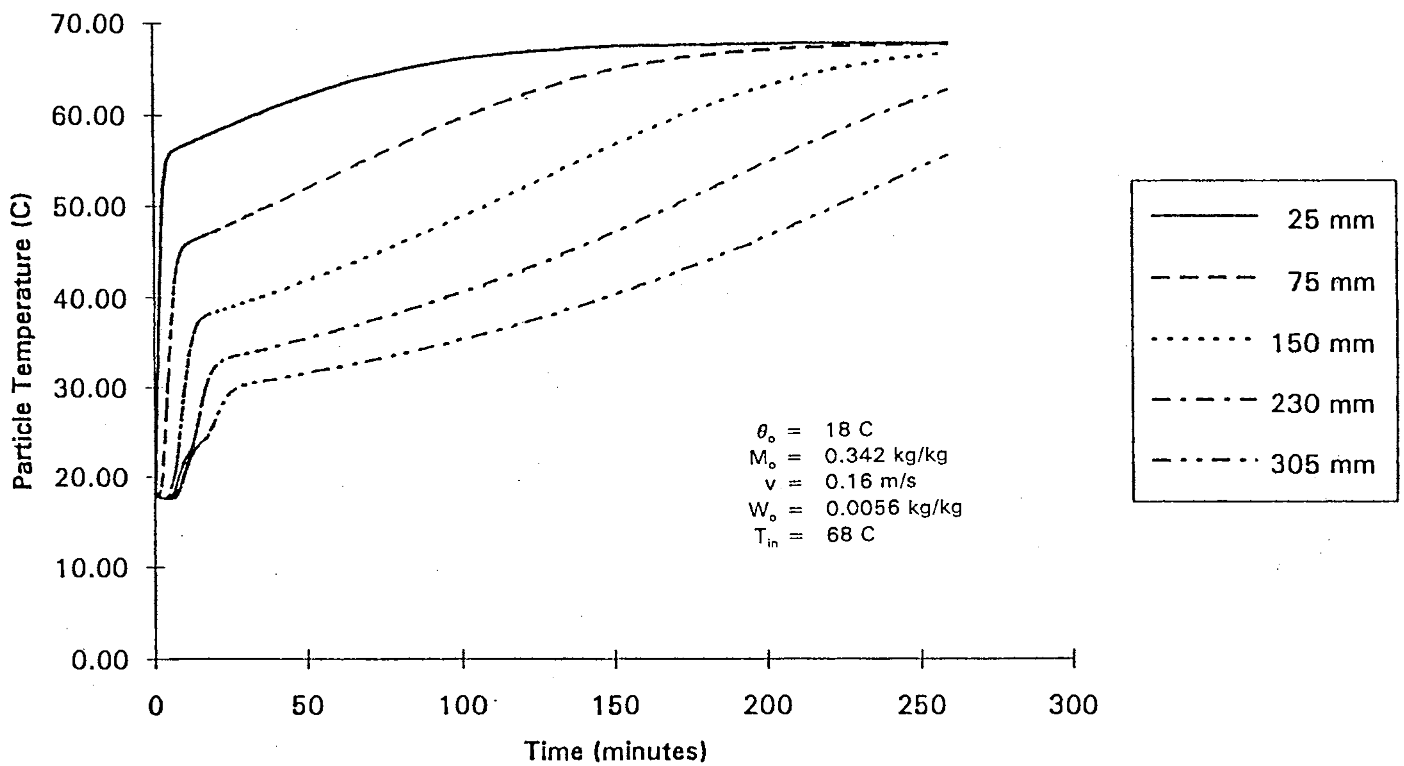

Figure 16. Profile of Barley Temperature

The temperature profile of the deep bed (Figure 16) mirrors the air temperature profile. It is noticeable that during the first five minutes, the solid temperature decreases, suggesting that the energy required for water evaporation in the upper layers, is taken from the product, causing the temperature decrease.

The profile of moisture content of barley is presented in Figure 17. It is evident that the curve of moisture evolution for each layer in the dryer exhibits a maximum slope at a different point in time, indicating the position of a drying front. Once a layer achieves the maximum slope, its moisture content decreases continually, approaching the value of the equilibrium moisture content, if the process were allowed to continue for an extended period of time.

The upper three layers show an increase in moisture content during the first twenty minutes of drying. The moisture profiles for this time interval are shown in Figure 18, and it is possible to identify the time when an increase in moisture, caused by condensation, occurred for each of the upper layers of the deep bed.

From the history files of this simulation, it was obtained that the maximum value of moisture content on the surface of the bed was 0.345 $kg\text{-}kg^{-1}$, and was achieved after 17.8 minutes in the drying process.

The history of relative humidity changes for this drying example is presented in Figure 19. This property increases rapidly during the first minutes of drying, and reaches the saturation point as the air crosses the upper layers. The relative humidity profile for the first fifty minutes is shown in Figure 20.

As drying time progresses, air becomes less saturated, condensation stops and drying in the upper layers is resumed.

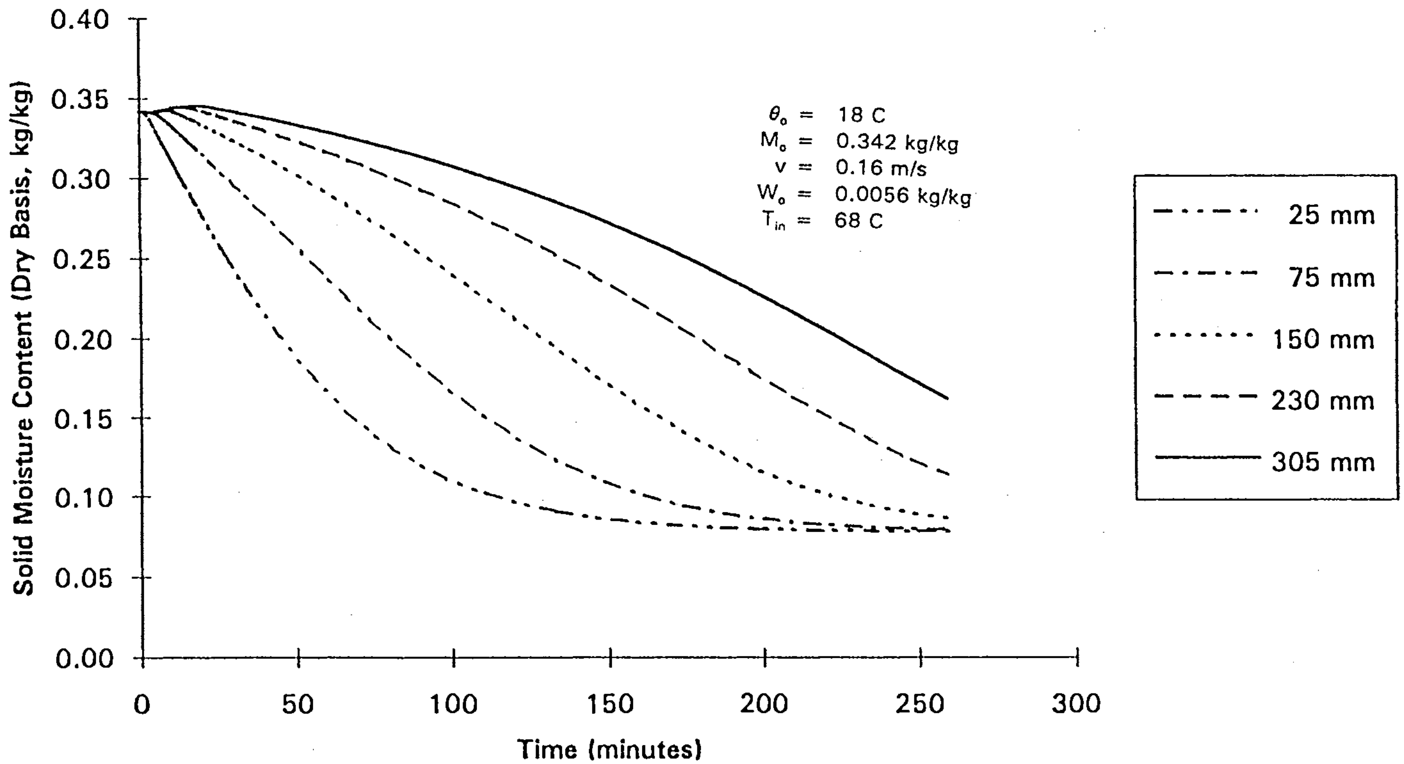

Figure 17. Profile of Moisture Content of Barley

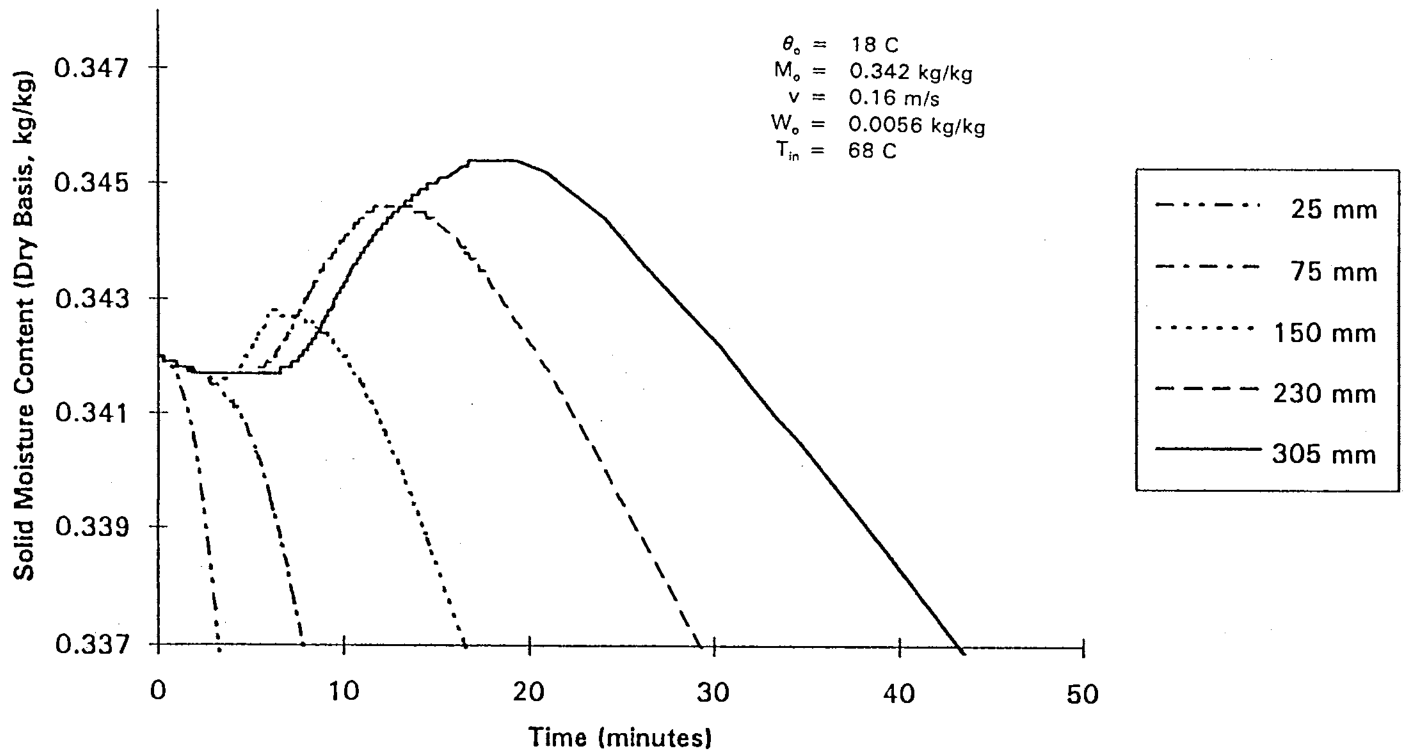

Figure 18. Increase in Moisture Content During Condensation

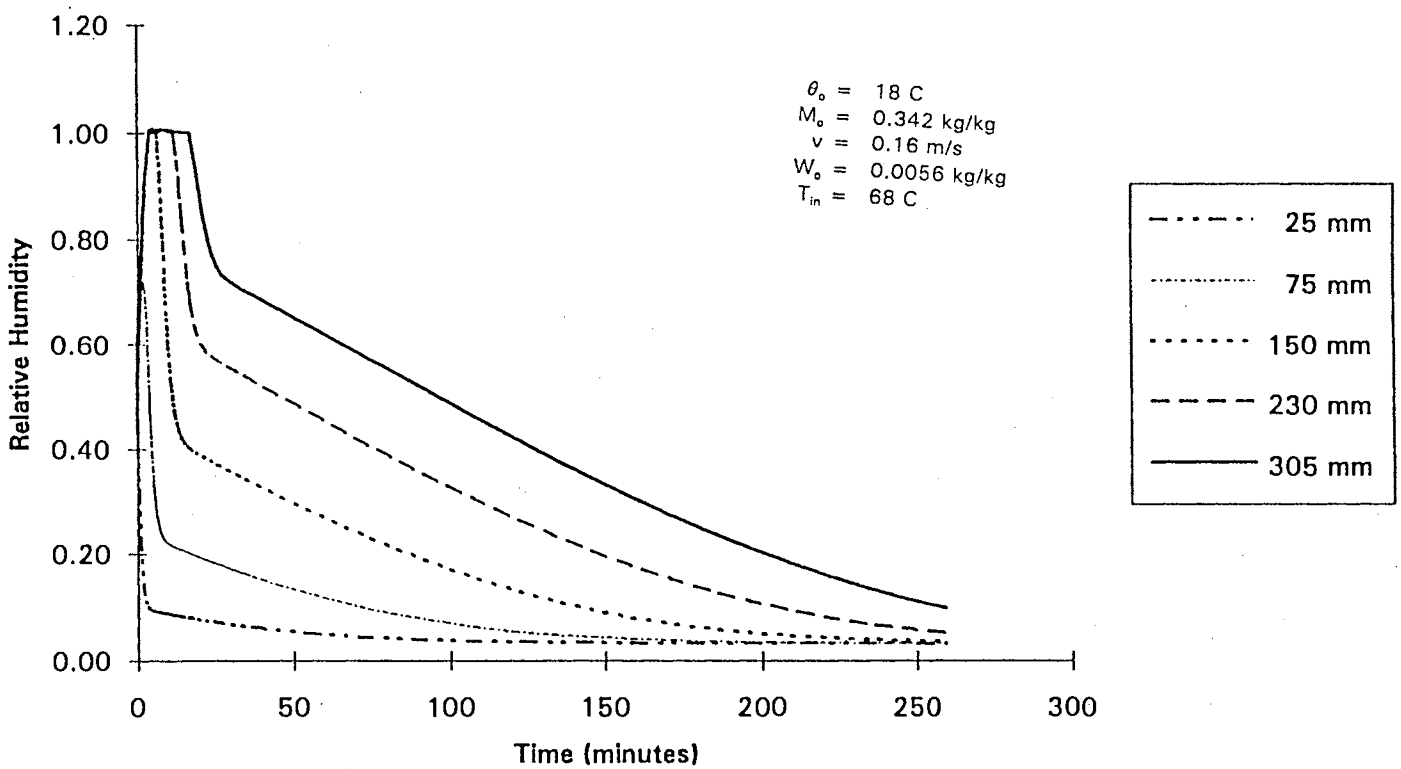

Figure 19. Air Relative Humidity Across the Deep Bed

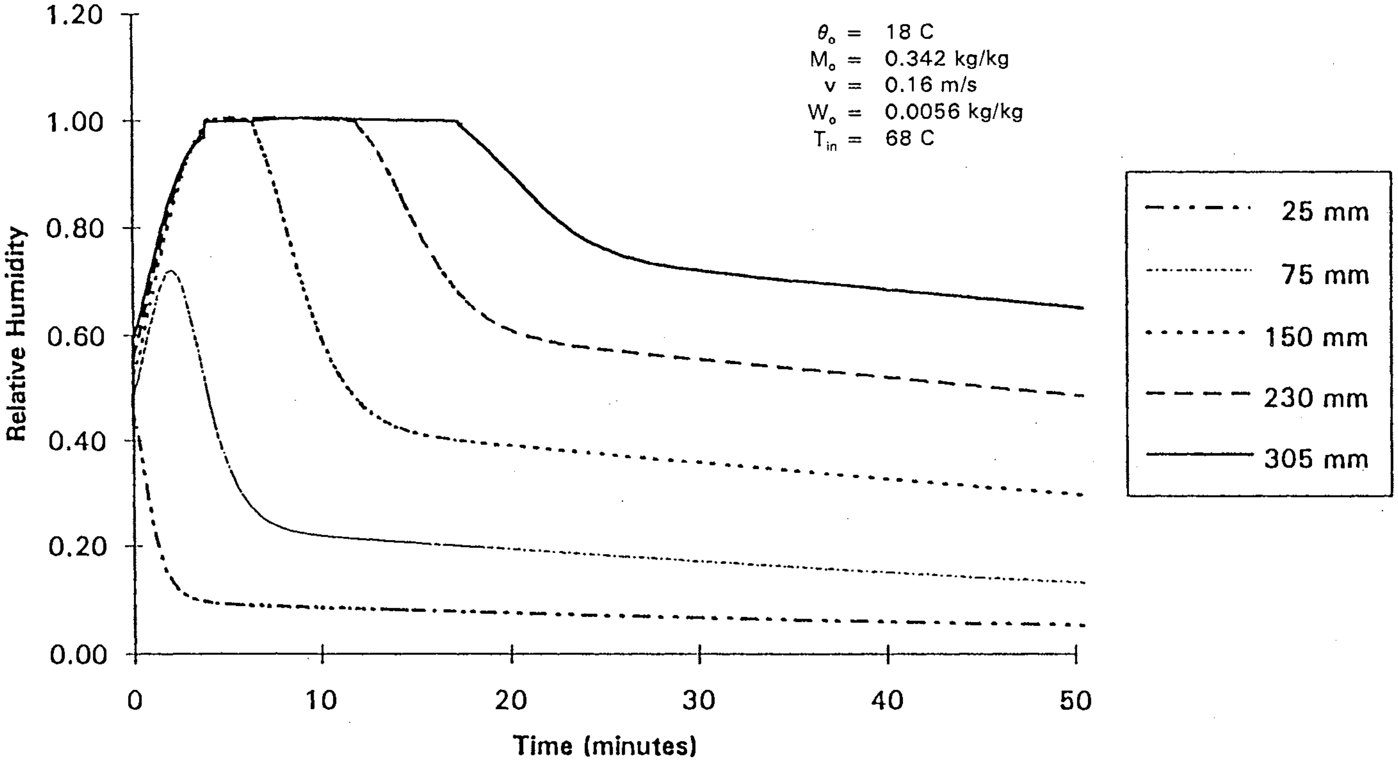

Figure 20. Relative Humidity Changes in the Condensation Interval

As explained for the air humidity curve (Figure 14), there is also a discontinuity in the relative humidity figure at the point where the calculation of dM/dt is changed from dehydration to condensation (approximately 4 minutes into the drying process).

Effect of Number of Nodes

The accuracy of predictions of drying models has been related to the number of intervals Δz used in the integration. The assumption is that the higher the number of nodes or intervals, the closer the system would be to a series of single layers, and the use of the drying equation to represent moisture changes in each thin layer is then valid (Costa and Figueiredo, 1990).

To test the effect of number of nodes on the accuracy of the results, the drying of a deep bed of 10 cm was simulated. Physical properties and air flow conditions for this run are summarized in Appendix E.

Profiles of the bottom (1) and a middle layer (3) are presented in Figures 21 to 25. It can be noticed that for this bed depth, the effect is only significant on the specific humidity of air (Figure 21). Results are practically the same for number of nodes of twenty or higher.

The computation time using an Alpha-based Digital computer (DEC, Hudson, MA) varied from 0.49 seconds for five nodes (Δz=0.02 m), to 18.87 seconds for the integration done with sixty nodes ($\Delta z = 1.7 \times 10^{-3}$ m).

The results shown in the previous section were generated using twenty nodes for each 10 cm of bed height.

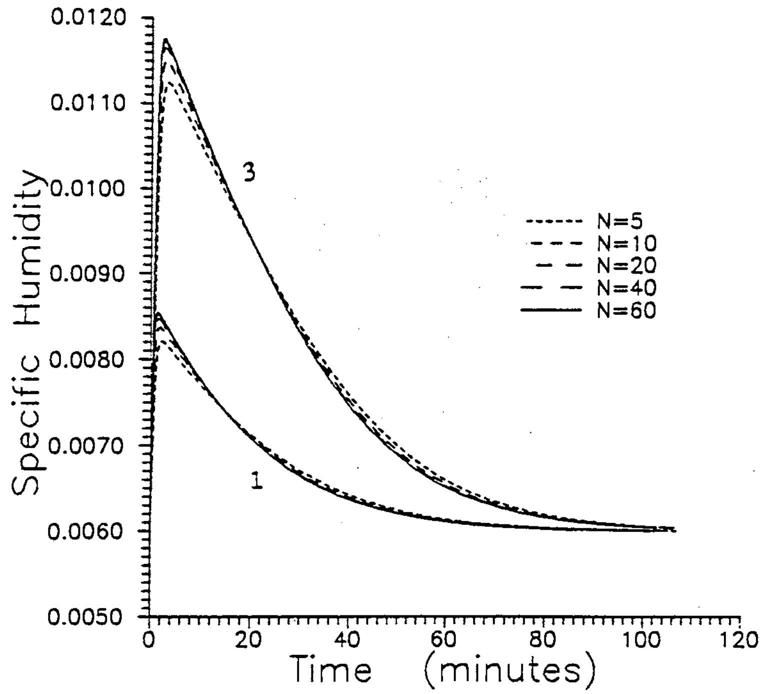

Figure 21. Effect of Number of Nodes on Specific Humidity

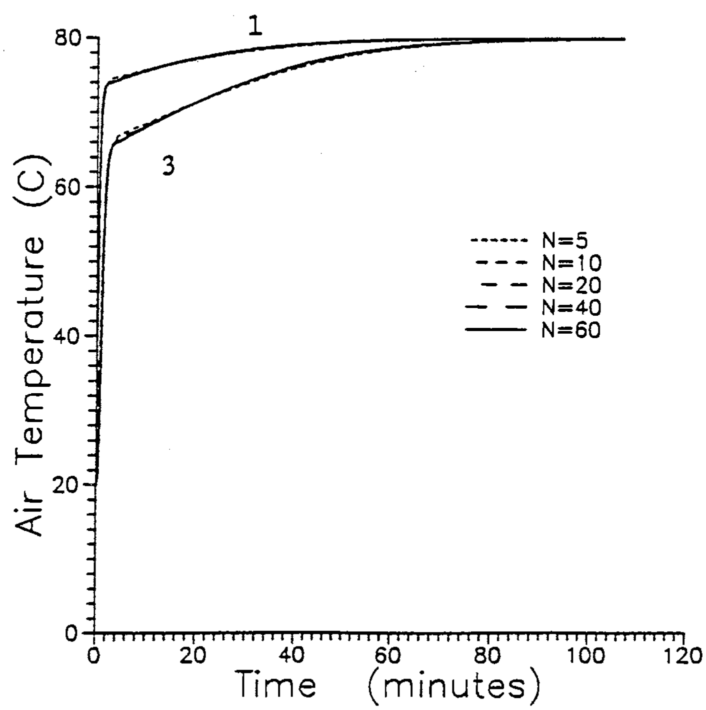

Figure 22. Effect of Number of Nodes on Air Temperature

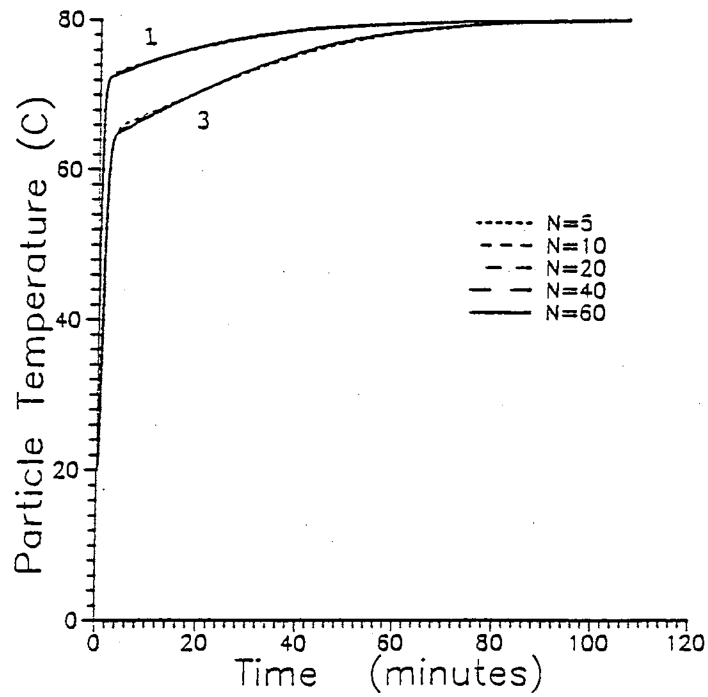

Figure 23. Effect of Number of Nodes on the Temperature of the Solid

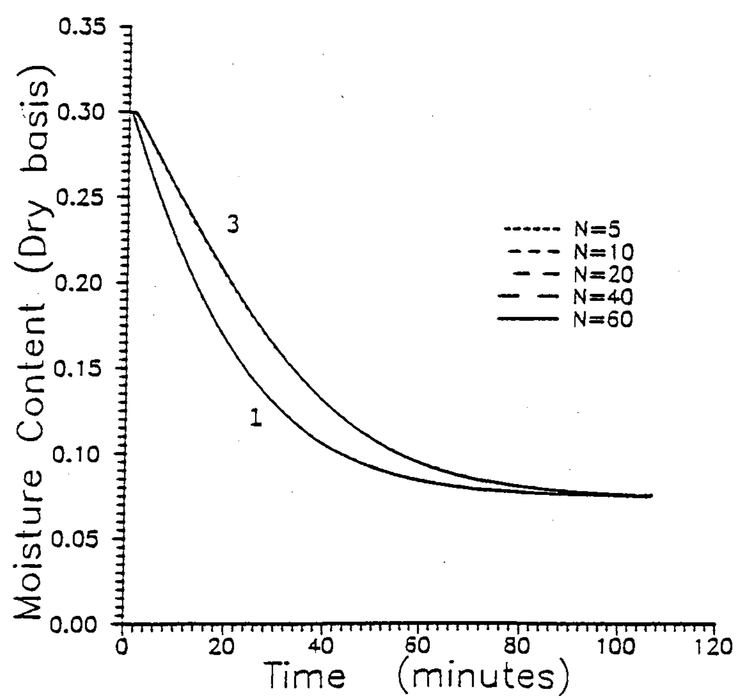

Figure 24. Effect of Number of Nodes on Moisture Content

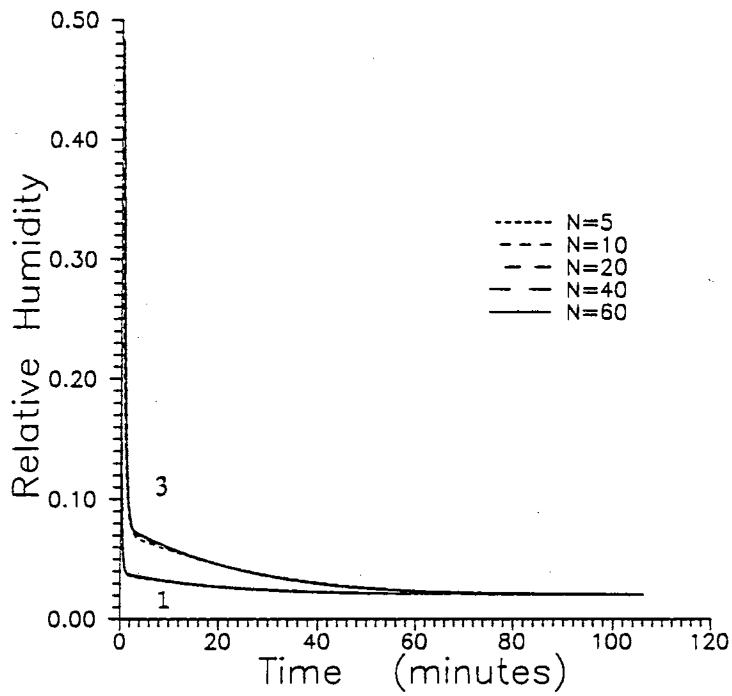

Figure 25. Effect of Number of Nodes on Relative Humidity

Comparison Between Present Model and Literature Data for Barley Drying

Figures 26 and 27 show the comparison between values of particle temperature obtained in the present work and the results of O'Callaghan (1971) and Costa and Figueiredo (1993). Operation conditions in the dryer are those shown in Tables XIX and XX (Appendix E).

Barley temperatures, as predicted by the present model, are higher than the results of O'Callaghan et al. for the upper layers of the dryer, but are very similar for the lower layers. There is better agreement with the results of Costa and Figueiredo, for all deep-bed positions and all times.

The present results were also compared with the experimental data of Boyce (1965) and are shown in Figure 28.

Values of predicted bed temperature are higher than the experimental results, particularly for the upper layers and at the end of the run. Similar behavior was found when the simulations of O'Callaghan et al. (1971) and Costa and Figueiredo (1993) were compared with the experimental data of barley drying , as reported by Boyce in his original article (1965). This comparison is presented in Figures 29 and 30.

In their article, Costa and Figueiredo (1993) compared their results of particle temperature with the simulation of results of O'Callaghan et al., and indicate that the comparison is "between the present numerical results and the experimental results of Boyce", and that "we can note a good agreement between them". However, examination of the original data of Boyce shows that the simulation of Costa and

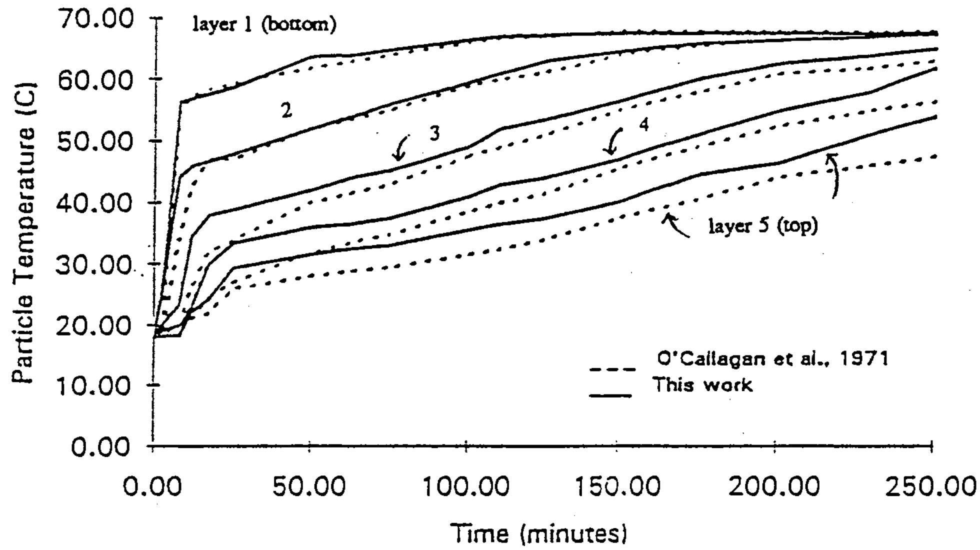

Figure 26. Comparison Between Present Work and the Simulation of O'Callaghan

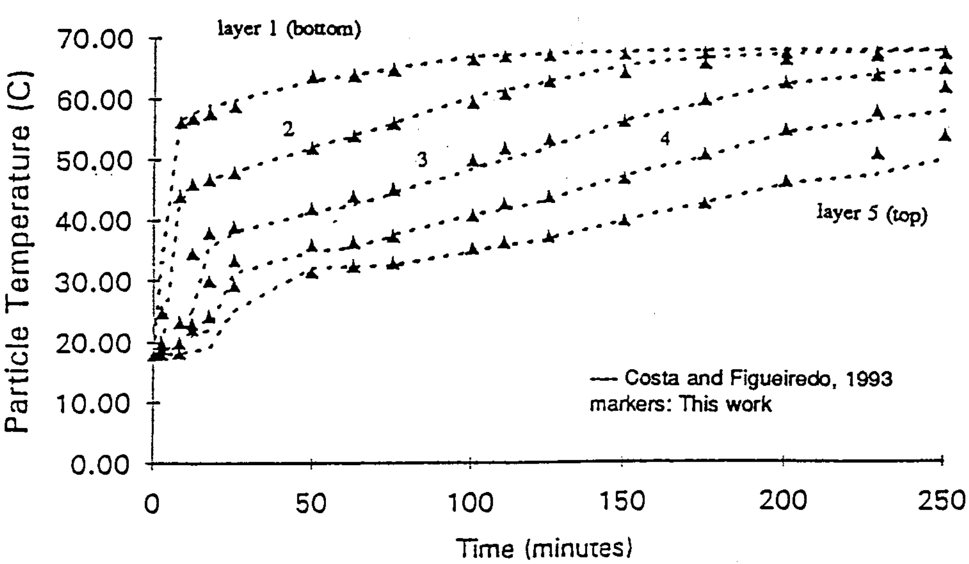

Figure 27. Comparison Between Present Work and the Simulation of Costa and Figueiredo

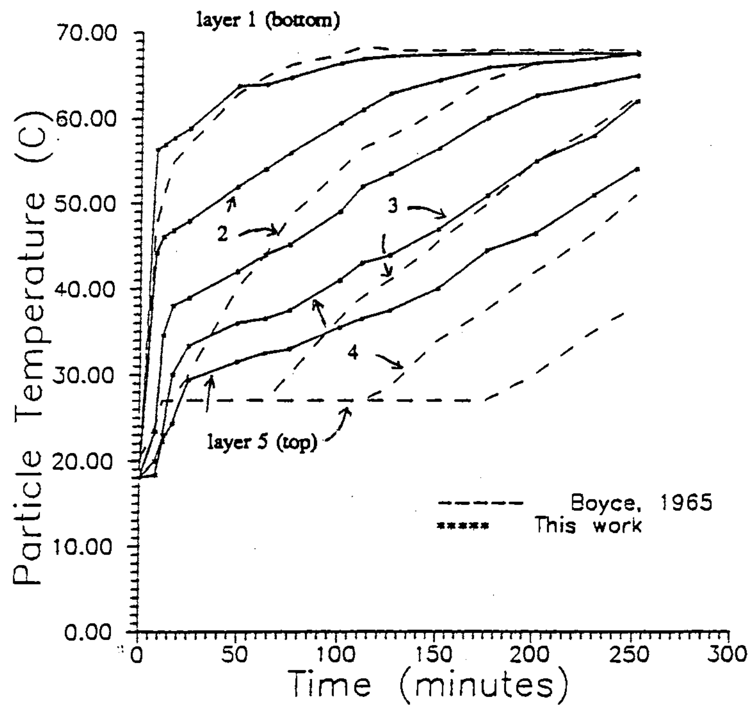

Figure 28. Comparison Between Predicted Results and the Experimental Data of Boyce

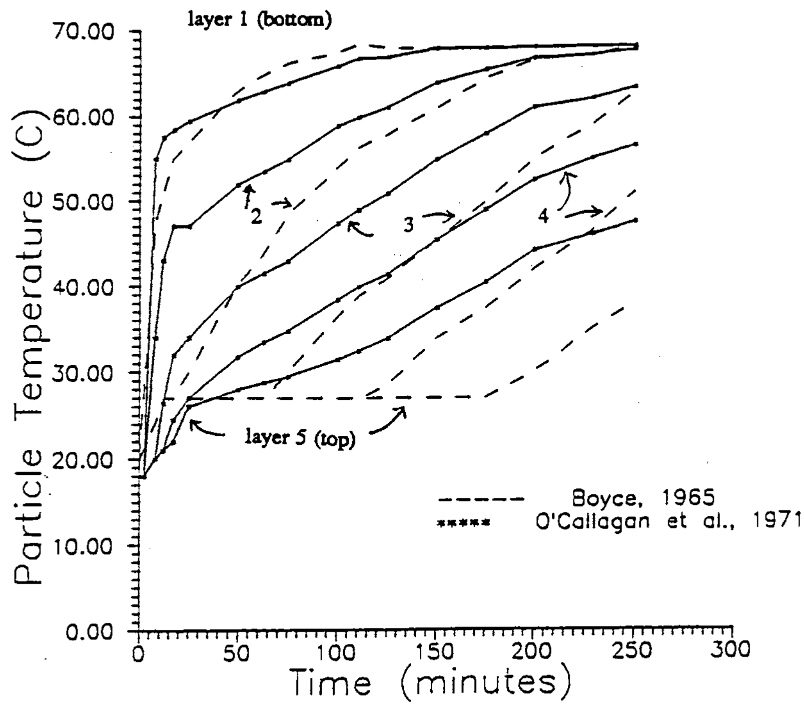

Figure 29. Comparison Between Experimental Data of Boyce and the Predicted Results of O'Callaghan

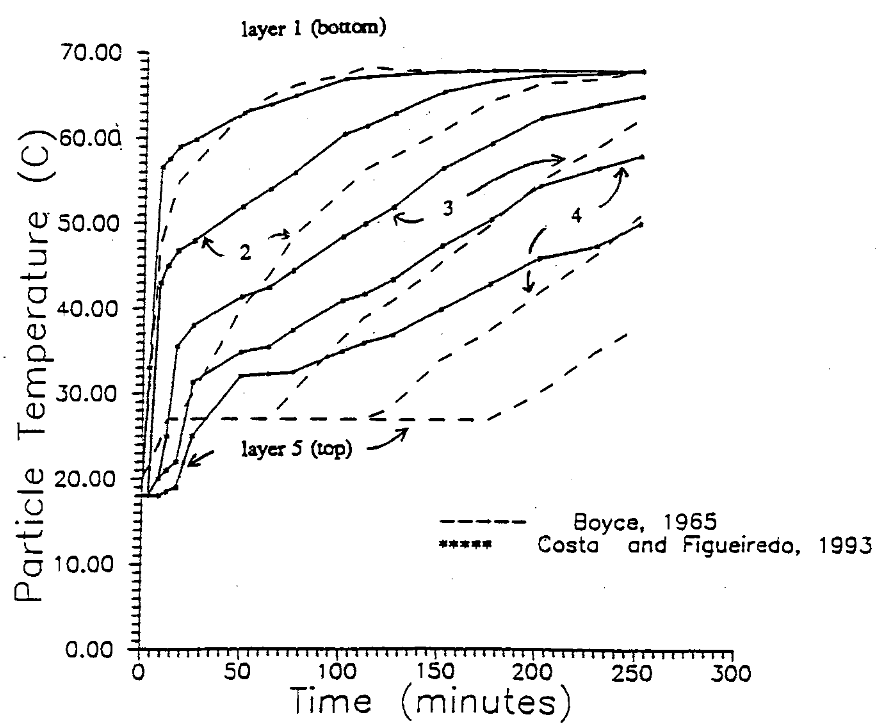

Figure 30. Comparison Between Experimental Data of Boyce and the Predicted Results of Costa and Figueiredo

Figueiredo predicts higher temperatures for the upper layers of the dryer, similar to the deviations found in this study. Apparently, Costa and Figueiredo (1993) misinterpreted the simulation results of O'Callaghan (1971) as the experimental data of Boyce (1965).

Differences of 10% between predicted and experimental values are typical of these type of models (Brooker, 1980), as occur for the lower layers of the dryer. However, simulated temperatures for the lower layers are 25% higher.

An examination of the model equations suggests that the slopes of the particle temperature plots depend on the value of the coefficients, which include physical properties of air and the drying solid.

The estimation of heat transfer coefficients, void fraction, specific area, drying rate parameters and equilibrium moisture content involve a high degree of uncertainty, and results depend on the method or correlation used for their estimation.

To illustrate the effect of adjusting the coefficients in the drying model equations, a simulation run was performed where the parameteres were modified within their range of uncertainty (25%).

Figure 31 shows that the model predicts the drying behavior with good accuracy, depending on the values of the parameter estimates used in the simulation (within their normal range of variation).

Costa and Figueiredo (1993) used a value of ϵ of 0.375, however if this parameter is calculated using the value of diameter they report, the result is 0.476. Changing ϵ alone results in a variation of 27% which would reduce the value of the coefficients proportionately.

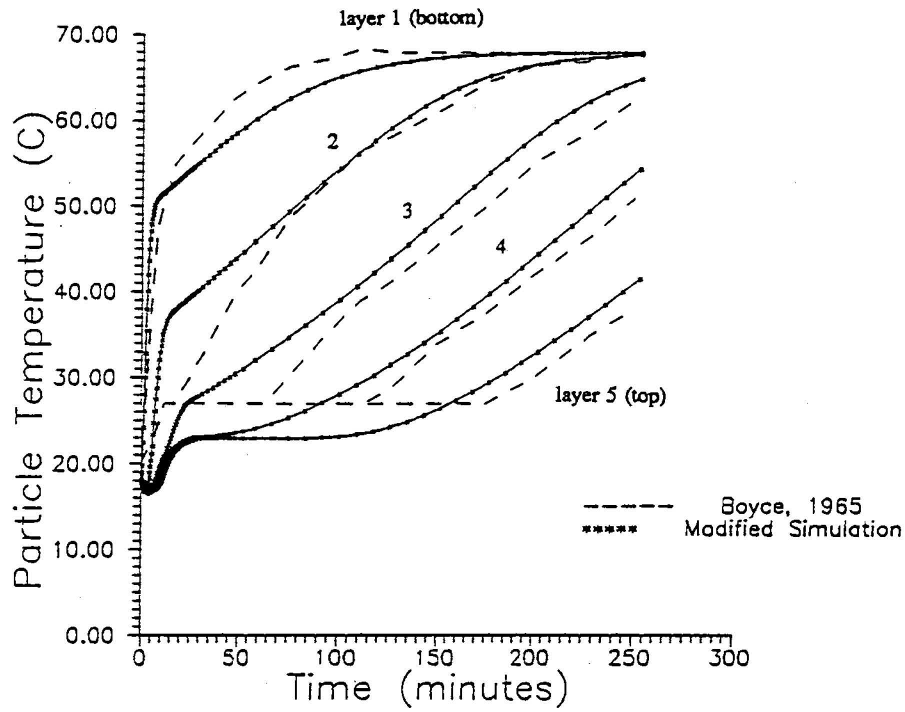

Figure 31. Comparison Between Experimental Data of Boyce and Results of the Modified Simulation

Values of the heat transfer coefficients may vary within a wide interval, depending on the parameters of the correlations, even if the same air flow rates and temperatures are considered in the evaluation (Steinberger and Treybal, 1960; Ranz and Marshall, 1952).

Probably, the most significant differences may be caused by the estimation of the drying parameter, k (Stone, 1982). O'Callaghan et al. (1971) examined the differences between their model and the experimental data of Boyce, and also attribute the variations to the value of k, which is calculated using equation (5) (Chapter VI). Reported estimates for a_0, the pre-exponential factor in equation (5) are 550,000 s^{-1} (O'Callaghan et al., 1971), and 348,500 s^{-1} (Costa and Figueiredo, 1993).

One common approach used to modify models and obtain more accurate results, is to adjust the coefficients in the model equations. This is valid for descriptive models, those that would be used to characterize the drying behavior of a specific product. However, their applicability is limited to the operation conditions at which the experimental data used for the validation were obtained. Although this is a valid practice, it limits the predictive power of the models. There is no assurance that the model will be accurate if the product or the air flow conditions are changed.

Predictive models include unadjusted coefficients, as obtained in the equations derived from first principles, and the accuracy of their performance depends entirely on the quality of the parameter estimates, and the validity of the assumptions made when the model was developed.

The unadjusted model was used for the simulation of surface-moisture removal and dehydration of blueberries. The results are discussed in the next section.

Simulation of Evaporation of Surface Moisture and Blueberry Drying

A summary of the physical properties, drying parameters and air flow conditions is presented in Tables XII and XIII (Appendix E).

For the purpose of the simulations, the tray-drying process was considered a deep-bed system, assuming that each tray is a single layer of a deep bed. Also, it was assumed that the conditions of air leaving one tray do not change until it reaches the next one.

The first part of this drying process consists of the evaporation of excess moisture from the surface of the blueberries. Variations in moisture content with time were obtained experimentally, and it was considered that all the surface moisture had been removed when the calculated moisture content reached the value of 7.547 $kg\text{-}kg^{-1}$. This is an average transition moisture content and was calculated from the water fraction present in the fresh blueberries.

The possibility of dehydration caused by additional exposure to the drying air was modeled using the drying parameters of Kim (1987).

As shown in Figure 32, air specific humidity changes almost instantaneously when the air enters the dryer. The three lower trays rapidly approach a constant value, while the upper two layers reach the constant value of humidity after ten minutes from the commencement of drying.

Profiles of air and blueberry temperature, and moisture content are shown in Figures 33 to 35. Blueberry temperature uniformly increases with drying time from the initial value of 7 C, except for berries of trays five and six (top).

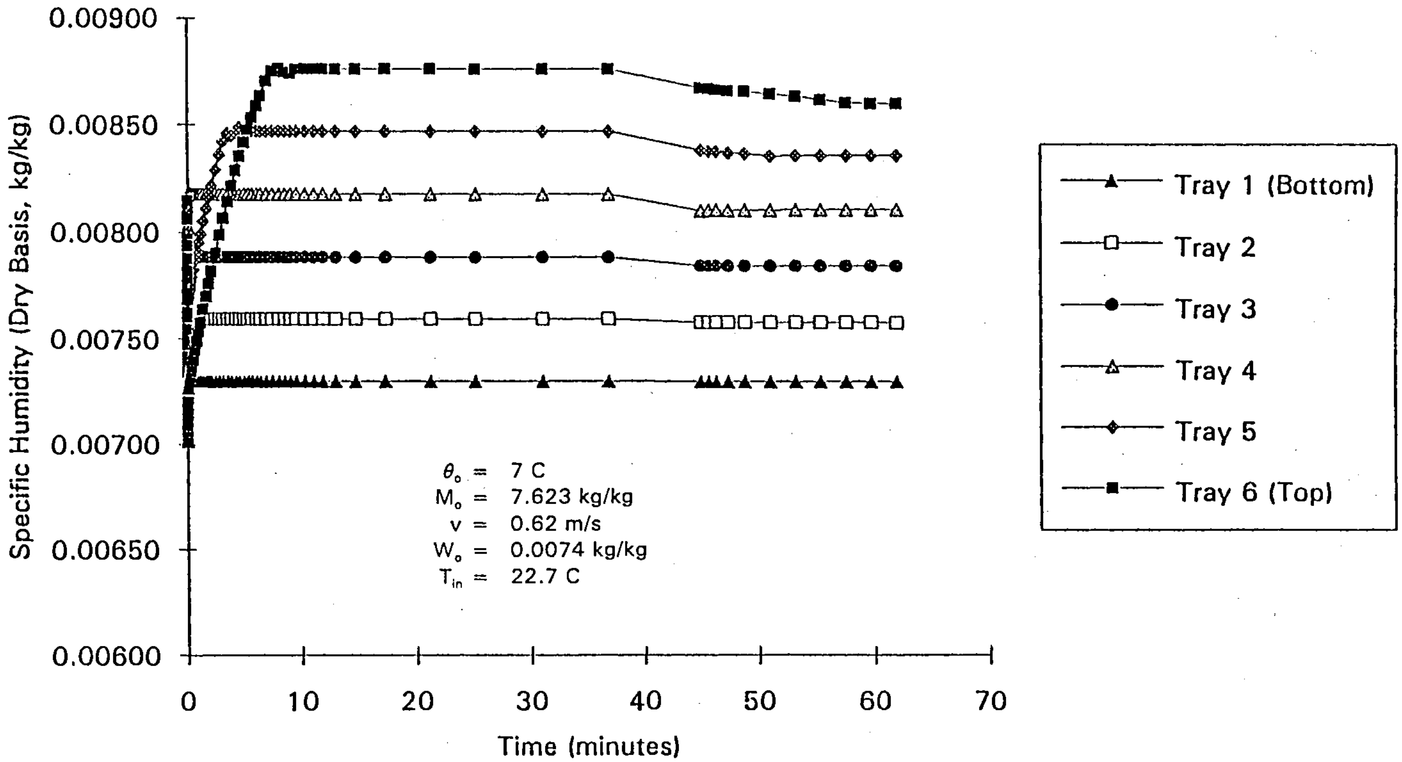

Figure 32. Specific Humidity Profiles During Evaporation of Surface Moisture and Blueberry Drying

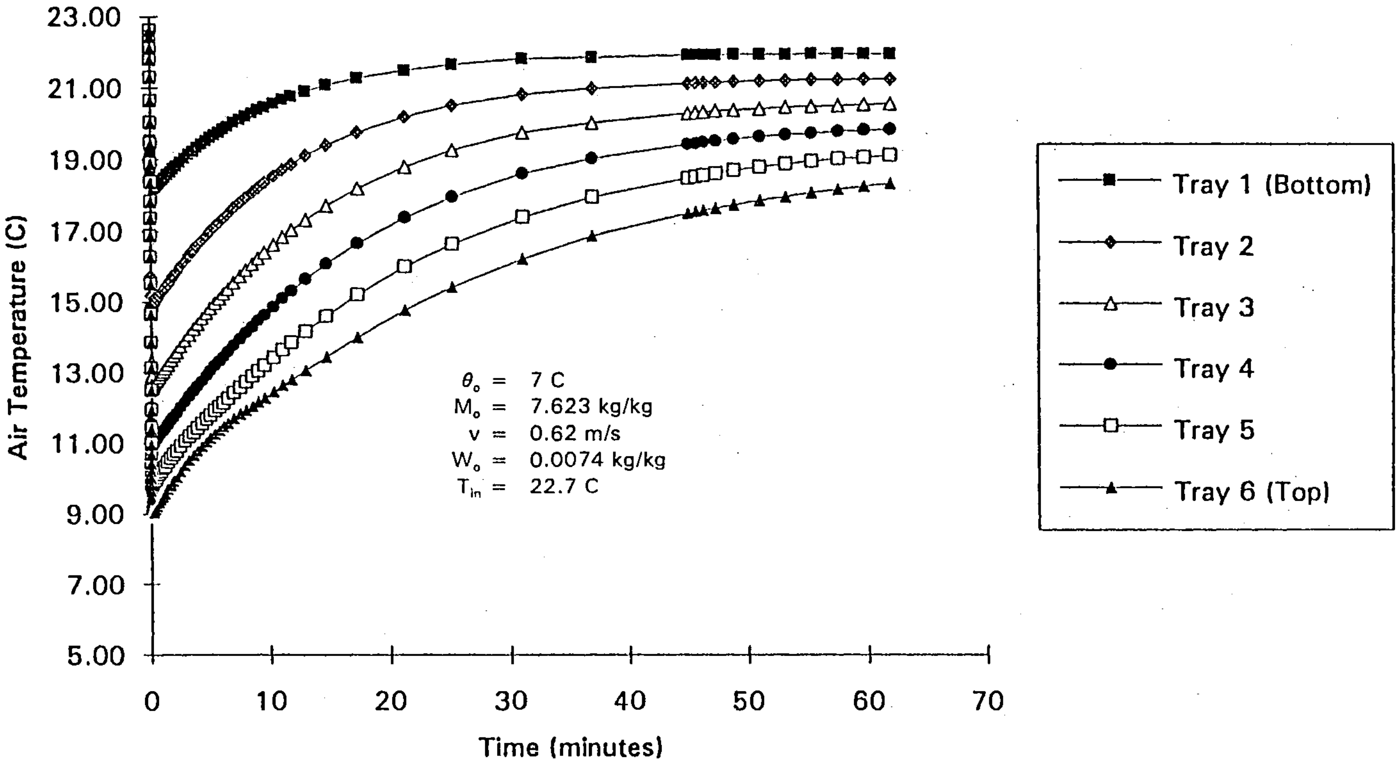

Figure 33. Air Temperature Profiles During Evaporation of Surface Moisture and Blueberry Drying

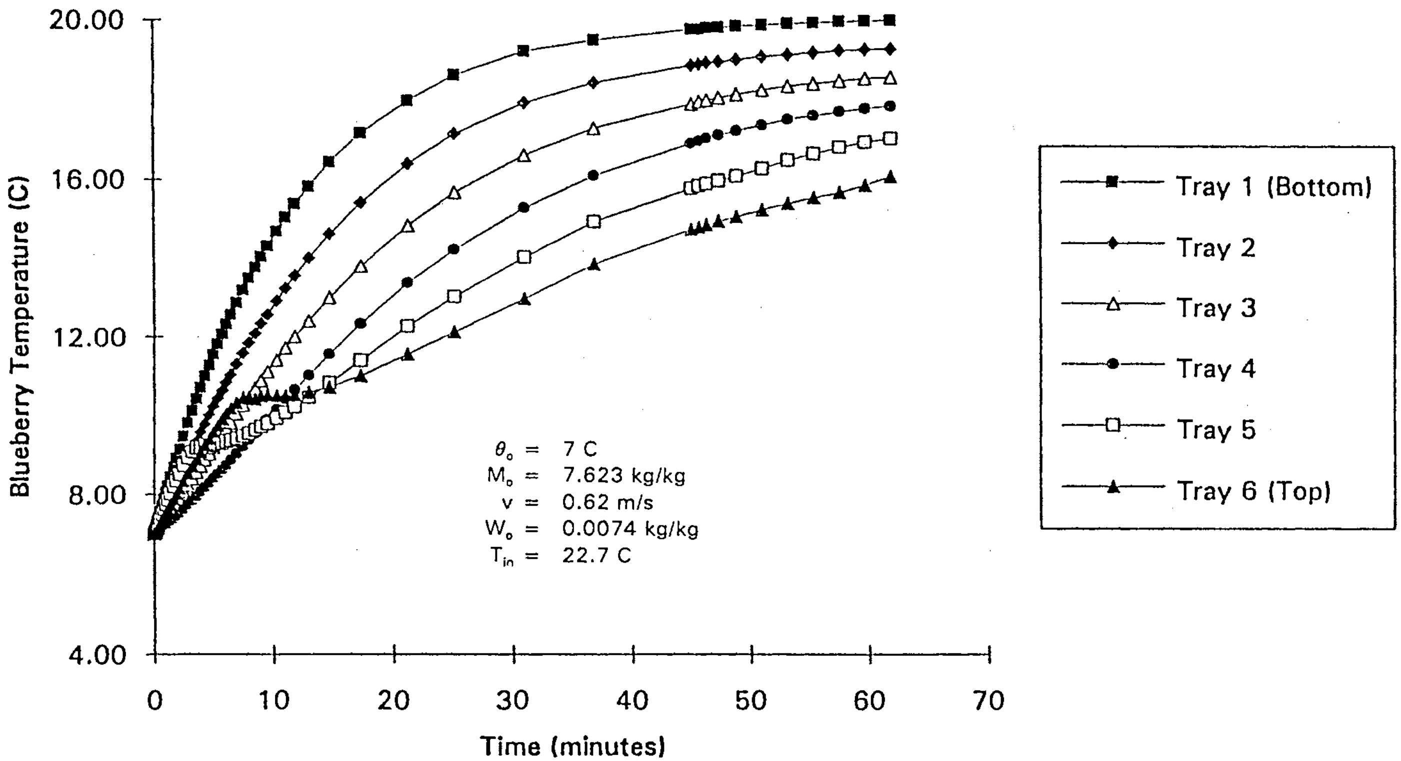

Figure 34. Blueberry Temperature Profiles During Evaporation of Surface Moisture and Drying

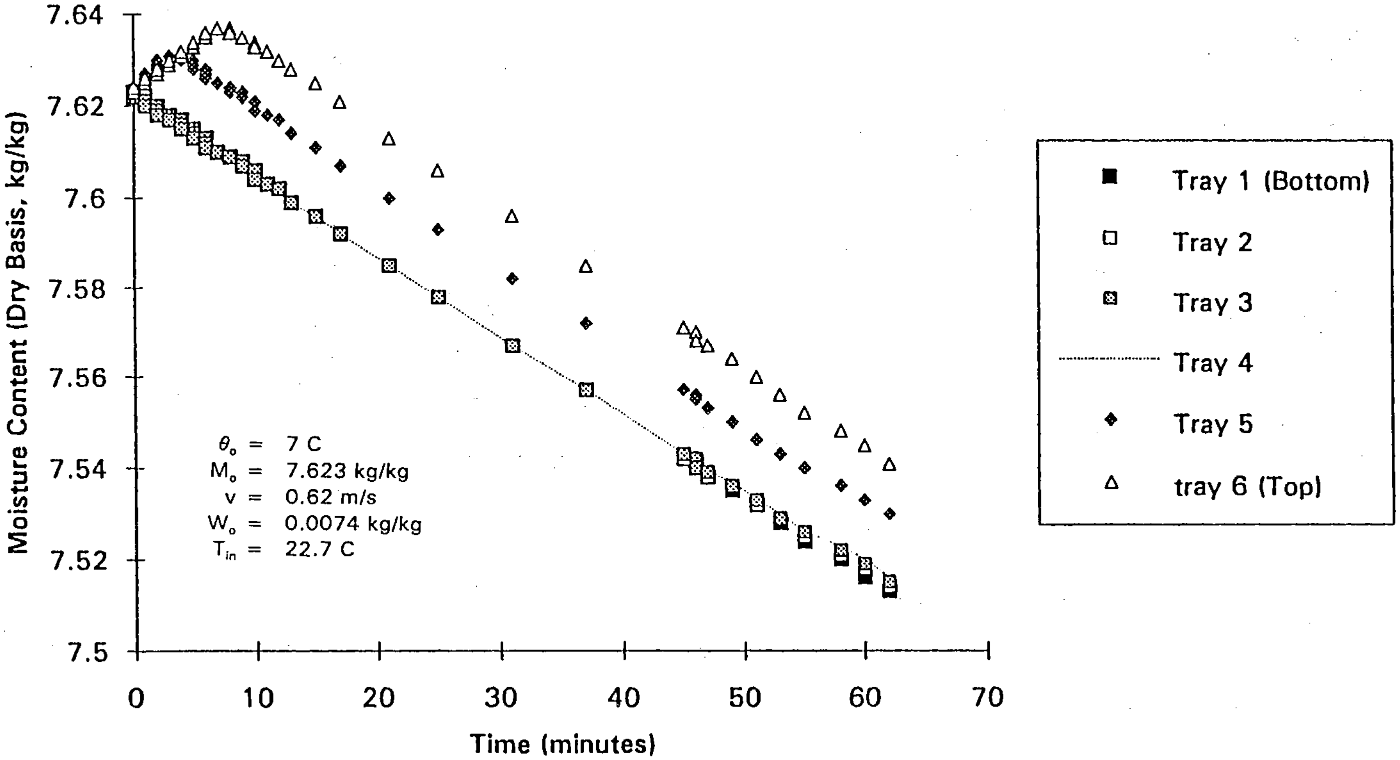

Figure 35. Moisture Content of Blueberries During Evaporation of Surface Moisture and Dehydration

Moisture variations during drying are presented in Figure 35. There is an increase in moisture content of the berries of the upper two layers, during the first ten minutes of drying. Condensation of water occurs in layers 5 and 6 almost from the beginning of the process, as the cool air reaches the upper layers and becomes saturated. The point of maximum condensation occurs after approximately 4 minutes in layer 5, and after nine minutes in layer 6. Once warmer air reaches these trays, it is capable of evaporating water, and the moisture content starts to decrease.

Trays 1 through 4 show constant evaporation rates, but after forty one minutes, when the transition moisture was reached, the variation in water content is slightly different for each tray, suggesting that each layer dries at a different rate.

When the evaporation experiments were run, it was decided to stop evaporation after 30 minutes, when there was no evidence of moisture remaining on the surface. However, results of the simulation suggest that excess water was completely removed after forty one minutes.

Changes in air relative humidity with position and time are illustrated in Figure 36. There is a noticeable increase in all layers from the initial value of 0.4. Air in trays 5 and 6 was saturated during the first 10 minutes of the process, which coincides with the time when condensation occurred, as was illustrated in the plot of moisture content (Figure 35).

Results of this simulation suggest that at the air conditions used in the experiments, condensation in the upper layers of the dryer occurs during the first 10 minutes of drying. Also, the model implementation allows to predict the time necessary to remove all excess moisture from the blueberry surface. Results show

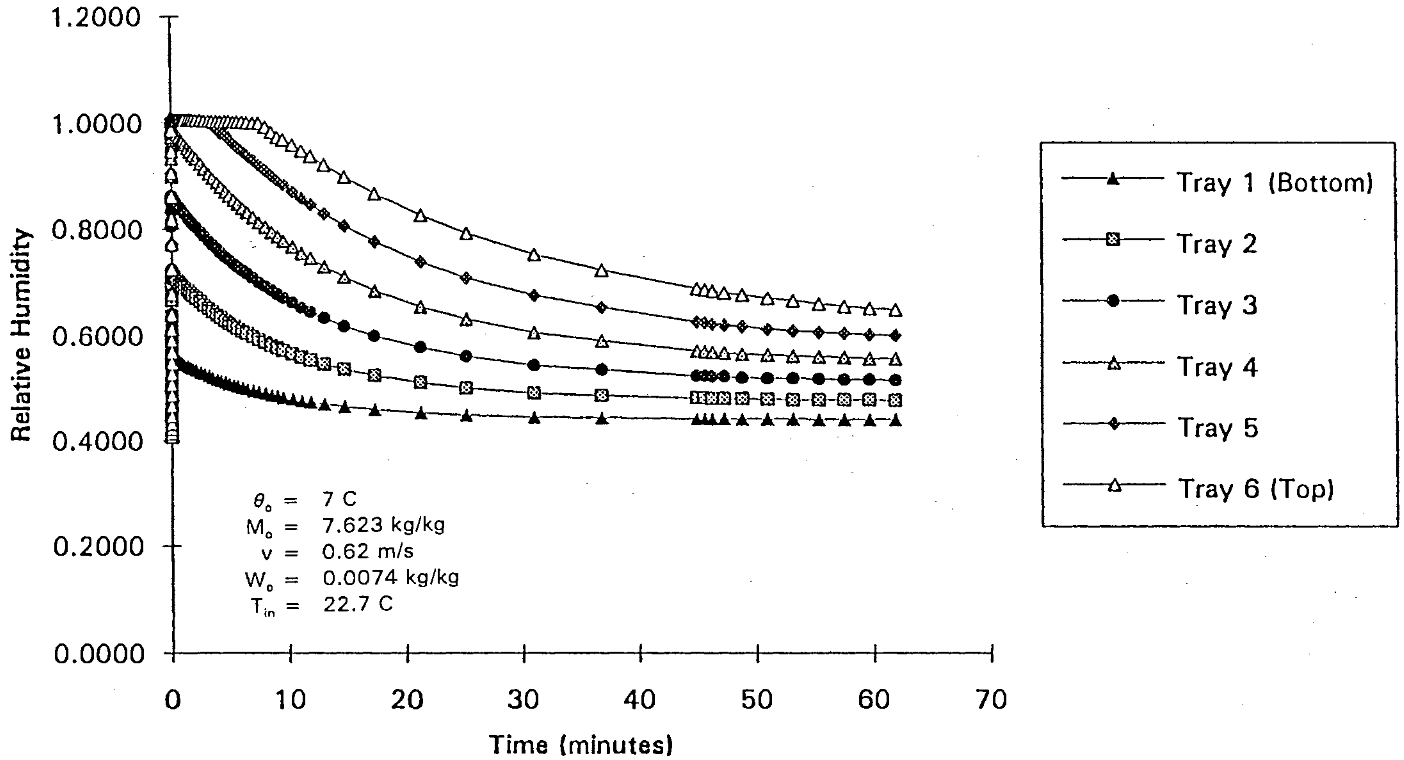

Figure 36. Air Relative Humidity Profiles During Evaporation of Surface Moisture and Blueberry Drying

that berries have to be exposed to the drying air during 41 minutes to ensure complete removal of the surface moisture.

Evaporation with Air at Higher Temperature

To illustrate the process of moisture evaporation and blueberry dehydration at a higher air temperature, another simulation run was made, this time using air at 35 C, and blueberries initially at 20 C and 0.4 relative humidity. Blueberry properties were the same as in the previous example (presented in Table XII, Appendix E).

Results are shown in Figures 37 through 41. Air temperature and specific humidity profiles follow the same pattern as in the previous simulation, however significant changes occur in particle temperature, moisture content and relative humidity. As shown in Figure 39, particle temperature increased uniformly from the commencement of drying, and there was a difference of approximately one degree from tray to tray. Temperature difference decreased as the drying time progressed.

The variation in moisture content of the blueberries is presented in Figure 40. Water content was the same for each tray during the evaporation period, but changes for each tray after approximately 45 minutes into the drying process. This time, all the surface water was evaporated after 38 minutes. From this graph there is no evidence of water condensation as occurred when air at lower temperature was used.

As can be seen in Figure 41, relative humidity never reached a saturation point, although it is noticeable that the upper layers of the dryer nearly approach one in the initial periods of drying.

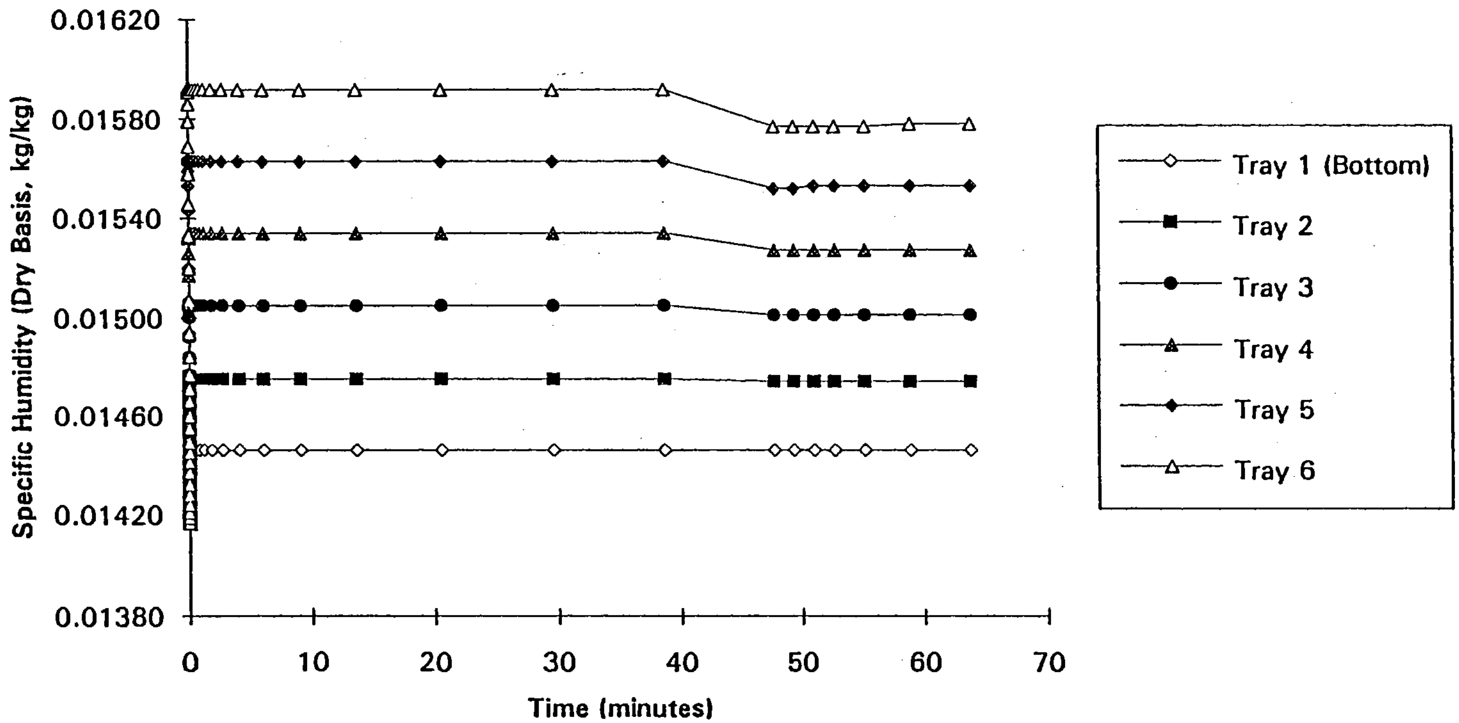

Figure 37. Specific Humidity Profiles in Blueberry Drying Using Air at 35 C

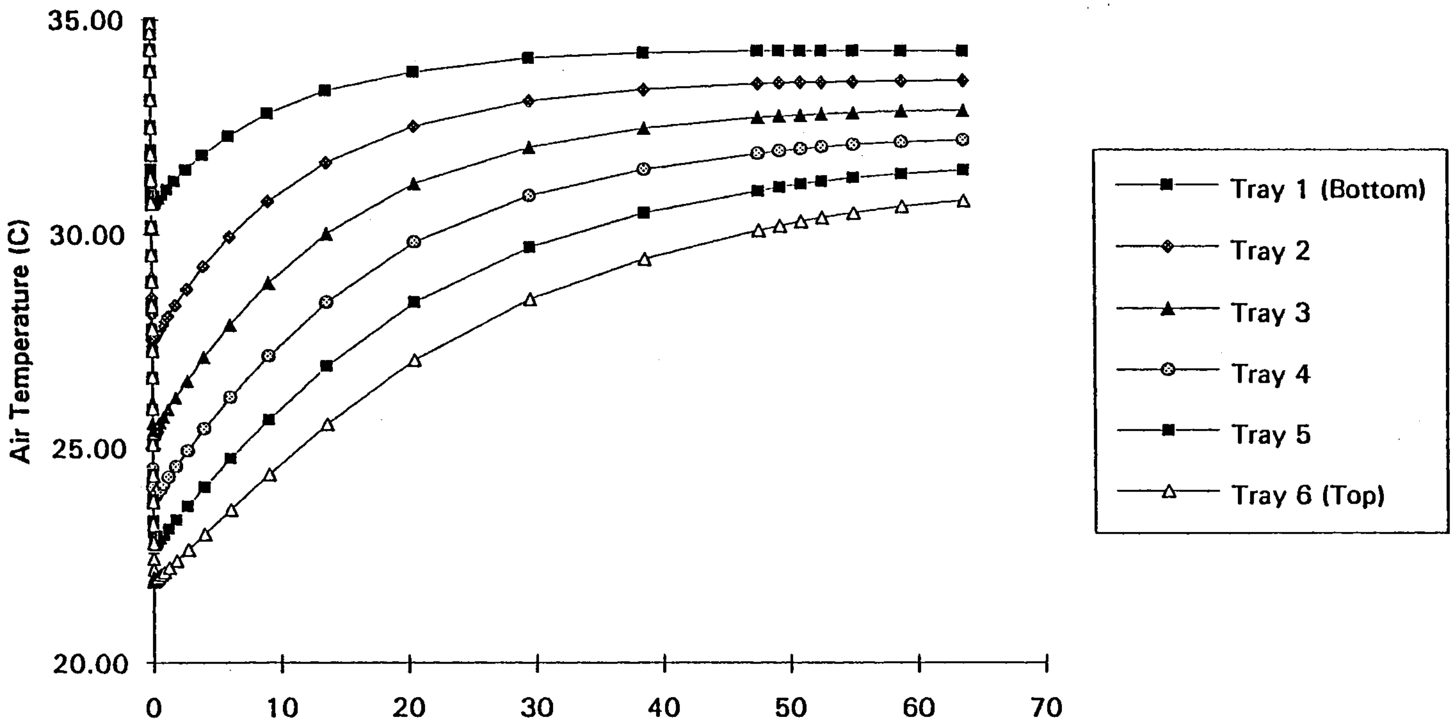

Figure 38. Air Temperature Profiles in Blueberry Drying Using Air at 35 C

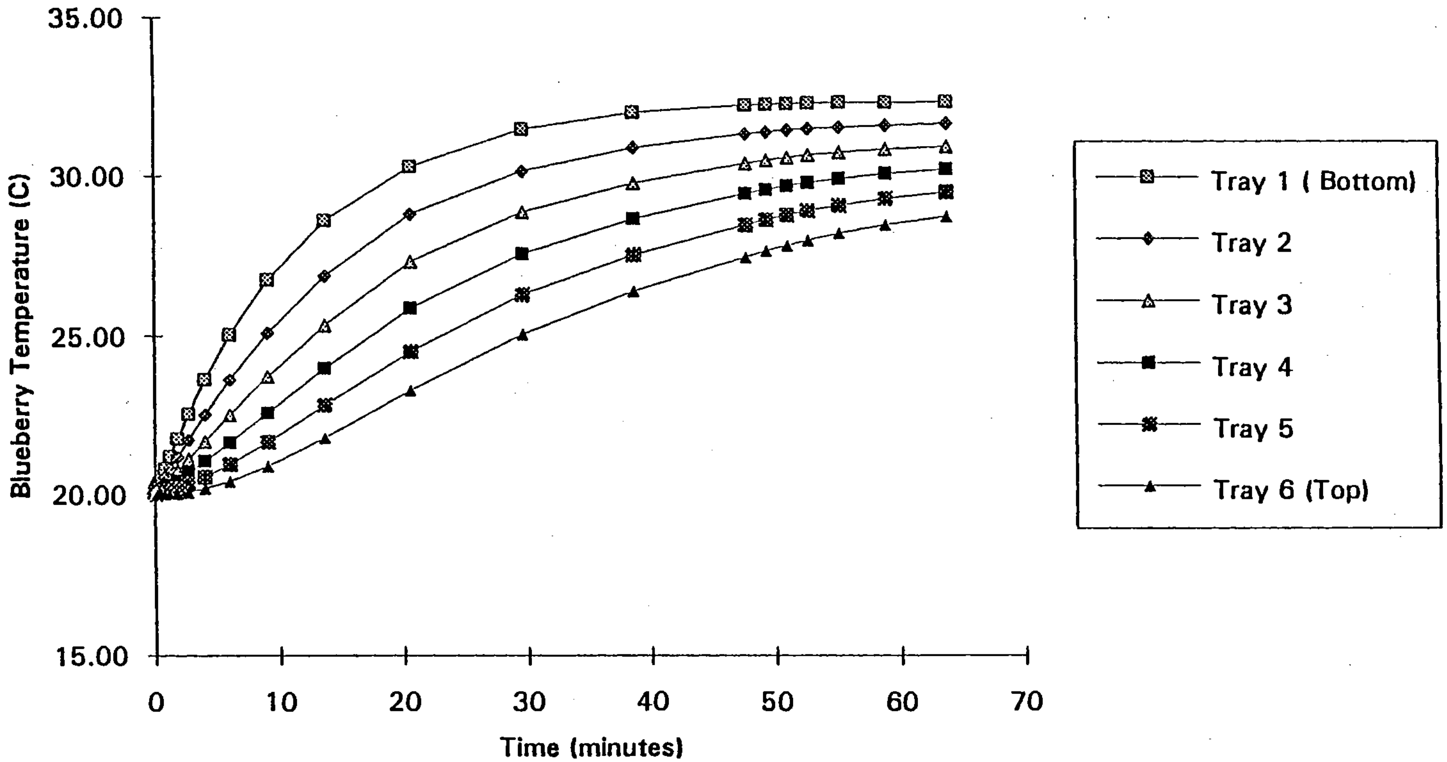

Figure 39. Blueberry Temperature Profile in Tray Drying Using Air at 35 C

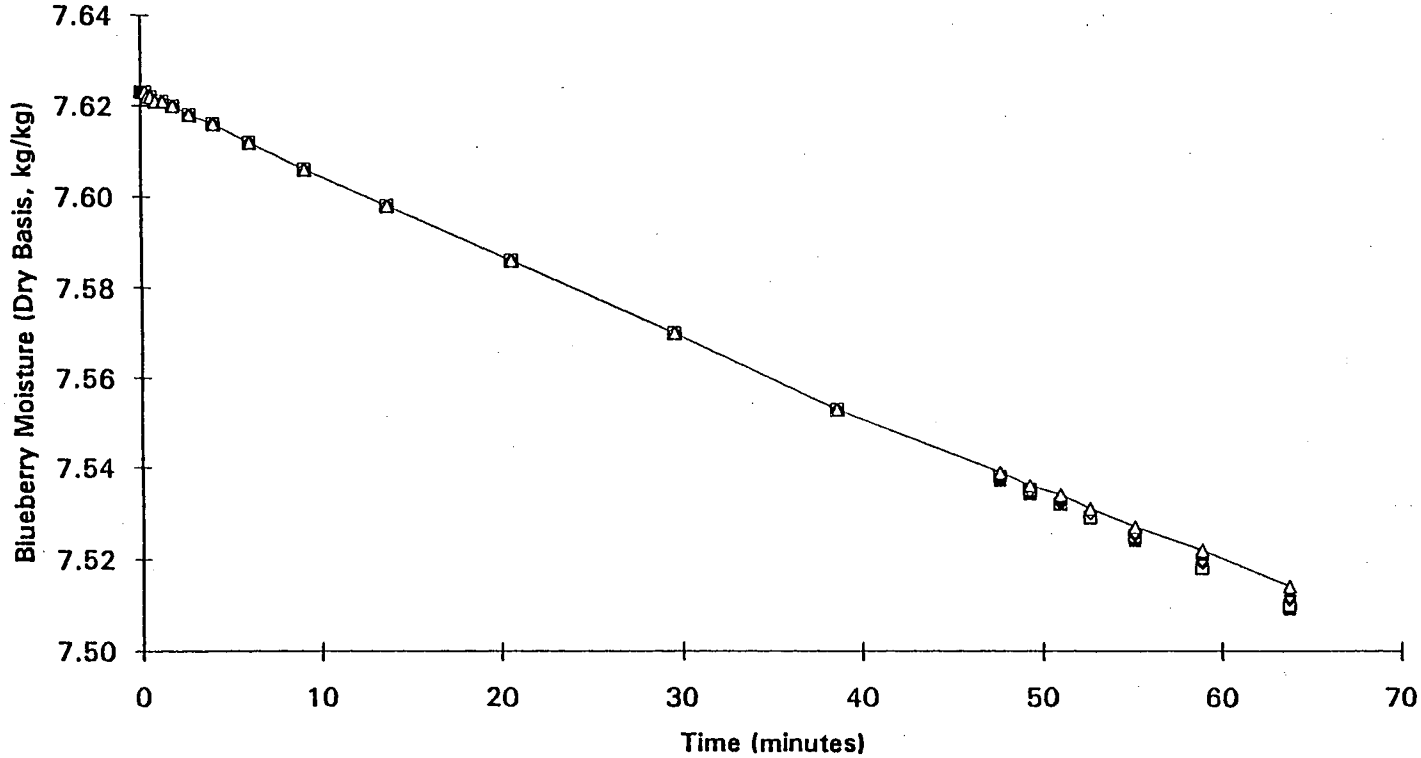

Figure 40. Moisture Profile of Blueberries During Tray Drying Using Air at 35 C

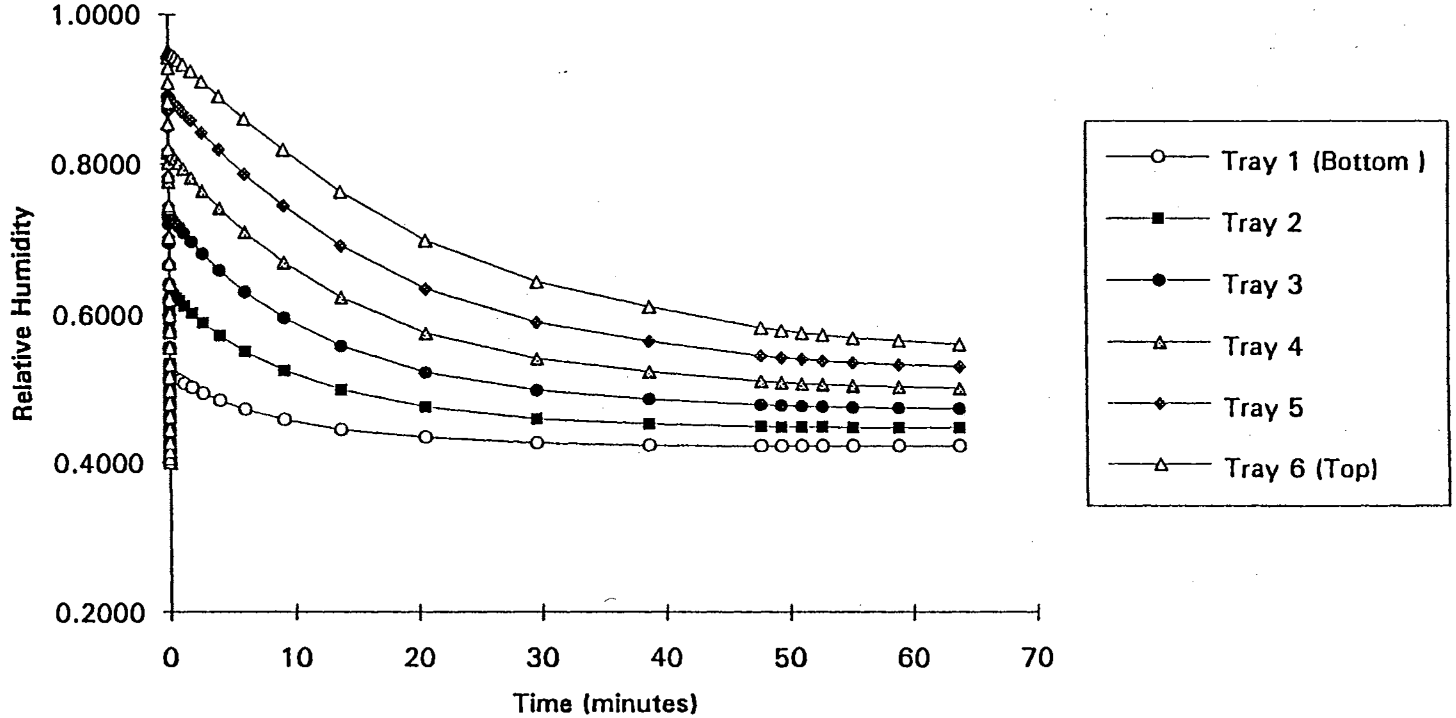

Figure 41. Relative Humidity Profile in Blueberry Drying Using Air at 35 C

CHAPTER VII

CONCLUSIONS

Several conclusions can be made about the effect of sodium hypochlorite applied as a rinse, on quality attributes of blueberries.

Results of the storage study indicate that the use of chlorine rinse did not affect water loss of berries, but this property was significantly influenced by duration of storage. Samples that were either water-rinsed or chlorine-rinsed, were less firm than the controls, suggesting that the application of the rinse and handling during drying caused softness of the fruits. To decrease the effect of handling on firmness, it is recommended that laboratory techniques that reduce impact be implemented.

The application of chlorine rinse reduced the appearance of molds. Percent soluble solids and pH of the juice increased with storage time, regardless of the rinse treatment. The ratio of soluble solids to acidity increased with time for all rinse treatments.

The reflectance study showed that the application of chlorine treatment reduced the reflectance (compared to fresh samples with intact bloom), an indication of the loss of bloom caused also by handling.

Contributions of red and green color components decrease, and the effect of blue on intensity increased with storage time. Intensity values increased with time, regardless of the rinse treatment, indicating that during storage samples lose some of the bloom, making the blueberries brighter.

Hue was the only property affected by the type of rinse and storage time. Its value significantly increased from harvest time to the end of storage, and was higher for samples that were chlorine-rinsed compared to the control.

A mathematical model to simulate the operation of a deep-bed dryer was developed. The numerical technique employed overcomes the stability problems usually associated with dynamic simulation, and provides useful information about the drying process. The model gives information about changes in temperature and humidity of air and the drying solid, with position and time. It allows simulation of drying cases where condensation occurs.

From barley drying simulations, it was evident that the accuracy of the predictions depend in great extent on the quality of the physical properties and drying parameter estimates.

The drying model was successfully used to simulate the process of excess moisture removal and dehydration of blueberries. Results suggest that to ensure that the surface moisture has been completely removed, it is necessary to dry blueberries for at least 40 minutes, at the experimental conditions used in this work. The rate of dehydration is low, and exposure to the drying air at low temperatures causes condensation in the early stages of the process, but does not cause significant dehydration even after prolonged exposure to the drying air.

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APPENDIXES

APPENDIX A

SUMMARY OF EXPERIMENTAL DATA

STORAGE STUDY

This section contains a summary of results of the statistical analysis of storage data. Mean and standard deviation values were calculated using the LSD option included in the GLM procedure of SAS (SAS Institute, Cary, NC).

This study was designed as a factorial, with three levels of Rinse (Water, Chlorine, and No-Rinse), and four levels of Storage Time (zero, one, two and three weeks). Four replicates were conducted, and samples were analyzed in triplicate. Mean values are the average of twelve readings.

TABLE X

PERCENT WATER LOSS

	Storage Time (Weeks)	
One	Two	Three
3.892^{a}	6.633^{b}	10.601^{c}

^{a,b,c}: Means with different superscripts are significantly different (at the 5% probability level).

Values of mean Water Loss shown in the table above, are presented graphically in Figure 3. LSD-value used for the mean comparison is 1.18.

TABLE XI

MOLD GROWTH AS PERCENT OF INITIAL SAMPLE WEIGHT

Type of Rinse	Mold Percent
No-Rinse	0.424[a]
Water	0.727[b]
Chlorine	0.346[c]

[a,b,c]: Means with different superscript are significantly different at the 0.05 p-level.

Values shown in the table above, were used in Figure 3. Means were calculated over all storage times, since the interaction Rinse x Storage was not significant at the 0.05 p-level.

TABLE XII

WEIGHT OF SOFT BLUEBERRIES AS PERCENT OF INITIAL SAMPLE WEIGHT

Type of Rinse	Storage Time (Weeks)		
	One	Two	Three
No-Rinse	8.92 (1.70)	9.29 (1.71)	12.25 (1.52)
Water	13.82 (1.75)	11.61 (1.34)	11.03 (1.30)
Chlorine	11.40 (1.91)	10.64 (1.50)	10.00 (1.75)

Values in parentheses are Standard Errors of the mean of each treatment combination. For each Rinse treatment, the effect of Storage Time is presented graphically in Figure 4.

APPENDIX B

RESULTS OF POST-STORAGE ANALYSIS

TABLE XIII

pH VALUES OF UNDILUTED BLUEBERRY JUICE AS A FUNCTION OF STORAGE TIME

Storage Time (Weeks)	Mean pH value
Zero (Control)	3.160[a]
One	3.193[a]
Two	3.240[b]
Three	3.260[b]

[a,b]: Values with the same superscript are not significantly different at the 0.05 probability-level.

The statistical analysis of these data used a value of the LSD of 0.047 to determine differences between treatment means. These results are also presented in Figure 5.

TABLE XIV

MEAN VALUES OF TOTAL SOLUBLE SOLIDS

Storage Time (Weeks)	Total Soluble Solids (Percent)
Zero (Control)	9.37[a]
One	10.20[b]
Two	10.75[c]
Three	11.79[d]

a,b,c,d: Means with different superscripts are significantly different at the 0.05 probability-level.

These averages indicate the amount of sugar present in the undiluted blueberry juice.

TABLE XV

MEAN VALUES OF TITRATABLE ACIDITY

Type of Rinse	Storage Time (Weeks)			
	Zero	One	Two	Three
No-Rinse	0.685	0.726	0.741	0.731
Water	0.744	0.773	0.728	0.692
Chlorine	0.714	0.704	0.678	0.675

Values of Titratable Acidity shown in the table above, correspond to titratable malic acid. In this case, both Type of Rinse and Storage Time had significant effects at the 5% probability-level.

TABLE XVI

RATIO OF SOLUBLE SOLIDS TO TITRATABLE ACIDITY

Type of Rinse	Storage Time (Weeks)			
	Zero	One	Two	Three
No-Rinse	14.11 (1.55)	14.19 (1.47)	14.90 (1.56)	16.37 (1.68)
Water	12.66 (1.18)	13.36 (1.24)	15.04 (1.46)	17.37 (1.55)
Chlorine	13.53 (1.48)	15.11 (1.63)	16.13 (1.42)	18.08 (1.42)

Values shown in parentheses are Standard Errors of the mean of each treatment combination. Mean values were significantly affected by both Type of Rinse, and Storage Time. Results are also presented graphically in Figure 6.

APPENDIX C

RESULTS OF MACHINE-VISION

STUDY

TABLE XVII

MEAN VALUES OF COLOR COMPONENTS
RELATIVE TO INTENSITY

Storage Time (Weeks)	R/I[a]	G/I[b]	B/I[c]
Zero (Control)	1.054	0.985	0.962
One	1.083	0.989	0.931
Two	1.053	0.976	0.970
Three	1.048	0.977	0.976

[a,b,c]: Red/Intensity, Green/Intensity, Blue/Intensity, respectively.

These values were used as an indicator of changes in composition of Intensity throughout the storage period. They are shown graphically in Figure 9 (Results Chapter).

TABLE XVIII

DISTRIBUTION OF COLOR COMPONENTS RELATIVE TO DISTRIBUTION OF INTENSITY

Storage Time (Weeks)	SD R/SD I[a]	SD G/SD I[b]	SD B/SD I[c]
Zero (Control)	0.977	0.963	1.107
One	1.014	0.911	1.154
Two	0.979	0.976	1.113
Three	0.970	0.995	1.121

[a,b,c]: Standard deviation of Red, Green and Blue, over Standard deviation of Intensity, respectively.

APPENDIX D

DEVELOPMENT OF THE MODEL EQUATIONS

This appendix describes the development of the equation system used to simulate the drying operation.

The equations show the rate of change in mass and energy for a stationary volume element in the dryer, and in general form are represented by:

$$\left\{ \begin{array}{c} \text{rate of mass} \\ \text{or energy in} \end{array} \right\} - \left\{ \begin{array}{c} \text{rate of mass} \\ \text{or energy out} \end{array} \right\} = \left\{ \begin{array}{c} \text{rate of mass} \\ \text{or energy accumulation} \end{array} \right\} \tag{36}$$

Energy Balance of Water in the Air Stream

The rate of change of energy of air is given by the following expression:

$$\left(\dot{M}_a \, \delta t \, H_a\right)_{in} - \left(\dot{M}_a \, \delta t \, H_a\right)_{out} + \dot{M}_w \, \delta t \, H_w - hA\left(T_a - \theta\right) \delta t = M_a H_a \Big|_{t+\delta t} - M_a H_a \Big|_t \tag{37}$$

For this analysis, $M_{a,\,in}$ is assumed equal to $M_{a,out}$.

Dividing by δt and taking the limit as δt approaches zero:

$$\dot{M}_a H_{in} - \dot{M}_a H_{out} + M_w H_w - hA\left(T_a - \theta\right) = \frac{\partial \left(M_a H\right)}{\partial t} \tag{38}$$

$\dot{M}_a$, the mass of air-water mix can also be calculated using the values of velocity, density and transversal area of the differential element.

$$\dot{M}_a = \rho_a V A \tag{39}$$

The volume, V can be calculated as:

$$V = A\,\Delta z \tag{40}$$

Making these substitutions, dividing by V, and taking the limit as Δz approaches zero, equation (38) becomes:

$$-\rho_a\, v \frac{\partial H_a}{\partial z} + \frac{\dot{M}_w}{V} H_w - h a_v (T - \theta) = \rho_a \varepsilon \frac{\partial H_a}{\partial t} \tag{41}$$

But

$$\frac{\dot{M}_w}{V} = -\rho_s (1 - \varepsilon) \frac{\partial M}{\partial t} \tag{42}$$

Finally, rearranging terms, the equation that describes energy changes in the air-water stream is:

$$\rho_a \left[\varepsilon \frac{\partial H_a}{\partial t} + v \frac{\partial H_a}{\partial z} \right] = -h a_v (T - \theta) - \rho_s (1 - \varepsilon) \frac{\partial M}{\partial t} H_w \tag{43}$$

Mass Balance of Water

in the Air Stream

The rate of change of the mass of water per volume unit in the differential element is given by:

$$\left(\frac{\dot{M}_w}{V}\right)_{in} \partial t + \rho_s (1-\varepsilon) \frac{\partial M}{\partial t} \partial t - \left(\frac{\dot{M}_w}{V}\right)_{out} \partial t = \frac{1}{V} \frac{\partial}{\partial t} (\rho_a V \varepsilon W) \tag{44}$$

Substituting volume by A Δz, and taking the limit as Δz approaches zero, the equation becomes:

$$-\rho_a v \frac{\partial W}{\partial z} + \rho_s (1-\varepsilon) \frac{\partial M}{\partial t} = \rho_a \varepsilon \frac{\partial W}{\partial t} \tag{45}$$

or, rearranging:

$$-\rho_s (1-\varepsilon) \frac{\partial M}{\partial t} = \rho_a v \frac{\partial W}{\partial z} + \rho_a \varepsilon \frac{\partial W}{\partial t} \tag{46}$$

Energy Balance in the Solid Particle

The energy equation for the solid in the volume element can be expressed as:

$$hA\left(T_a - \theta\right)\delta t - M_w H_w \partial t = \left(M_s \quad H_s\right)_{t+\partial t} + \left(\dot{M}_s \quad H_s\right)_t \tag{47}$$

$\dot{M}_w$ is the value of the mass of water that evaporates from the particle, and is transferred to the air in the elemental volume. It is given by:

$$\dot{M}_w = -\rho_s(1-\varepsilon)\frac{\partial M}{\partial t} \tag{48}$$

Dividing by V, substituting $\dot{M}_w$, and expressing the solid enthalpy by the water and dry basis contributions,

$$ha_v(T_a - \theta) + \rho_s(1-\varepsilon)\frac{\partial M}{\partial t}H_w = \frac{\partial}{\partial t}\left[\rho_s(1-\varepsilon)H_s\right] \tag{49}$$

Rearranging terms, the equation finally becomes:

$$ha_v(T_a - \theta) + \rho_s(1-\epsilon)\frac{\partial M}{\partial t}\left[H_w^{vapor}\right] = \rho_s(1-\epsilon)\left[\frac{\partial H_s}{\partial t}\right] \tag{50}$$

Mass Balance of Water in the Solid Particle

The variation in M, the moisture content of the solid, was obtained as a function of the equilibrium moisture content, the initial moisture content and the drying kinetics parameter K.

The expressions for dM/dT are usually found experimentally, and are reported in the literature as equations of the form:

$$\frac{\partial M}{\partial t} = f\left(M_e, M_o, K, T, v\right) \tag{51}$$

Equations for $\frac{\partial M}{\partial t}$, M_e and K used in the simulation examples for barley and for blueberry are presented in Appendix E.

Water Condensation

When relative humidity is greater than one, the function for $\partial M/\partial t$ is changed to reflect water condensation at the node conditions. The equations are:

$$W^{sat} = (MW_{H2O}/MW_{air}) * (P/P^{sat} - 1) \qquad (52)$$

$$\partial M/\partial t = ((\rho_a\ v)/(\rho_s\ (1-\varepsilon)\Delta z))\ (W-W^{sat}) \qquad (53)$$

where: W^{sat} is the specific humidity of air at saturation conditions.

APPENDIX E

PHYSICAL PROPERTIES AND DEEP BED CONDITIONS

USED IN THE DRYING MODEL

Drying of Barley

These physical properties and flow conditions were used to run simulations illustrating the features of the model developed in this work, and to compare the results with those of Costas and Figueiredo (1993), O'Callaghan et al. (1971), and Boyce (1965). Data were obtained from these references.

TABLE XIX

PROPERTIES OF BARLEY

Property	Value	Units
a_v	935.5	m^{-1}
Cp_s	1300	$J\text{-}kg^{-1}\text{-}C^{-1}$
D	0.0039	m
ε	0.385	
ρ_s	642.6	$kg\text{-}m^{-3}$
θ_o	18	C
a_o	348500	s^{-1}
a_1	6942	K
M_o	0.342	$kg\text{-}kg^{-1}$

The value of the equilibrium moisture content is given by:

$M_e = 0.143 - 0.016 \ln (T) - 0.079 \ln (1 - RH)$

TABLE XX

PROPERTIES AND FLOW CONDITIONS
OF AIR

Property	Value	Units
W_o	0.0056	$kg\text{-}kg^{-1}$
W_{in}	0.0056	$kg\text{-}kg^{-1}$
T_o	18	C
T_{in}	68	C
v	0.1637	$m\text{-}s^{-1}$
ρ_a	1.086	$kg\text{-}m^{-3}$
h	60.3	$J\text{-}s^{-1}\text{-}m^{-2}\text{-}C^{-1}$

The height of the bed considered for this example was 0.305 m, and the value of Δz used for the space integration was 0.005 m.

A second set of runs was performed to compare the effect of number of nodes on model accuracy. Values of barley properties were the same shown in Table XIX, and air flow conditions were as shown in Table XXI.

In this case, the value of L, the bed height was 0.1 m. The initial temperature (θ_o) and initial moisture content (M_o) of the barley were 20 C and 0.3 $kg\text{-}kg^{-1}$, respectively. Spatial increments (Δz) varied depending on the number of nodes considered.

TABLE XXI

AIR CONDITIONS IN STUDY OF EFFECT
OF NUMBER OF NODES

Property	Value	Units
W_o	0.006	$kg\text{-}kg^{-1}$
W_{in}	0.006	$kg\text{-}kg^{-1}$
T_o	20	C
T_{in}	80	C
v	0.5	$m\text{-}s^{-1}$
h	116.0	$J\text{-}s^{-1}\text{-}m^{-2}\text{-}C^{-1}$

Evaporation of Excess Moisture and

Dehydration of Blueberries

The first simulation case illustrated the evaporation of excess moisture from blueberry surface. Air flow conditions were obtained experimentally, and blueberry properties were measured or determined from correlations available in the literature.

The value of water content of fresh blueberries was measured experimentally, and used for the calculations of Cp_s and M_o.

Specific heat was estimated using the Choi and Okos correlation (Toledo, 1991), which gives Cp_s as a function of basic composition of food and temperature. The amount of water as fraction of initial weight of fresh blueberry was 0.88, and the remaining fraction 0.12 was assumed to be carbohydrate and ash.

The initial moisture content, M_o (kg water per kg of dry matter) includes the original water present in the fresh blueberries and the surface moisture, which was determined experimentally from the weight of the wet samples immediately before the drying runs.

The diameter was determined by machine-vision techniques, and the error associated with this measurement was calculated following the method of Doebelin (1990). Inaccuracy of the readings was found as three times the standard deviation of the diameter estimates, and had a value of 2.5×10^{-4} m.

The average value of diameter was used for the determination of ε, the void fraction in the deep bed, and a_v, the specific area.

TABLE XXII

PHYSICAL PROPERTIES OF BLUEBERRIES

Property	Value	Units
a_v	483.87	m^{-1}
Cp_s	3900	$J\text{-}kg^{-1}\text{-}C^{-1}$
D	0.0124	m
ε	0.476	
ρ_s	1009	$kg\text{-}m^{-3}$
θ_o	7.0	C
M_o	7.623	$kg\text{-}kg^{-1}$

The evaporation rate was determined from experimental data, as a function of M, the moisture content versus time. The result was a straight line with slope -3.0×10^{-5} $kg\text{-}kg^{-1}\text{-}s^{-1}$.

For the dehydration case, the equilibrium moisture content, M_e was considered 0.097 kg-kg-1, and was estimated from the data reported by Kim (1987).

The drying curve was obtained also from data of Kim (1987), and was given as as an Ahrrenius-type function with a pre-exponential value that was calculated as a function of the air temperature. The exponential constant, a_1 was 3876.53 K^{-1}.

A transition moisture content was considered between evaporation of the surface moisture and beginning of dehydration. This value was the original moisture content of the blueberries, which was 7.547 kg-kg^{-1}.

The air flow conditions are presented in Table XXIII. Velocity, temperature and relative humidity were measured as described in Experimental Methods.

The heat transfer coefficient, h, was estimated from correlations of Steinberger and Treybal (1960) using a Reynolds number of 470 and a Prandtl number of 0.70.

TABLE XXIII

AIR CONDITIONS IN EVAPORATION AND BLUEBERRY DRYING

Property	Value	Units
W_o	0.0074	kg-kg^{-1}
W_{in}	0.0074	kg-kg^{-1}
T_o	22.7	C
T_{in}	22.7	C
v	0.62	m-s^{-1}
h	40.6	J-s^{-1}-m^{-2}-C^{-1}

Initial moisture content was calculated using a value of 0.40 for relative humidity, which was determined experimentally.

In the last simulation case, the values of initial air and blueberry temperature were 35 and 20 C, respectively. All other physical properties remained constant.

APPENDIX F

PROGRAM CODE OF THE DRYING MODEL

This appendix contains the listing of the subroutines used to simulate the deep bed drying operation.

The first section includes the subroutine used to describe the input to the O.D.E. solver, and the second part describes the drying model.

```
C
C     THIS IS THE ROUTINE WHERE THE FUNCTION VALUES & DERIVATIVES
C     ARE COMPUTED
C
C
      SUBROUTINE bdryer( NMATI , SIN    , NINFI , SINFI , NMATO ,
     1                   SOUT  , NINFO , SINFO , IDSMI , IDSII ,
     2                   IDSMO , IDSIO , NTOT  , NSUBS , IDXSUB,
     3                   ITYPE , NINT  , INT   , NREAL , REAL  ,
     4                   IDS   , NPO   , NBOPST, NIWORK, IWORK ,
     5                   NWORK , WORK  , NSIZE , SIZE  , INTSIZ,
     6                   LDMAT , NWDIR , IWDIR ,
     7                   MODEL1, MODEL2, MODEL3,
     8                   K     , NDE   , NAE   , NIV   , NAV   ,
     9                   Y     , YMIN  , YMAX  , YSCALE, YSBND ,
     *                   F     ,
     *                   NZ    , ISTOR , JSTOR , BJ    ,
     *                   X     , XEND  , NONNEG, NLAB  ,
     *                   LABX  , LABY  , LABF  ,
     1                   KDIAG , NPOINT, XVAL  , YVAL  ,
     *                   NREPV , IREPV ,
     2                   IFAIL , ISTOP , KSTOP , IRESET, KERROR )
C
      IMPLICIT REAL*8 ( A-H, O-Z )
C
      EXTERNAL MODEL1, MODEL2, MODEL3
C
      DIMENSION Y(NDE+NAE+NIV+NAV), F(NDE+NAE+NIV+NAV)
      DIMENSION YMAX(NDE+NAE+NIV), YMIN(NDE+NAE+NIV)
      DIMENSION YSBND(NDE+NAE+NIV)
      DIMENSION NONNEG(NDE+NAE+NIV), YSCALE(NDE+NAE+NIV)
      DIMENSION LABX(NLAB,1)
      DIMENSION LABY(NLAB,NDE+NAE+NIV+NAV)
      DIMENSION LABF(NLAB,NDE+NAE+NIV+NAV)
      DIMENSION XVAL(NPOINT), YVAL(NDE+NAE+NIV+NAV,NPOINT)
      DIMENSION INT(NINT), REAL(NREAL), IWORK(NIWORK), WORK(NWORK)
      DIMENSION IWDIR(NWDIR)
      DIMENSION HWAT(70),EW(70),EM(70)
```

```
C     DIMENSION USER2 VARIABLES
C
C     DIMENSION SIN(NTOT,NMATI), SINFI(NINFI), SOUT(NTOT,NMATO),
C    1         SINFO(NINFO), IDSMI(2,NMATI), IDSII(2,NINFI),
C    2         IDSMO(2,NMATO), IDSIO(2,NINFO), IDXSUB(NSUBS),
C    3         ITYPE(NSUBS), IDS(2,3), NBOPST(6,NPO), SIZE(NSIZE),
C    4         INTSIZ(NSIZE)
C
      COMMON /COEF/ C1,C2,C3,C4,C5,C6,C7
      COMMON /CURVE/ A1,A2,B1,B2,B3
      COMMON /INIT/ W0, H0, HP0, AM0, NODES
      COMMON /USER/ RMISS, IMISS, NGBAL, IPASS, IRESTR, ICONVG,
     $              LMSG, LPMSG, KFLAG, NHSTRY, NRPT, NTRMNL,
     $              ISIZE
C     END COMMON /USER/ 09-07-81
C
C     VARIABLE  I/O  TYPE  DIMENSION       DESCRIPTION AND RANGE
C
C  F       O    R    NDE+NAE+NIV+NAV FUNCTION VALUES, AS FOLLOWS:
C                                         IF NDE > 0 :
C                        1..NDE          DERIVATIVES WRT X
C                        NDE+1..NDE+NAE   CONSTRAINT RESIDUALS
C                       NDAE+1..NDAE+NIV INTERPOLATING VAR.VALUES
C                                         IF NDE = 0 :
C                        1..NAE          FUNCTION RESIDUALS
C
C  Y       I/O   R    NDE+NAE+NIV+NAV VAR. VALUES, AS FOLLOWS:
C                                        IF NDE > 0 :
C          I          1..NDE           DEP. VARS.
C          O          NDE+NAE+1..+NAV  ADDITIONAL VAR. VALUES
C                                       IF NDE = 0 (NIV = 0 ) :
C          I          1..NAE           UNKNOWNS
C          O          NAE+1..NAE+NAV   ADDITIONAL VAR. VALUES
C
C     IFAIL      O    I                 FAILURE CODE. SET TO 1 IF
C                                   REQUESTED FUNCTION EVALUATIONS
C                                              CANNOT BE PERFORMED.
C     ISTOP      I    I                 IF >0, VAR. INDEX FOR VAR.
C                                       WHICH REACHED A STOP CRIT.
C     KSTOP      I    I                     STOP REASON CODE:
C                                          +1 = MAX. VALUE REACHED
C                                          -1 = MIN. VALUE REACHED
C     IRESET     O    I                     RESET FLAG:
C                                           1 = PARTIAL RESET
C                                           2 = TOTAL RESET
C                                           3 = 2 + NEW PROBLEM
C     KERROR     I                          ERROR FLAG FROM INPUT
C                                           CHECKING (=1) OR C
                                            INTEGRATOR (<0).
C
C
C     THIS ROUTINE WILL BE CALLED WITH THE ACTION CODE "K" :
C     ====================================================
C
C     K = 0 : CALL FOR INITIALIZATION
C     K = 1 : CALL FOR ONLY FUNCTION VALUES
C     K = 2 : CALL FOR ONLY DERIVATIVES
C     K = 3 : CALL FOR FUNCTION VALUES AND DERIVATIVES
C     K = 4 : CALL FOR ADDITIONAL HISTORY PRINTOUT
C     K = 5 : CALL FOR ADDITIONAL REPORT PRINTOUT
C     K = 6 : CALL AT THE END OF A GOOD STEP FOR THE INTEGRATOR
C     K = 7 : CALL AT THE END OF CALCULATIONS
C     K = 8 : CALL AT AN OUTPUT POINT
C
C     KERROR = 0    : NO ERRORS IN DAEIF
C              1    : PROBLEM DEFINITION ERROR(S)
C              < 0  : INTEGRATOR ERROR
C=============================================================
```

```
C   THIS IS THE SUBROUTINE USED TO SIMULATE THE OPERATION OF A
C    DEEP BED DRYER.  IT WAS TESTED FOR DRYING OF BARLEY, USING THE
C   DATA OF BOYCE (1965), O'CALLAGHAN (1971) AND COSTAS AND
C   FIGUEIREDO (1993).
C   IT WAS ALSO USED WITH EXPERIMENTAL DATA TO SIMULATE THE
C    EVAPORATION OF EXCESS MOISTURE AND DEHYDRATION OF BLUEBERRIES.
C
C
C                                DRYER MODEL:
C
C     INT(1) =   # OF NODES
C    REAL(1)=  INITIAL AIR WATER CONTENT AT ALL POSITIONS IN DRYER
C    REAL(2)=  INITIAL AIR TEMPERATURE AT ALL POSITIONS IN DRYER
C    REAL(3)=  PARTICLE TEMPERATURE
C    REAL(4)=  INITIAL MOISTURE CONTENT
C
C    INLET AIR CONDITIONS:
C
C    REAL(5)=  INLET AIR TEMPERATURE
C    REAL(6)=  INLET AIR WATER CONTENT
C    REAL(7)=  VELOCITY
C    REAL(11) = DENSITY OF AIR
C    REAL(12) = HEAT TRANSFER COEFF. OF AIR
C
C    BED CONDITIONS
C
C    REAL(8)=  EPSILON ( BED POROSITY )
C    REAL(9)=  BED HEIGHT
C    REAL(10) = DENSITY OF PARTICLE
C    REAL(13) = SPECIFIC AREA OF PARTICLES
C
C
C    DRYING CURVES
C
C
C    REAL(14) = PRE-EXPONENTIAL FACTOR FOR CALCULATION OF K
C    REAL(15) = ACTIVATION ENERGY IN AHRRENIUS-TYPE EQUATION
C    REAL(16) = CONSTANT 1 IN ME EQUATION
C    REAL(17) = CONSTANT 2 IN ME EQUATION
C    REAL(18) = CONSTANT 3 IN ME EQUATION
C
C    VARIABLES
C
C    NDD     =  DISCRETIZATION POINTS (OR NUMBER OF NODES)
C    Y(1....NDD) = AIR WATER CONTENT W(I)
C    Y(NDD+1,.........,2*NDD) =  AIR ENTHALPIES  HMIX(I)
C    Y(2*NDD+1,.......,3*NDD) =  PARTICLE ENTHALPY HP(I)
C    Y(3*NDD+1,........,4*NDD)=  MOISTURE CONTENT IN SOLID  M(I)
C
C
C
      IFAIL=0
      IRESET=0
C
C     INITIALIZATION : INITIALIZE PROBLEM
C
      IF ( K .EQ. 0 ) THEN
          NODES = INT(1)
          W0 = REAL(1)
          T0 = REAL(2)
          CALL AENTH( H0, T0, W0, 1 )
          TP0 = REAL(3)
          AM0 = REAL(4)
          CALL PENTH( HP0, TP0, AM0, 1 )
          TIN = REAL(5)
          WIN = REAL(6)
          CALL AENTH (HIN, TIN, WIN, 1)
          NDE = 4*(NODES)
          NAE = 0
          NIV = 0
          NAV = 3*NODES
          NDD = NODES
          DO 10  II=1,NDD
```

```
            Y(II) = 1.0
            YMIN(II) = 0.0
            YMAX(II) = 10.0
            Y(NDD+II) =  1.0
            YMIN(NDD+II) = -50.0
            YMAX(NDD+II) = 50.0
            JJ = 2*NDD + II
            Y(JJ) = 1.0
            YMIN(JJ) = -50.0
            YMAX(JJ) = 50.0
            KK = 3*NDD + II
            Y(KK) = 1.0
            YMIN(KK) = 0.0
            YMAX(KK) = 2.0
 10       CONTINUE
      VELOC = REAL(7)
      EPS   = REAL(8)
      HEIGHT = REAL(9)
      DELTZ = HEIGHT/DBLE(NODES)
      DENS = REAL(10)
      DENA = REAL(11)
      HCOEF = REAL(12)
      AV = REAL(13)
      C1 = VELOC/(EPS*DELTZ)
      C2 = DENS*(1.0D0-EPS)*AM0/(DENA*EPS*W0)
      C3 = HCOEF*AV/(EPS*DENA*H0)
      C4 = DENS*(1.0D0-EPS)*AM0/(DENA*EPS*H0)
      C5 = HCOEF*AV/(DENS*(1.0D0-EPS)*HP0)
      C6 = AM0/HP0
      C7 = DENA*VELOC/(DENS*(1.0D0-EPS)*DELTZ)
      A1 = REAL(14)
      A2 = REAL(15)
      B1 = REAL(16)
      B2 = REAL(17)
      B3 = REAL(18)
      X=0.0
      XEND= REAL(19)
      OPEN(71,FILE='GLORIA1.TXT')
      OPEN(72,FILE='GLORIA2.TXT')
      OPEN(73,FILE='GLORIA3.TXT')
      OPEN(74,FILE='GLORIA4.TXT')
      OPEN(75,FILE='GLORIA5.TXT')
      ENDIF
C
C     EVALUATE FUNCTION VALUES FOR STEADY-STATE SOLUTION
C
      IF ( K .EQ. 1) THEN
      ENDIF
C
C     EVALUATE DRYER EQUATIONS
C
      IF ( ( K.EQ.2) .OR. (K .EQ. 3)) THEN
C
C     DERIVATIVES FOR MOISTURE CONTENT
C
      DO 100 I=1, NODES
         JHA= NODES + I
         J = 3*NODES + I
         JTG = NDE+NAE+NIV+I
         JOM = JTG + 2*NODES
         HTEMP = Y(JHA)*H0
         WW = Y(I)*W0
         CALL AENTH (HTEMP, TT, WW, 2)
         Y(JTG) = TT
         AK = A1*DEXP(-A2/(Y(JTG)+273.15-REAL(21)))
         PT=101325.0D0
         CALL ANT(Y(JTG),PSAT)
         Y(JOM) = (Y(I)*W0*PT/PSAT)/((18.0D0/29.0D0)+Y(I)*W0)
         IF ( Y(JOM) .GT. 0.995 ) THEN
             YTEMP =  (18.0D0/29.0D0)/((PT/PSAT-1.0D0)*W0)
           IF( I.EQ.1) THEN
               F(J) =  C7*W0*(Y(I)-YTEMP)/AM0
           ELSE
```

```
                F(J) =  C7*W0*(Y(I)-YTEMP)/AM0
            ENDIF
         ELSE
           AME = (B1-B2*DLOG(Y(JTG))-B3*DLOG(1.0D0-Y(JOM)))/AM0
           F(J)= -(AK + REAL(20))*(Y(J)-AME)
         ENDIF
 100  CONTINUE
C
C     DERIVATIVES FOR AIR WATER CONTENT
C
      DO 110 J=1,NODES
         JJ = 3*NODES + J
         IF(J .EQ. 1 ) THEN
           F(J) = -C1*Y(J) + C1*(WIN/W0) - C2*F(JJ)
         ELSE

           F(J) = -C1*Y(J) + C1*Y(J-1) - C2*F(JJ)
         ENDIF
 110  CONTINUE
C
C     DERIVATIVES FOR AIR ENTHALPY
C
      DO 120 I=1,NODES
         J = NODES + I
         JTG = NDE+NAE+NIV+I
         II = 3*NODES + I
         K=2*NODES+I
         HTEMP = Y(K)*HP0
         AMM = Y(II)*AM0
         CALL PENTH (HTEMP, TT , AMM,2)
         Y(JTG+NODES) = TT
         CALL WENTH (HH, Y(JTG), 1)
         HWAT(I) = HH
         IF (I .EQ. 1 ) THEN
            F(J) = -C1*Y(J) + C1*(HIN/H0)
     1             -C3*(Y(JTG)-Y(JTG+NODES))-C4*HWAT(I)*F(II)
         ELSE
            F(J) = -C1*Y(J) + C1*Y(J-1)
     1             -C3*(Y(JTG)-Y(JTG+NODES))-C4*HWAT(I)*F(II)
         ENDIF
 120     CONTINUE
C
C     DERIVATIVES FOR SOLID ENTHALPY
C
      DO 130 I=1, NODES
         J = 2*NODES + I
         JTG = NDE+NAE+NIV+I
         II = 3*NODES + I
         F(J) = C5*(Y(JTG)-Y(JTG+NODES))+C6*HWAT(I)*F(II)

 130  CONTINUE
C
C
      ENDIF
C
C     ADDITIONAL HISTORY PRINTOUT
C
      IF ( K .EQ. 4 ) THEN
      ENDIF
C
C     ADDITIONAL REPORT PRINTOUT
C
      IF ( K .EQ. 5 ) THEN
      ENDIF
C
C     END OF GOOD STEP
C
      IF( K .EQ. 6) THEN
         JTG = 4*NODES
         JTB = 5*NODES
```

```
          JM = 3*NODES
          JOM = 6*NODES
          XX = X/60.0D0
          DO 1000 I=1,NODES
             EW(I) = Y(I)*W0
             KK = JM + I
1000         EM(I) = Y(KK)*AM0
          IBEG = NODES / 5
          ISTEP = IBEG
          WRITE(71,2000) XX,(EW(I),I=IBEG,NODES,ISTEP)
          WRITE(72,2000) XX,(Y(JTG+I),I=IBEG,NODES,ISTEP)
          WRITE(73,2000) XX,(Y(JTB+I),I=IBEG,NODES,ISTEP)
          WRITE(74,2000) XX,(EM(I),I=IBEG,NODES,ISTEP)
          WRITE(75,2000) XX,(Y(JOM+I),I=IBEG,NODES,ISTEP)
2000      FORMAT( E12.4,5('  ',E12.4))
       ENDIF
C
C      CALCULATIONS ENDED. PERFORM ADDITIONAL BOOK-KEEPING IF
C      NECESSARY.
C
       IF ( K .EQ. 7 ) THEN
          CLOSE(71)
          CLOSE(72)
          CLOSE(73)
          CLOSE(74)
          CLOSE(75)
       ENDIF
C
C      OUTPUT POINT
C
       IF ( K .EQ. 8 ) THEN
       ENDIF
C
 999   RETURN
       END
C
C    CALCULATION OF AIR ENTHALPY
C
       SUBROUTINE AENTH( H, T, W, IMODE)
       IMPLICIT REAL*8 ( A-H, O-Z )
       CP = 1006.0D0
       CW = 1900.0D0
       TREF = 0.0d0
       IF (IMODE .EQ. 1) THEN
           H = CP*(T-TREF) + W*CW*(T-TREF)
       ELSE
           T = TREF + H/(CP + W*CW)
       ENDIF
       RETURN
       END
C
C      CALCULATION OF SOLID ENTHALPY
C
       SUBROUTINE PENTH( HP, TP, AM, IMODE )
       IMPLICIT REAL*8 ( A-H, O-Z )
       CPS = 1300.0D0
       CW = 1900.0D0
       DELHV = 2.5008D+06
       TREF = 0.0d0
       IF (IMODE .EQ. 1) THEN
           HH2O = CW*(TP - TREF) -  DELHV
           HP = CPS*(TP-TREF) + AM*HH2O
       ELSE
           TP = TREF + (HP+AM*DELHV)/(CPS+AM*CW)
       ENDIF
       RETURN
       END
C
C      CALCULATION OF WATER ENTHALPY
C
       SUBROUTINE WENTH( HW, TW, IMODE )
       IMPLICIT REAL*8 ( A-H, O-Z )
       CW = 1900.0D0
       DELHV = 2.5008D+06
```

```
      TREF = 0.0d0
      IF (IMODE .EQ. 2) THEN
          HW = CW*(TW - TREF) -  DELHV
      ELSE
          HW = CW*(TW-TREF)
      ENDIF
      RETURN
      END
C
C     CALCULATION OF THE VAPOR PRESSURE BY THE ANTOINE METHOD
C
      SUBROUTINE ANT(TAIR,PSAT)
      IMPLICIT REAL*8 (A-H, O-Z)
      PL1= 6.51544D01
      PL2=-6.84291D03
      PL3= 0.0D0
      PL4= 2.78351D-03
      PL5= -6.13638D0
      PL6=3.31168D-18
      PL7=6.0D0
      TT = TAIR + 273.15
C
      IF ( TT .LT. 273.15 )  TT = 273.15
C
      PSAT=PL1+PL2/(TT+PL3)+PL4*TT+PL5*DLOG(TT)+
     1     PL6*(TT**PL7)
      IF ( PSAT .GT. 12.0    ) THEN
         PSAT=0.82 * 101325.0D0
      ELSE
         PSAT=DEXP(PSAT)
      ENDIF
      RETURN
      END
```

2

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: EFFECTS OF POST-HARVEST CHLORINE TREATMENT ON BLUEBERRY QUALITY

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