To the Graduate Council:

I am submitting herewith a dissertation written by Timothy Joel Bowser entitled "Thin Film Drying on a Permeable Surface." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Agricultural Engineering.

Luther R. Wilhelm, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

THIN FILM DRYING ON A PERMEABLE SURFACE

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Timothy Joel Bowser

May, 1994

DEDICATION

To the One who makes all things possible,

to my glory and the lifter of my head.

I dedicate this document as a sacrifice of praise

and thanksgiving for all that You have done.

O LORD, Most High.

Paraphrased from: Psa 3:3
Heb 13:15
Psa 7:17

ACKNOWLEDGMENTS

Many thanks to my major professor, Dr. Luther R. Wilhelm for his patience, guidance and resourcefulness in making this project possible and enjoyable. Special thanks go to Dr. William Morris for his assistance concerning starch products. Appreciation is expressed to Dr. Fred Tompkins, Dr. Bobby Bledsoe and the late Dr. Rabindra Biswal for their kind assistance and encouragement. Deep gratitude is given to my brother, Todd S. Bowser, who provided expert assistance on the coding of the computer program and to my father, George H. Bowser, who gave advice on the desiccant selection. Honorable mention goes to all of my family and friends and to the staff and students, electronics technician and the mechanics of the Agricultural Engineering Department with whom I consulted for support and information. Sincere thanks are expressed to the United States Department of Agriculture for providing a National Needs Fellowship to support this project and my participation in the Ph.D. program at the University of Tennessee.

ABSTRACT

A new drying technique for thin films of colloidal slurries and solutions has been proposed and evaluated. A bench top representation of the proposed drying system was constructed to test feasibility and performance of a mathematical model of the drying process. Preliminary tests showed that a water-vapor permeable drying surface could be an attractive alternative to traditional, thin-film drying methods. Four experiments, using modified corn, potato and rice starch films, were conducted.

The advantage of the new drying method is twofold: (1) the process of dehydration is up to 70 percent faster than traditional methods, and (2) the quality of the final product may be improved due to lower solids temperatures. Energy savings, a third possible advantage, remain undetermined in this study.

Shrinkage and heat and mass transfer of the proposed thin film drying system are described by the mathematical model. Physical properties of starch including moisture diffusivity, heat of sorption, modules of elasticity, bulk shrinkage, water activity, and thermal diffusivity have been taken from the literature and used in the model. The mathematical model accurately predicted drying curves for thin films of starches used in this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

This section alphabetically lists and describes the notation, primarily used in Chapter 2 (Theory), of this dissertation. Numbers in parenthesis after the description refer to equations in which the symbols are first used or defined. Dimensions are given in terms of the actual unit, following the conventions of the American Society of Agricultural Engineers (1990).

c_p specific heat of product film (4), kJ/kg·K

D diffusivity of moisture (1), m^2/sec

D_A moisture diffusivity of the film, nearest surface A (2), m^2/sec

D_B moisture diffusivity of the film, nearest surface B (3), m^2/sec

E Young's modulus of elasticity (9), MPa

F force vector before time step (19)

$f^{(e)}$ element force vector (13)

h_A convective heat transfer coefficient for surface A (5), $W/m^2 \cdot K$

h_B convective heat transfer coefficient for surface B (6), $W/m^2 \cdot K$

h_{MA} mass transfer coefficient for surface A (2), m/sec

h_{MB} mass transfer coefficient for surface B (3), m/sec

k thermal conductivity (4), W/m·K

k_A thermal conductivity of the film, nearest surface A (5), W/m·K

k_B thermal conductivity of the film, nearest surface B (6), W/m·K

L	length of segment (11), m
M	moisture concentration (1), kg/m^3
M_A	moisture concentration of the film nearest surface A (2), kg/m^3
M_B	moisture concentration of the film nearest surface B (3), kg/m^3
$M_{\infty A}$	moisture content of ambient air over surface A (2), kg/m^3
$M_{\infty B}$	moisture content of ambient air over surface B (3), kg/m^3
t	time (1), sec
T	temperature (1), K
T_A	temperature of the film nearest surface A (5), K
T_B	temperature of the film nearest surface B (6), K
$T_{\infty A}$	temperature of ambient air over surface A (5), K
$T_{\infty B}$	temperature of ambient air over surface B (6), K
u	displacement of member (10), m
V	volume (8), m^3
W	work done by external forces (7), J
z	distance perpendicular to the thin film surface (1), m
$[c^{(e)}]$	element capacitance matrix (12)
[C]	the capacitance matrix (19)
$[k^{(e)}]$	element stiffness matrix (11)
[K]	global stiffness matrix (19)

β	linear coefficient of hydral shrinkage (10) %/%
ΔM	change in moisture content (10), %
Δt	time step, sec (19)
ε_{xx}	normal strain (8), m/m
Λ	strain energy (7)
Π	total potential energy (7)
ρ	density of product film (4), kg/m^3
σ_{xx}	normal stress (8), MPa
Φ_a	nodal values before time step Δt (19)
Φ_b	nodal values after time step Δt (19)

In all your ways acknowledge him, and he will make straight your paths.
Proverbs 3:6 (KJV)

INTRODUCTION

A thin film of translucent carbohydrates falls in a continuous sheet from the intensely hot surface of a revolving drum. The appearance and texture of the film are of onion skin that reduces to flakes when crumpled. The process is called drum dehydration and the purpose is to produce a shelf-stable food product such as instant-mashed potato flakes. This is one example of the application of a flexible thin-film dehydration device called the drum dryer.

Drum dryers consist of one or more revolving, internally heated, metallic drums on which a thin, uniform layer of wet material is applied (Spadaro et al., 1966). The material dries as the drum rotates and is scraped from the surface by a stationary knife called a doctor blade. A schematic of a single drum drier is shown in Figure 1. The product is spray applied and the drum is internally heated by steam.

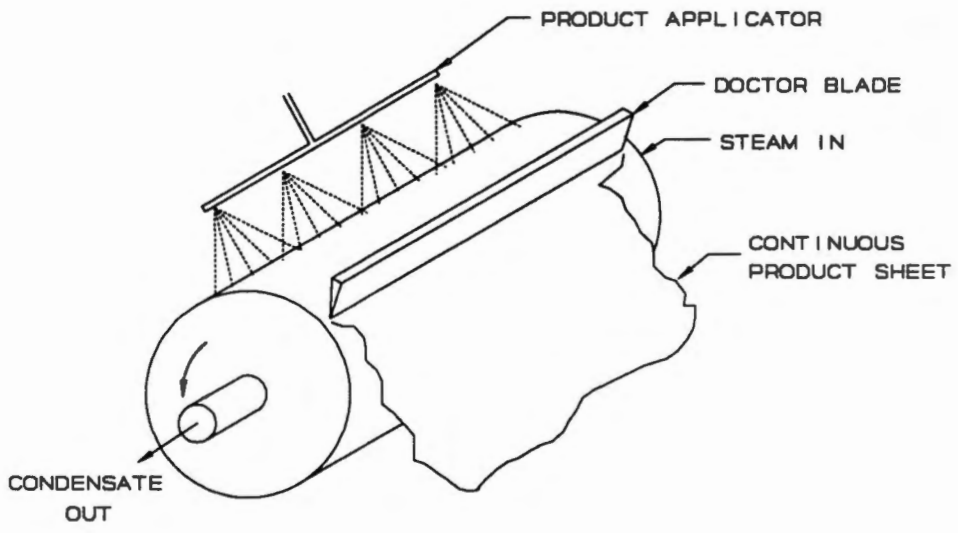


Figure 1. Typical drum dryer

Thin-film drying begins when product moisture vaporizes at the hot surface of the drum. Vapor diffuses through the film toward the lower temperature side of the film (outside) and rapidly transfers heat. The corresponding reduction of liquid water at the heated surface causes a moisture concentration gradient to be established in the film. The result is a movement of liquid water from the body of the film toward the hot surface. Moisture vapor pressure at the open surface increases until it surpasses atmospheric pressure and evaporation occurs. Evaporation establishes another concentration

gradient causing liquid water to diffuse toward the open surface of the film (Spadaro et al., 1966; Cowan, W.F., 1964; Dreshfield, A.C., 1957). Figure 2 shows the liquid water (a) and water vapor (b) concentration gradients established in a thin-film during the drum drying process. The "Z" direction shown in the figure is perpendicular to the surface of the film and points toward the atmosphere.

Water can only escape to the atmosphere by diffusing to the exposed surface of the film. This means that vapor generated at the heating surface must diffuse through the entire thickness of the film to escape. When the drying process is limited by diffusion, the speed of drying might be improved if water vapor could escape through the heated surface as well as from the open surface of the product. To achieve this "double-sided drying," a thin product

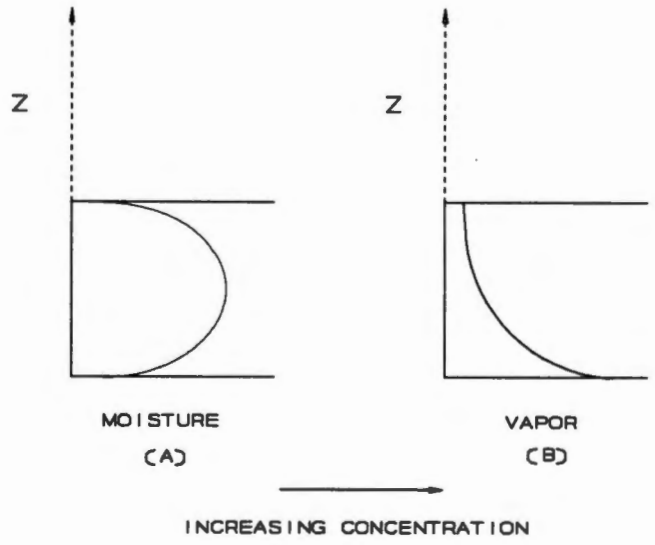


Figure 2. Thin film water concentration gradients during the drum drying process

film could be cascaded through a heated atmosphere; the exposed surface area of the film would be doubled and the pathway for water escape by diffusion reduced substantially. Unfortunately the shape of the film could not be maintained during this process. As an alternative, the film can be transformed into tiny droplets and sprayed into heated air to accomplish nearly the same drying task. The process of air-drying droplets of product is known as spray drying. Spray drying is currently the industry standard for the drying of liquids and slurries. It is especially useful for drying temperature-sensitive products, such as milk and tomato, since evaporation from the entire product surface area maintains a low solids temperature.

Despite the advantages of spray drying, drum dryers are still in use today. They are less expensive to operate than spray dryers and are necessary to obtain certain properties (mostly textural) of the reconstituted product. Examples of drum-dried products are: baby food cereals, mashed potato flakes, distillers' solids, (van Arsdel et al., 1973b), starch, glue, pharmaceuticals (Pakowski and Mujumdar, 1987), minerals, coated webs (Mujumdar, 1987a) and polymers (Hasan and Mujumdar, 1987). Many small-scale applications exist for a variety of reasons. See the review of literature for more information on drum dryer applications.

This dissertation proposes and evaluates a new drying method for thin films of colloidal slurries and solutions. The new method amounts to an adaptation of the traditional drum dryer technology that would make it more

comparable to spray drying. The traditional drum dryer surface is to be replaced by a water-vapor permeable material. The main advantage of the proposed method is an increase in the avenues of water vapor transmission. Water vapor could escape through the water-vapor permeable surface as well as from the open surface of the product. A representation of the moisture transport on a water-vapor permeable drying surface is shown in Figure 3. Figure 4 shows how the product liquid (a) and water vapor (b) profiles would look during the proposed thin-film drying process. Note that the water-vapor concentration is fairly level throughout the film, since the vapor can escape from both surfaces. The "Z" direction is perpendicular to the surface of the film.

A water-vapor permeable drying surface may have the following advantages over the traditional thin-film dryer (drum dryer).

1. Reduced drying time.
2. Improved product quality.
3. Improved energy efficiency.

Since thin-film drying on a water-vapor permeable surface is a new technology, this study is preliminary in nature. The short-term purposes are to verify the feasibility of the technology and to provide the groundwork for future studies and commercial applications. The long range purpose is to increase product quality and energy efficiency of a thin-film drying process for colloidal slurries and solutions.

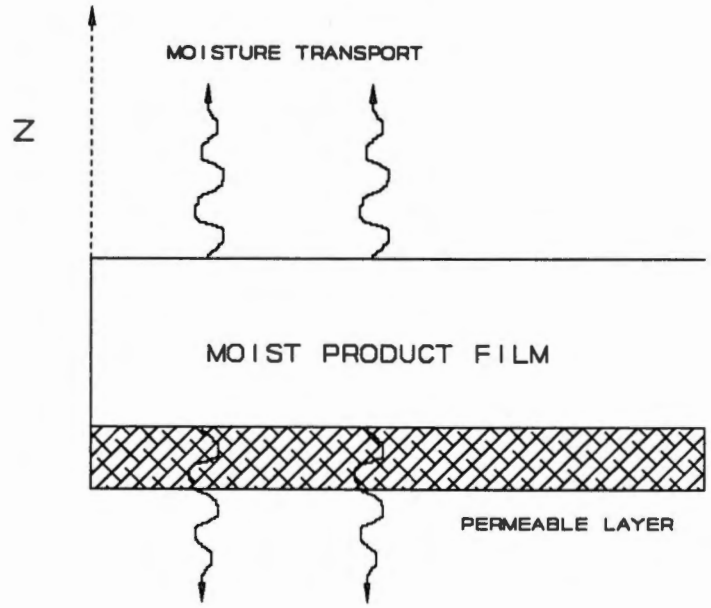


Figure 3. Moisture transport on a permeable surface dryer

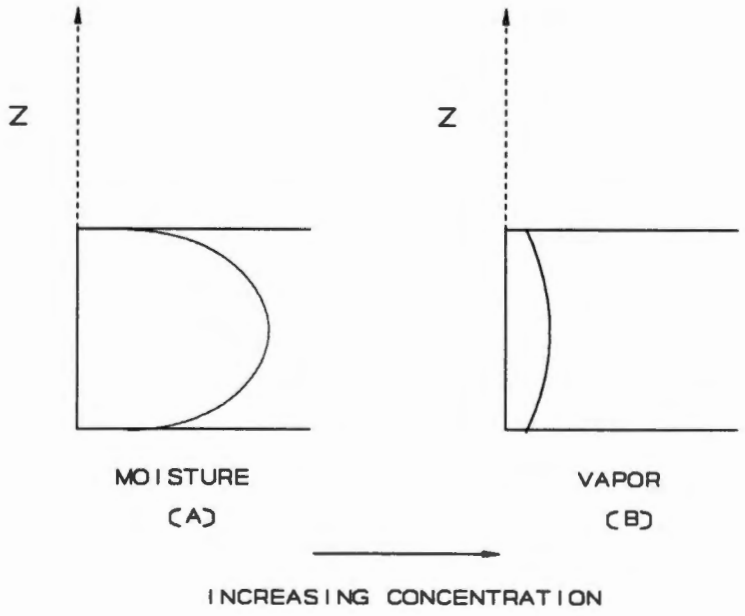


Figure 4. Thin film water concentration gradients during drying on a permeable surface

The objectives of this work follow.

1. Propose and evaluate a new type of drying technique for thin-film slurries and solutions.

2. Develop a practical mathematical model to describe the heat and mass transfer of the proposed system.

3. Construct a model of the proposed drying system and devise an experimental method to test the mathematical model.

4. Conduct experiments to test the feasibility of the drying surface and the application of the mathematical model.

5. Report results, recommendations and conclusions.

The imaginative reader will soon discover a myriad of applications and construction possibilities that exist for a thin-film drying system based on a water-vapor permeable surface. This dissertation is not intended to name all of the applications and variations of construction of said system, but simply to list the more obvious and to report results of representative tests. It should be noted that the type of drying surface and dryer construction selected will depend heavily upon the product to be dried, the manufacturing techniques, the energy source available and related factors.

It is the glory of God to conceal a thing: but the honor of kings to search out a matter.
Prov 25:2 (KJV)

CHAPTER 1

LITERATURE REVIEW

1.1 ORIGINS OF DEHYDRATION

Dehydration provides a tremendous advantage to humanity. Several hundred thousand years ago man noticed the convenience of dry firewood, and dry leaves and straw for bedding (Kröll et al., 1980). The exact origins of food dehydration are unrecorded (van Arsdel et al., 1973a), however, it has been reported that meat strips were sun-dried as much as 20,000 years ago (Kröll et al., 1980). The ancients of China, India, Persia, Greece and Egypt all dried fruits and vegetables thousands of years ago (Salunkhe et al., 1973). Man's desires and necessities have forced him to make certain perishables more

durable and certain materials less moist, consequently, things had to be dried (Sokhansenj, 1987). To this end, water is recognized as the most important component in food systems, since it influences many variables such as physical characteristics and stability (Schmidt and Lai, 1991).

Traditional dehydration employs energy sources such as the sun, wind and open wood-burning to remove moisture from foods. Moisture removal from foods has always been an integral part of processing. Since the end of World War II, mechanical, large-scale dehydration has largely replaced traditional methods (Hayashi, 1989). The main objectives of food dehydration are summarized as follows (Sokhansenj, 1987):

1. Extend storage life
2. Enhance quality (palatability and digestibility)
3. Ease handling (more stable, compact and lighter product)
4. Allow further processing (mix, mill or separate)

Commercial dehydration can be described as a mature industry in the United States, Japan and Europe. Industrial growth in this area is slow. On the other hand, the uses of powdered milk and dried foods are increasing rapidly in the developing nations. Developing nations are plagued with a shortage of refrigeration and freezing equipment and the means to operate them (Hayashi, 1989). Dehydration is a necessity of life for their burgeoning populations. It is important that high quality, inexpensive, shelf-stable, dehydrated foods are available to these nations.

1.2 DRUM DRYERS

The drum dryer was developed in 1902 by Just Hatmaker (Hayashi, 1989) as a convenient means to dehydrate certain foods and industrial products. A description and figure of a single drum dryer can be found in the introduction to this work. Detailed descriptions of the many configurations of drum dryers are found in: Marlow, 1910, Harte, 1936, Harcourt, 1938, van Marle, 1938, van Loesecke, 1943, Spadaro et al., 1966, Williams-Gardner, 1977 and Moore, 1987. Most of these works focus on the machinery of drum drying, especially single and double drum driers, raw product feed and handling mechanisms, and finished product handling.

Drum dryers are normally used to dry thin, water-based films of slurries, solutions and colloids. The final form of the product is a dried or nearly dried flake that can be handled by belt, screw or pneumatic conveyors. Many food and non-food products have been drum-dried commercially and in the laboratory. Table 1 lists examples of drum-dried food products and descriptive references. In some cases, the drum dryer must be modified to properly dry and handle the film. This is especially true of high-sugar products like apple sauce (Lazar and Morgan, 1965; Wadsworth et al., 1967; and Lazar, 1968). Table 2 lists some industrial materials dried on drum dryers.

TABLE 1. Drum-dried foods

FOOD	REFERENCE
Apple pomace	Wang and Thomas, 1989
Applesauce	Lazar and Morgan, 1966
Apricot	Lazar and Morgan, 1965
	Salunkhe, Do and Bolin, 1973
Baby food cereals	Gerber Products Company, 1993
Beet	Kopelman and Saguy, 1977
Chicken	van Arsdel et al., 1973b
	Lazar, 1968
Chickpea	Bencini, 1986
Citrus vesicle and peel fiber	Braddock, 1983
Cowpea	Okaka and Potter, 1979
Cranberry	van Arsdel et al., 1973b
Distillers solids	van Arsdel et al., 1973b
	Lazar, 1968
Egg	Mitchell and Studer, 1963
Fig	Brekke and Talburt, 1950
Fish meal	Toles, 1964
Fruit trimmings	Kitson and Britton, 1978
Guava	Nip, 1979
Milk	van Arsdel et al., 1973b
Papaya	Nip, 1979
Peach	Lazar and Morgan, 1965
Pear	Lazar and Morgan, 1965
Potato (crystals)	Asselberys, Hamilton and Saldak, 1961
Potato (flakelets)	Eskew and Drazga, 1962
Potato (flakes)	Cording et al., 1954
	Cording et al., 1955
	Eskew and Drazga, 1956
	Willard and Cording, 1957
	Cording, Sullivan and Eskew, 1959
	Sullivan et al., 1985
Potato (flour)	Willard, 1959
Pumpkin	Komanowsky Cording and Eskew, 1964
	Komanowsky Cording and Eskew, 1968
Soup stock	Tressler and Joslyn, 1961
	van Arsdel et al., 1973
Starch	Perry, 1950
Soy-egg flour	Erdman et al., 1977
Taro	Nip, 1979

Table 1. Drum-dried foods (continued)

FOOD	REFERENCE
Tomato	Tressler and Joslyn, 1961 Fergusson, 1976
Wheat gluten	Pfeifer, Vojnovich and Anderson, 1958
Sweet Potato	Spadaro and Patton, 1961 Lazar and Morgan, 1966 Spadaro et al., 1966 Manlan et al., 1985
Yeast	Fritze, 1972

TABLE 2. Drum-dried industrial products (Williams-Gardner, 1977)

Ceramic Industry
- Prepared slip for tiles
- Stone and flint slops
- Ceramic colors
- Glazes
- Insulator body
- Zirconium Silicate

Chemical industry
- Insecticides
- Detergents
- Soap
- Organic sulphonates
- Inorganic salts
- Dyestuffs and pigments
- Tanning extracts
- Benzoates

Fine chemical and pharmaceutical industry
- Calcium and barium carbonates
- Antibiotics
- Glandular extracts
- Inorganic and organic salts
- Insecticides
  - D.D.T.
- Photographic chemicals

Others
- Polymers (Hasan and Mujumdar, 1987)
- Coated webs (Mujumdar, 1987a)
- Starch (Pakowski and Mujumdar, 1987)

Drum dryer theory, design and application have largely been developed from practical experience. Drum dryers must be the subject of exhaustive pilot-scale testing before a choice is made of the dryer design, type, size and method of feed (Williams-Gardner, 1977). Feasibility (drying) studies are usually conducted on very small, six-inch diameter by eight-inch long rolls (Moore, 1987). Karel (1973) claims that the dependence of drying rate on operational characteristics and on properties of the drying material is reasonably well understood:

> The production rate has been found to be proportional to the ratio of initial to final solids contents and inversely proportional to the film thickness raised to the 0.3 power. Since retention time on the drum is proportional to film thickness raised to the 1.3 power, drying rate decreases rapidly as retention time increases. A high rate of production combined with a low moisture content can be achieved by operating at a high temperature. The maximum drying rate is often limited by the temperature tolerance of the specific product.

Nevertheless, unknown factors of an overall heat transfer rate, the effect of drum speed and film thickness make pilot-scale tests imperative in sizing industrial drum dryers (Williams-Gardner, 1977). It has been the author's experience that operational characteristics of a drum dryer can be estimated by calculation, but pilot-scale and full-scale tests are necessary when production equipment is to be sized, purchased and installed. Fritze (1972) gives examples of how operational parameters can be adjusted to minimize damage to the drying material and still maintain a good drying rate.

The drum dryer may be the most inexpensive means of product dehydration available. Spadaro et al. (1966) estimated an average cost of 17.6 cents per kg of water removed. Hayashi (1989) rated the relative costs of operating six different drying systems. The results are shown in Table 3. Moore (1987) claims that drum dryers require 1.3 to 1.1 kg of steam/kg of water evaporated (70 to 90% efficiency). He also states that water removal may be as high as 88 kg water/hour·m^2. Van Marle (1938) gives a similar figure of 90 kg water/hour·m^2. Heat transfer coefficients, for a double drum dryer under optimum conditions vary from 2.0 kW/m^2·K at the nip to 1.2 kW/m^2·K in the area next to the knives (van Marle, 1938). Moore (1987) reports that drum dryers require low energy to rotate, minimum maintenance personnel to operate and have a low initial installation cost. Williams-Garner (1977) disagrees, declaring that overall drum dryer maintenance costs can be high and are generally higher than those of spray dryers. Drum dryers are certainly not as

TABLE 3. Relative operating costs for drying systems

Drum Drying	1
Spray Drying*	2
Freeze Drying	8 - 12
Microwave Heating	3
Film Mat Drying	4.5
Vacuum Drying	6.4

*Production costs of spray drying 15 cents per kg powder

popular as they once were, probably because of their tendency to overheat products, causing discoloration, off-flavor and vitamin degradation. Drum dryers can be the preferred method for medium and small scale productions of particular products where the cost of steam is low and processing flexibility is required. As stated earlier, drum drying may be a necessary processing step to achieve certain textural properties in the reconstituted product.

Effective research and development must be conducted to continually improve drying equipment and procedures. Hayashi (1989) describes the future needs for food dehydration technique and equipment:

> The basic pattern for favorable food drying is a choice of the dryer compatible to physical, chemical and biological properties of food, together with superiority in mechanical and heating performance of the dryer selected.

Based on this viewpoint, the optimization of a dehydration process can be served by:

1. Speeding up the drying process.
2. Improving the quality of the final product.
3. Reducing the energy costs.

These three goals inspired the present research for an improved thin-film dryer. The proposed water-vapor permeable drying surface is a direct result of their consideration.

1.3 WATER-VAPOR PERMEABLE DRYING SURFACE

The concept of a water-vapor permeable drying surface (PDS) is described in the introduction to this work. A review of the literature has revealed no information pertaining to the commercial use of a PDS for the dehydration of thin films of colloidal slurries and solutions. It is assumed that this is a new drying technique for said applications.

1.3.1 Feasibility of a Water-Vapor Permeable Drying Surface

As a principle component in a new dehydration scheme, the feasibility of a PDS can be evaluated by considering the design criteria of existing dehydration equipment. Bell (1983) lists the design criteria for a basic heat exchanger (numbers one through six) as follows:

1. Fulfills process requirements
2. Withstands the service conditions of a plant environment
3. Maintainable
4. Low cost
5. Flexible operation
6. Meet dimensional limitations
7. Sanitary
8. Improves existing drying techniques by one or more of the following:
    a. speeds up dehydration

b. improves the quality of the final product

c. reduce energy costs

Numbers seven and eight are added to Bell's original list by the author to cover cases of dehydration equipment used in the food processing industry.

1.3.2 Materials for a Water-Vapor Permeable Drying Surface

What types of materials might be used as an industrial, water-vapor permeable drying surface? Cotton cloth is certainly water vapor permeable, but may not fit the process requirements, since the product could stick to the surface and the fabric might not withstand the high temperatures of short-time drying. In this section, we explore a wide range of possibilities for materials that may be used as a PDS. The review is by no means comprehensive. It is worthwhile at this time to expand upon design criteria number one (given in the previous paragraph) and state that a PDS must meet process requirements by (1) allowing dried product release, (2) withstanding the temperatures of short-time drying and (3) remaining permeable over long periods of processing time.

A water-vapor permeable surface can be called a membrane, since it forms a barrier that separates two phases and restricts the transport of various chemical species in a specific manner (Porter 1990). There are many types of commercial membranes available for almost as many purposes. The reader is encouraged to consider the works of McDermott (1972), Hsieh (1988), Rautenbach and Albrecht (1989), Porter (1990), and Bhave (1991) for further

information. For the purpose of identifying a PDS, we will classify all membranes into two categories: inorganic and organic.

Inorganic membranes are made from materials such as metals, ceramics, chemicals and inorganic polymers. Hsieh (1988) presents an excellent technical overview of the various types, preparation and uses of inorganic membranes. Dynamic membranes are one type of inorganic membrane that has already found a place in the food processing industry. Carre, Inc. markets a dynamic membrane commonly used in milk and juice production. Dynamic membranes are formed on microporous surfaces by deposition of colloidal particles or soluble components contained in a feed solution (Hsieh, 1988). Pioneering work in this area was conducted at the Oak Ridge National Laboratory (Johnson et al., 1972). The dynamic aspect of the membrane is especially convenient when frequent cleaning of contact surfaces is required. A porous, metallic carrier surface would make a good heat transfer media for the conduction drying of thin films.

Glass membranes are mechanically stable, relatively inert and are simple to steam clean. Pore sizes range from 3 μm to 40 Å (Hsieh, 1988). Porous Vycor glass has long been used as a membrane and has been evaluated for the desalination of sea and brackish water and many other purposes. Porous ceramic materials are similar in nature to glass. A thin, ceramic membrane can be formed over a porous support by a method called slipcasting where a dispersion of free particles is deposited in the pores (Leenaars et al., 1986).

Pyrolysis is a relatively new method used to form highly porous inorganic membranes from organic polymers such as silicone rubber. High temperatures and special gas environments are used to burn the organic molecules out of the material. The result is a highly stable, temperature insensitive membrane that has an average permeability of 10-50 times that of Vycor glass and a porosity of about 50% (Lee and Khang, 1987).

Thin-film deposition is a well established technology used to apply abrasion and corrosion resistant coatings to a variety of materials. Normally, the objective is to deposit a uniform, non-porous coating. Several reporters have shown (Hsieh, 1988; Eyraud et al., 1962) that under the proper conditions, porous membranes can be deposited on porous ceramic, glass or stainless steel surfaces. If the surface can be made to facilitate product release, thin-film deposition may be an excellent means to fabricate an inexpensive and durable PDS.

Microporous metals are available for use as membranes and filters and may be used directly as a PDS or as a support for a slipcast or film. The Bekaert Steel Wire Corp. (1992) manufactures a non-woven stainless steel mat with nominal pore sizes ranging from 5 to 60 μm. Mott Metallurgical Corp. (1987), Alcoa Separations Technology Division (Bhave and Fleming, 1988) and others offer sintered metals in a wide range of shapes, sizes and finishes. Most of these membranes can be treated with a hydrophobic agent such as General Electric's SM 2138 silicone emulsion (General Electric Corp., 1992) or

a titanate (Kenrich Petrochemicals, Inc., 1987) to improve product release from the surface.

Most organic membranes are made from modified natural or synthetic materials. The most common modified natural materials are cellulose derivatives such as cellulose acetate and cellulose nitrate. Examples of synthetic materials are polyamide, polybenzomidazole, vinyl polymers and polyolefins (Rautenbach and Albrecht, 1989). Organic membranes show an incredible variety in their physical structure, however, we will focus on three general structural groups: symmetrical, asymmetrical and composite.

Symmetrical membranes have a cross section that does not vary. A microporous, symmetric membrane contains uniform pores throughout the thickness of the film. Microporous symmetric membranes were first developed using the phase inversion process (Zsigmondy and Bachmann, 1918). The phase inversion process can be used to make membranes out of almost any polymer that is soluble in an appropriate solvent and can be made to be precipitated in a nonsolvent (Strathmann, 1985). Examples of commercial applications are: nylon 6, polysulfone, polycarbonate and polytetrafluoroethylene (PTFE) (Porex Technologies Corp., 1989).

Stretched membranes are a common example of a microporous, symmetric membrane. A film of PTFE is extruded and then stretched perpendicular to the direction of extrusion. The film partially fractures, which results in a uniform pore size ranging from 0.1 to 3 μm (Gore, 1976). Stretched

membranes are widely used in water repellent textiles for clothing. The membrane is hydrophobic, making it fairly waterproof. It also has a high permeability to water vapor, which allows the perspiration of the wearer to escape through the garment.

Organic, nonporous membranes can be used very effectively to separate gases and vapors (Brubaker and Kammermeyer, 1952). The mechanism of gas separation by non-porous membranes is different from that of porous membranes. Gas molecules actually dissolve and diffuse into the dense membrane matrix. Pervaporation is a special case of gas separation where the feed mixture is supplied as a liquid to the membrane and the permeate is recovered as a vapor on the low pressure side of the membrane (Fritzsche and Kurz, 1990). A comprehensive and up to date discussion of membranes used for pervaporation and other purposes is given by Kesting (1985).

A nonporous, symmetric membrane would make an excellent PDS, since there are no pores to clog. Lynch (1978) and Hwang et al. (1974) report data showing that dimethyl silicone rubber has an unusually high water vapor permeability compared to other nonporous membranes. Silicone rubber is also inert and has excellent product release characteristics. Unfortunately, pervaporation rates are very slow (several orders of magnitude slower than drying rates of existing thin-film dryers) and large-area, long-time dryers are necessary. Perhaps future improvements in non-porous membrane technology and formulation could improve this deficiency.

Nuclepore® is a commercially marketed organic membrane made using the track-etch method. Polycarbonate material is irradiated then acid etched. The etchant removes the "track" left behind by radio-active particles that have passed through the material. The result is a thin, smooth, tough membrane with capillary-shaped pores (Costar Corp., 1992).

An asymmetric membrane consists of a very thin (0.1 to 1 μm) selective skin layer on a highly porous (100 to 200 μm) thick substrate. The thin skin represents the actual membrane. Asymmetric membranes have high filtration rates and are the most clog resistant. Phase inversion and thin film deposits on microporous substrates are two techniques used to prepare these types of membranes (Strathmann, 1990).

Composite membranes are, in general, an improvement over phase inversion membranes. The composite technique allows the production of support and active (skin) layers from different materials that are selected for optimum function (Rautenbach and Albrecht, 1989). In pervaporation, the actual mass separation is achieved by a solution-diffusion mechanism, where the diffusion process is slow. To compensate for the slow diffusion process these membranes must be as thin as possible, making an asymmetric membrane mandatory (Strathmann, 1990). Dip coating is preferentially used for pervaporation applications (Henis and Tripodi, 1980) with coating thicknesses ranging from 0.05 to 1 μm (Strathmann, 1990).

1.4 THIN-FILM PRODUCT SELECTION

Starch is considered the "material of choice" for film drying feasibility tests on a PDS. It is preferred to study the drying behavior of a representative material on a PDS rather than a multitude of products. Starch gel is the logical selection, since it is the principle constituent of dried vegetable material (Fish, 1957). Many food products listed in Table 1 contain starch as their principle ingredient. Starch materials are readily available and simple to handle in the laboratory. The literature contains a great deal of information concerning the properties of starch. Table 4 lists selected physical properties of starch and references where relevant descriptive and quantitative information can be located.

TABLE 4. Selected references for physical properties of starch

1. Density	Okos, 1986
2. Diffusivity	Fish, 1957; 1958
	Rulkens and Thijssen, 1969
	Menting et al., 1970
	Chirife et al., 1977
	Callaghan et al., 1983
	Leslie et al., 1991
3. Elastic Modulus	Fish, 1957
	Görling, 1958
	Maxwell and Zobel, 1978
	Zobel, 1984
	Russell and Oliver, 1989
4. Sorption Isotherm	van den Berg et al., 1975
	Iglesias and Chirife, 1976
	Boquet et al., 1978
	van den Berg, 1991
5. Specific heat	Okos, 1986
6. Shrinkage	Görling, 1958
	Suzuki et al., 1976
	Lozano et al., 1983
7. Thermal conductivity	Okos, 1986
8. Thermodynamics	Fish, 1957; 1958
	Chirife et al., 1977
	Ginzburg, 1981
	Soekarto and Steinberg, 1981

But oh, that God would speak and open his lips to you, and that he would tell you the secrets of wisdom! For he is manifold in understanding. Job 11: 5, 6a RSV

CHAPTER 2

THEORY

In this chapter, a theoretical model for predicting the drying rate of a thin starch film on a water-vapor permeable membrane is presented and explained. Some observed complexities of the drying rate of a thin film have been ascribed to product shrinkage and the variability of the physical properties with changing moisture content and temperature (van Arsdel, 1941; Kozempel et al., 1986). Classical thermodynamics and heat transfer theory have been used to develop mathematical models describing the temperature and moisture distributions in films and slabs (Philip and de Vries, 1957; de Vries, 1958; Luikov and Mikhailov, 1965; Mikhailov, 1973; Raats, 1975; Whittaker, 1977 and others).

Chirife (1983) and Keey (1990) question the use of complex mathematical models unless they can be supported by experimental results. Hougen et al. (1940) and Bruin and Luyben (1990) state that the solution to the classical equations in their most general form is not available and they must be solved using numerical techniques.

2.1 FINITE ELEMENT MODEL

Van Arsdel (1947), Rulkens and Thijssen (1969) and Okazaki et al. (1974) used numerical techniques to investigate the effects of variable diffusivity as a function of moisture content in a drying film with a shrinking coordinate system. These researchers successfully simplified the analysis by assuming a constant film temperature. Constant film temperature is not, however, a valid assumption for thin-film drying, since the film temperature is critical to finished product quality and greatly affects moisture diffusivity (Fish, 1957; Whitney and Porterfield, 1968; Zhou et al., 1992).

Haghighi and Segerlind (1988) used a finite element formulation to determine the simultaneous moisture and heat diffusion equations for the drying of an isotropic sphere (soybean kernel). Haghighi (1990) later improved upon the model by considering volumetric changes in addition to the heat and moisture diffusion. Since soybean drying is a relatively slow process (measured

in days), Haghighi was able to assume constant physical properties (specific heat, density, thermal conductivity and moisture diffusivity) with good results. This is not practical with a starch film, since the physical properties change radically during the short drying process.

A finite element approach, based upon the work of past researchers, is taken to build a model for the short-time drying of a thin film of starch. The model considers shrinkage and simultaneous heat and mass transfer. Physical properties of the starch film are evaluated as a function of the instantaneous film temperature and moisture content. Figure 5 shows the geometry of the thin-film drying system. Results of the model will be compared with actual thin-film drying curves in the results section (Chapter 4) of this work. It is intended that the model will add to the available theoretical knowledge on thin-film drying without becoming so sophisticated as to have little utility in dryer design.

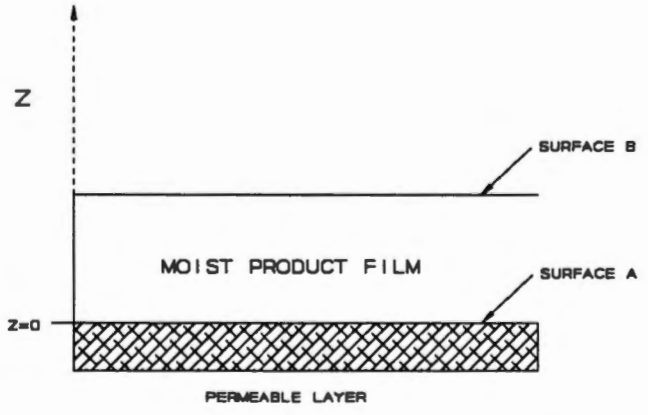


Figure 5. Cross section of a drying starch film, showing geometry

2.1.1 Model Assumptions

Assumptions of the general model follow:

1. Shrinkage and gradients in temperature and diffusivity are one dimensional, perpendicular to the surface of the film ("Z" direction in Figure 5).
2. All moisture movement is by diffusion.
3. Shrinkage is due to moisture migration and any thermal expansion is neglected.
4. Free shrinkage is directly proportional to the change in moisture concentration.
5. Observed shrinkage at any instant during drying is the cumulative effect of free shrinkage due to moisture loss.
6. Elastic shrinkage is simulated as a Hookean solid (perfectly elastic) (numbers three through six from Misra and Young, 1980).
7. The rate of work done by viscous forces in a volume element is negligible (Bruin, 1969).
8. Calculations are based on a unit surface area of the film.

2.1.2 Moisture Diffusion

T.K. Sherwood (1931) was one of the first researchers to apply a parabolic partial differential equation to model the moisture gradient in drying solids. This equation, now commonly known as the diffusion equation, (Press et al., 1989) is given as

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial M}{\partial z}\right) \quad (1)$$

where
- M = moisture concentration, kg/m^3
- t = time, sec
- z = distance perpendicular to the thin film surface, m
- D = Diffusivity of moisture, m^2/s

Hougen et al. (1940) point out that the diffusion equation does not hold when drying phenomena such as capillarity, porous transport and gravity are present. Equation (1) is only valid for simple materials such as solutions and gels (eg. starch) when the molecular transport of water takes place by diffusion (Hougen et al., 1940; Bruin and Luyben, 1990).

The initial condition for equation (1) is a uniform product moisture content. Boundary conditions implicit to equation (1) are

$$D_A\left(\frac{\partial M}{\partial z}\right) = h_{MA}(M_A - M_{\infty A}) \quad (2)$$

$$D_B\left(\frac{\partial M}{\partial z}\right) = h_{MB}(M_B - M_{\infty B}) \quad (3)$$

where
- D_A = Moisture diffusivity of the film, nearest surface A, m^2/sec
- D_B = Moisture diffusivity of the film, nearest surface B, m^2/sec
- h_{MA} = Mass transfer coefficient for surface A, m/sec
- h_{MB} = Mass transfer coefficient for surface B, m/sec
- M_A = Moisture concentration of the film nearest surface A, kg/m^3
- M_B = Moisture concentration of the film nearest surface B, kg/m^3

$M_{\infty A}$ = Moisture content of ambient air over surface A, kg/m^3
$M_{\infty B}$ = Moisture content of ambient air over surface B, kg/m^3

2.1.3 Heat Diffusion

The one-dimensional heat diffusion equation is an analog of the mass diffusion equation and is given by Bird et al. (1960)

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) \tag{4}$$

where
ρ = Density of product film, kg/m^3
c_p = Specific heat of product film, kJ/kg·K
T = Temperature, K
k = Thermal conductivity, W/m·K

The initial condition for equation (4) is a uniform product temperature. Boundary conditions implicit to equation (4) follow

$$k_A\left(\frac{\partial T}{\partial z}\right) = h_A(T_A - T_{\infty A}) \tag{5}$$

$$k_B\left(\frac{\partial T}{\partial z}\right) = h_B(T_B - T_{\infty B}) \tag{6}$$

where
k_A = Thermal conductivity of the film, nearest surface A, W/m·K
k_B = Thermal conductivity of the film, nearest surface B, W/m·K
h_A = Convective heat transfer coefficient for surface A, $W/m^2·K$
h_B = Convective heat transfer coefficient for surface B, $W/m^2·K$
T_A = Temperature of the film nearest surface A, K
T_B = Temperature of the film nearest surface B, K

$T_{\infty A}$ = Temperature of ambient air over surface A, K
$T_{\infty B}$ = Temperature of ambient air over surface B, K

2.1.4 Shrinkage

The shrinkage of a starch film can be modeled using the principle of minimum potential energy as discussed by Segerlind (1984) and presented by Misra and Young (1979). The starch film is considered as an axial force member with total potential energy given as

$$\Pi = \Lambda - W \tag{7}$$

where Π = Total potential energy
Λ = Strain energy
W = Work done by external forces

The work done by external forces, W, on the starch film is equal to zero and the strain energy is given by Popov (1976) as

$$\Lambda = \int \frac{\sigma_{xx}\varepsilon_{xx}}{2} dV \tag{8}$$

where σ_{xx} = Normal stress, MPa
ε_{xx} = Normal strain, m/m
V = Volume, m^3

and

$$\sigma_{xx} = E\varepsilon_{xx} \tag{9}$$

where E = Young's modulus of elasticity, MPa

and

$$\varepsilon_{xx}=\frac{du}{dz}-\beta\Delta M \tag{10}$$

where u = Displacement of member, m
β = Linear coefficient of hydral shrinkage, %/%
ΔM = Change in moisture content, %

Equations (9) and (10) are substituted into equation (8). Since the potential energy of a starch-film, axial-force member is zero, equation (8) can be set equal to zero and solved for member displacement.

2.2 FINITE ELEMENT EQUATIONS

The finite element equations are formulated using the direct stiffness method given by Segerlind (1984). Refer to Figure 5 (page 27) for the geometry of the system.

2.2.1 Moisture Diffusion

The element equations for the moisture diffusion equation are given as

$$[k^{(e)}]=\frac{D}{L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix} \tag{11}$$

where $[k^{(e)}]$ = Element stiffness matrix
L = Length of segment, m

and using the lumped formulation

$$[c^{(e)}] = \frac{L}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{12}$$

where $[c^{(e)}]$ = Element capacitance matrix

and

$$f^{(e)} = \begin{bmatrix} 0 \\ h_{mA}M_{\infty A} \end{bmatrix} + \begin{bmatrix} h_{mB}M_{\infty B} \\ 0 \end{bmatrix} \tag{13}$$

where $f^{(e)}$ = Element force vector

The first term on the right-hand side of equation (13) applies to the surface of the film at z=0. The second term applies to the surface of the film at z=z. All other terms in the force vector are zero.

2.2.2 Heat Diffusion

Element matrices for the heat diffusion equation are similar to those given for the moisture diffusion equation. The stiffness matrix is given by

$$[k^e] = \frac{k}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{14}$$

and again using the lumped formulation, the capacitance matrix is

$$[c^{(e)}] = \frac{\rho c_p}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{15}$$

and

$$f^{(e)} = \begin{bmatrix} 0 \\ h_A T_{\infty A} \end{bmatrix} + \begin{bmatrix} h_B T_{\infty B} \\ 0 \end{bmatrix} \tag{16}$$

is the force vector. The first term in equation (16) applies only to the surface of the film at z=0. The second term applies to the surface of the film at z=z. All other terms in the heat diffusion force vector are set equal to zero.

2.2.3 Shrinkage

The elemental formulations for the axial force member shrinkage model are given below. A capacitance matrix is not required. The element stiffness matrix is

$$[k^{(e)}] = \frac{E}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{17}$$

and the element force vector is

$$f^{(e)} = \begin{bmatrix} -E\beta\Delta M \\ E\beta\Delta M \end{bmatrix} \tag{18}$$

2.2.4 General Finite Element Solution

The forward difference method is selected to find the finite element solution in time (since the boundary conditions are not known at each time step). The general format of the forward difference equation is

$$[C]\Phi_b = ([C] - \Delta t[K])\Phi_a + \Delta t F \tag{19}$$

where
- [C] = The capacitance matrix
- Φ_b = Nodal values after time step Δt
- Δt = Time step
- Φ_a = Nodal values before time step Δt
- [K] = Global stiffness matrix
- F = Force vector before time step

Equation (19) can be solved for Φ_b using a computer and standard matrix manipulation routines that are available from many references listed in Press et al. (1989).

2.2.5 Time Step

The time step size must be greater than zero and satisfy

$$\Delta t < \frac{L^2}{4D} \tag{20}$$

for the moisture diffusion equation and

$$\Delta t < \frac{\rho c_p L^2}{4k} \tag{21}$$

for the heat diffusion equation. The time step restriction is necessary to insure that the quantity ([C] - Δt[K]), from equation (19), remains positive definite. See Mohtar and Segerlind (1992), Haghighi and Segerlind (1988), Misra and Young (1979) and others for information on stability of numerical calculations and time step size. For starch films, equation (20) will always be satisfied when equation (21) is true.

2.3 CONCLUSION

Simultaneous solution of equations (1), (4) and (8) will give the instantaneous moisture concentration, temperature and thickness of a drying starch film. This is accomplished by first numerically solving equation (1) for a given time step to obtain the moisture profile. Second, the results are used in a numerical solution of equation (4) to obtain the temperature profile for the same time step. Equations (1) and (4) are coupled in the finite element formulation by means of their forcing functions, equations (13) and (14), respectively. The thermal energy required to evaporate the moisture from the first and/or last node of the film during a drying-time interval is added to the forcing function of the heat diffusion equation at the particular node(s). Finally the moisture and temperature profiles can be used in the numerical solution of equation (8) to find film shrinkage. This procedure is repeated iteratively until the system reaches equilibrium conditions or the desired drying period expires.

And I told them of the hand of my God which had been upon me for good, and also of the words which the king had spoken to me. And they said, "Let us rise up and build." So they strengthened their hands for the good work.
Neh 2:18 (RSV)

CHAPTER 3

DESIGN

A small drying chamber was constructed to test the feasibility and performance of thin-film drying on a water-vapor permeable surface. Separate air flows were maintained above and below the thin film during the drying period. Desiccant columns were used to measure the moisture dried from the film into the air streams. Instruments monitored the temperature, air flow, mass of moisture dried from the film and pressure conditions of the system. The drying chamber and its support equipment are referred to in this chapter as the "drying system." The drying system was not designed to simulate an operational dryer.

3.1 DESCRIPTION

The thin-film drying system was developed at the University of Tennessee, Knoxville, Tennessee, and tested on the same campus at the New Agricultural Engineering Building, Food Engineering Laboratory. A flow chart of the system (excluding data collection instrumentation) is given in Figure 6. A centrifugal fan (model 4C108, Dayton Electric Mfg. Co., Chicago, IL) driven by a 746-watt blower motor (model 5K901C, 3450 rpm, Dayton Electric Mfg. Co., Chicago, IL) supplied room air to the system. A fiberglass furnace filter, taped over the fan inlet, prevented large airborne particles from entering the system. Air was piped throughout the system using a combination of PVC piping and fittings and four-inch flexible dryer hose. The dryer hose is convenient for tortuous routing and was secured over PVC and other components with metal hose clamps. Insulation (5/16" Reflectix, Reflectix, Inc. Markelville, IN) was applied to some sections of the dryer hose to retard heat loss.

A bypass valve, located on the discharge tube of the fan, was used to bleed excess air from the system and to allow for some adjustment in system pressure. Room air was dried by passing it through a custom-made dehumidifier. The dehumidifier consisted of a 220V refrigeration system (model CM10B822CA, Bristol Compressors, Inc., Bristol, VA) and a heavily insulated, double wooden box. The evaporator was mounted inside the box and the compressor and condenser were mounted on the top, outside of the box. Air

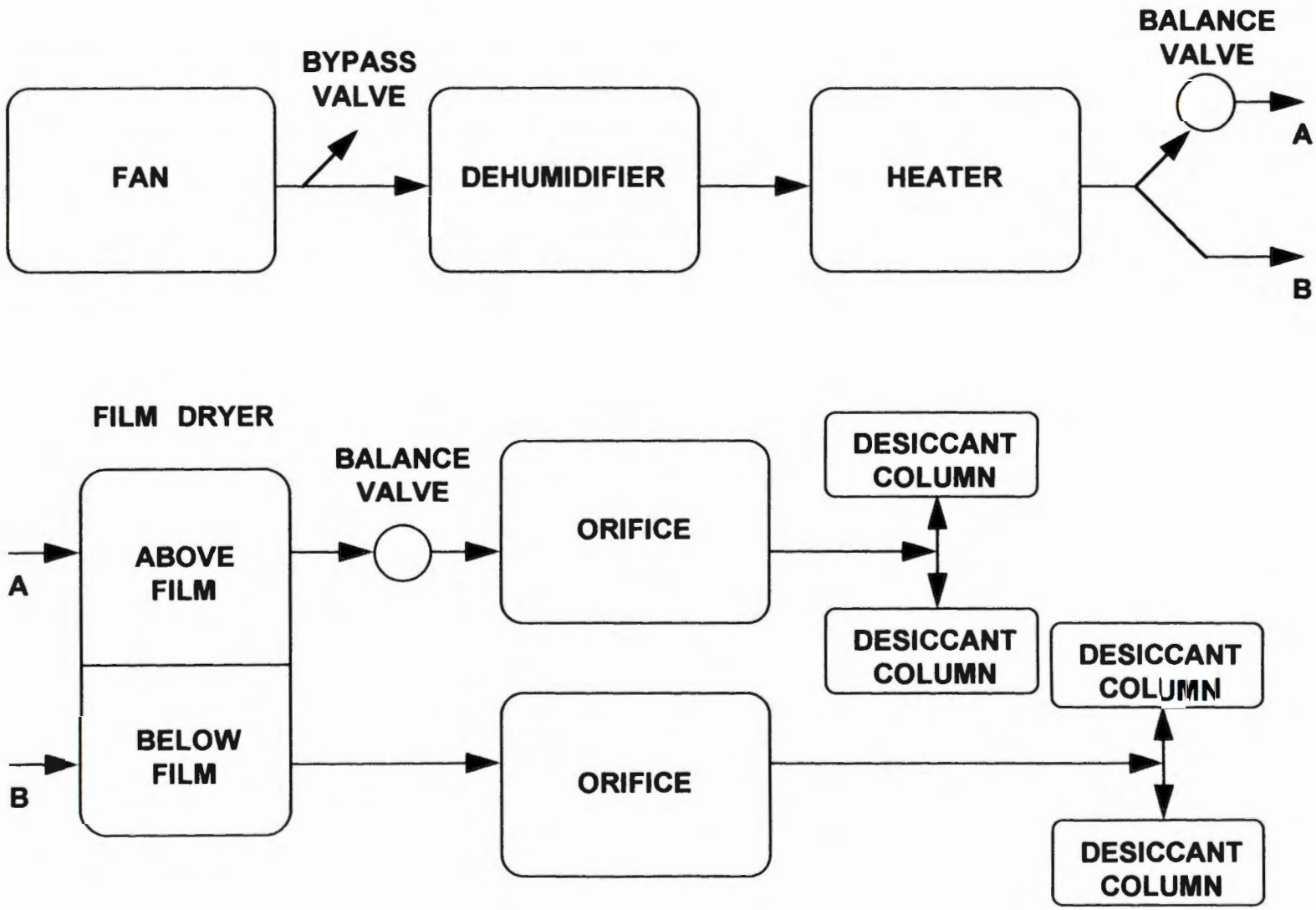


Figure 6. Flow sheet of the experimental, thin-film drying system

was directed over the evaporator coils and chilled to below 6°C before it exited the dehumidifier. A pan collected condensate and a tube drained it to the outside of the chamber. The actual cooling capacity of the unit was about 700 Watts.

Cooled, saturated air was piped to a custom-made heater where its temperature was raised to process conditions. The heater consisted of a heavily-insulated, double sheet metal box and a 220V, coiled, 15 Ω resistance, nichrome wire heater. Baffles directed the air across the heater coil and out the opposite side of the container. Exit air temperature was controlled using a feed-back loop scheme consisting of a PID temperature controller (Series 76, Partlow Corp., New Hartford, NY) and a type T thermocouple.

The heater discharge air stream was split using a three-inch PVC "wye." The two separate air streams (A and B) were piped to the film dryer. Airstream A was directed over the open face of the drying film and airstream B was directed underneath the water-vapor permeable drying surface. The air flows were maintained separate throughout the remainder of the experiment to find the mass transfer from the faces of the drying film.

Airstream A passed through two, two-inch PVC gate valves. One valve was located on the inlet side and the other on the discharge side of the drying chamber. The valves were used to balance the pressure between the A and B air streams in the film drying chamber. A complete description of the film-drying chamber is given later in this chapter.

Film dryer discharge air streams A and B passed through separate orifice plates to find flow. The identical, 1 3/8 inch diameter orifice plates were manufactured, installed and operated according to the Power Test Codes of the American Society of Mechanical Engineers (1959). A manometer (model 400, F.W. Dwyer Mfg. Co., Michigan City, IN) was used to measure the pressure drop across each orifice. Flow rates were calculated according to the procedure given by the American Society of Mechanical Engineers (1963).

Metered air streams A and B were directed through separate, custom-made desiccant columns to absorb moisture from the air. The columns were designed to be easily removed from the system and weighed on a scale (model BA6100, Sartorious Corp., Bohemia, NY). Column weight change over time was proportional to moisture evaporated from the drying film. A system of valves and piping allowed each airstream to be directed to a desiccant column while a second column remained off-line. The air flow could be switched between columns to facilitate periodic weighing without a loss of data or continuity of the experiment. A detailed description of the desiccant columns and their plumbing is given later in this chapter.

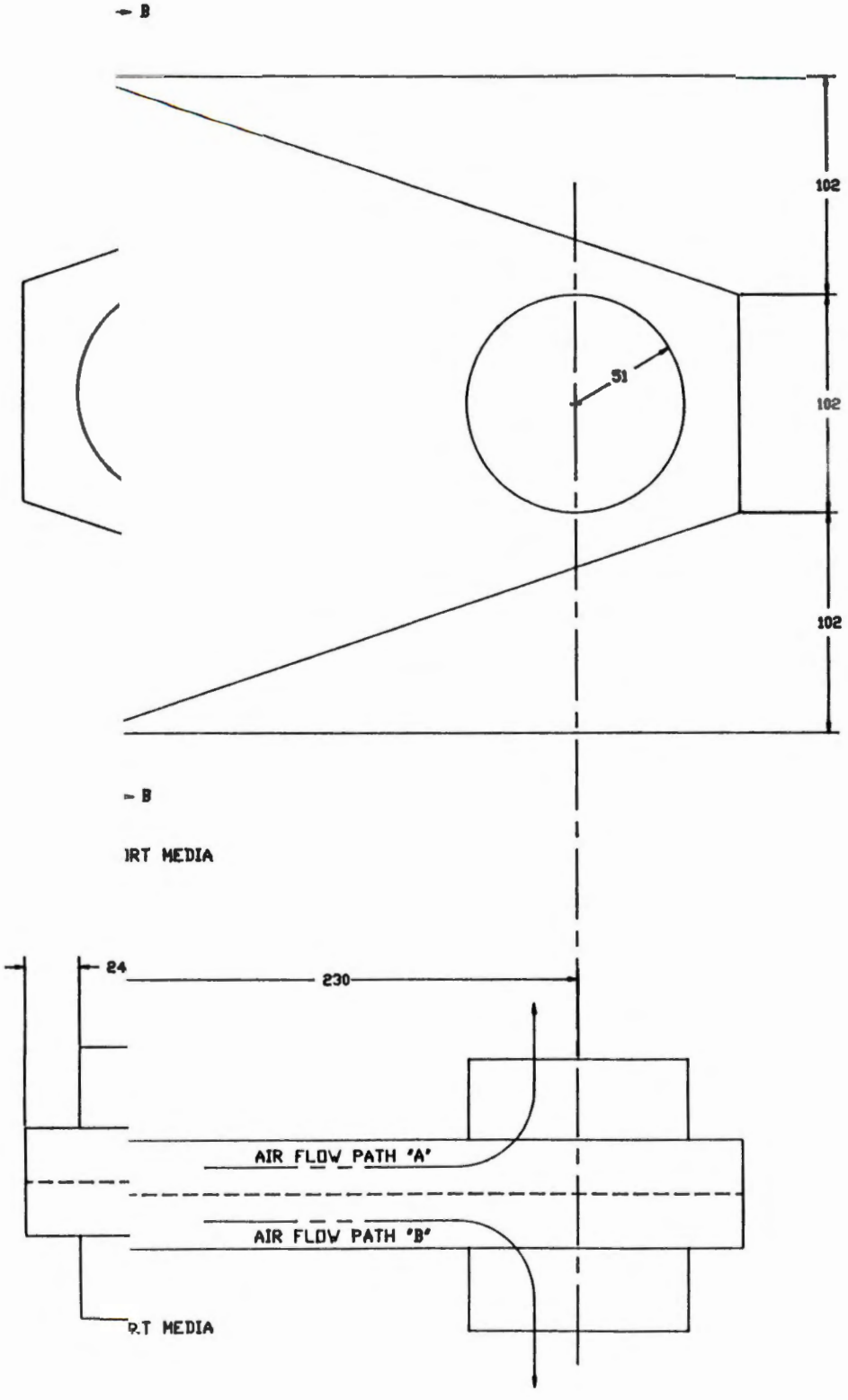
3.1.1 Drying Chamber

A drying chamber was custom fabricated in the precision mechanical shop located in the New Agricultural Engineering Building at the University of Tennessee, Knoxville. The entire device (excluding fasteners and the clear,

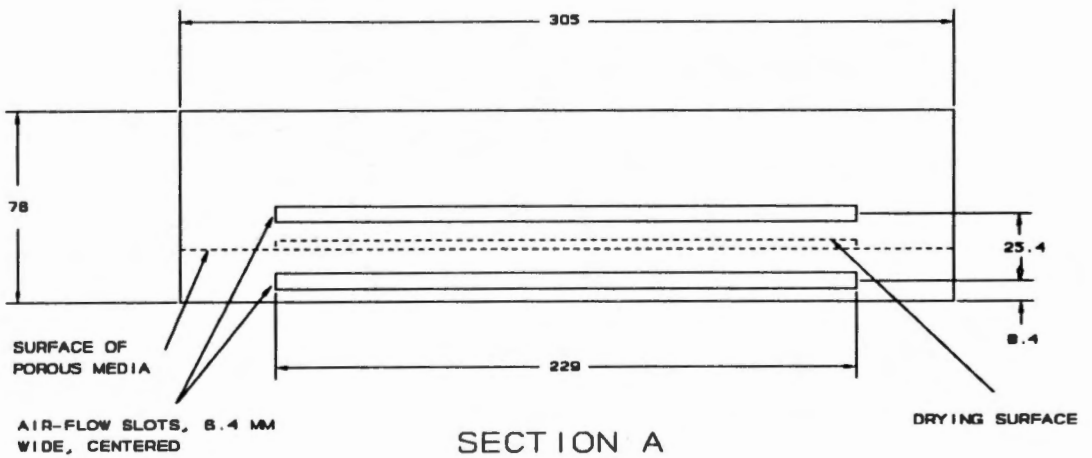
lexan cover) was cut from gray, PVC sheet stock. The lexan cover allowed access to the chamber and was attached with wingnuts for quick removal. Diagrams of the drying chamber are given in Figures 7 and 8. Air flow paths through the chamber are shown on the right side view in Figure 7. Air connections were made using four inch, flexible dryer hose. Figure 8 shows a detailed section from Figure 7 giving the air-flow slot pattern. All joints and seams of the drying chamber were sealed air tight with a white, silicone caulking compound.

3.1.2 Drying Surface

Requirements for the drying surface used for this study were ruggedness, good heat conduction capability (since air was used below the drying surface to provide energy for drying), low cost and availability. Selection of the drying surface proved simple. The Bekaert Steel Wire Corp. (Marietta, GA) kindly provided a sample sheet of their Bekipor® 30AL3 series, non-woven, 316 L stainless steel fiber media. The mean filter rating of the material is 30 µm with a porosity of 85%. Dimensions of the sample sheet were 230 x 300 x 0.9 mm. The 30AL3 series sheet was treated with General Electric's (Waterford, NY) SM2059 Reactive Silicone Emulsion release agent (also provided as a free sample). The 30AL3 sheet was dipped into a 0.5% solution of the SM2059 and dried in a convection oven at 260°C. The hydrophobic SM2059 provided excellent protection from product sticking and pore clogging.


B
102
51
102
102
B
IRT MEDIA
24
230
AIR FLOW PATH 'A'
AIR FLOW PATH 'B'
R.T MEDIA

hs



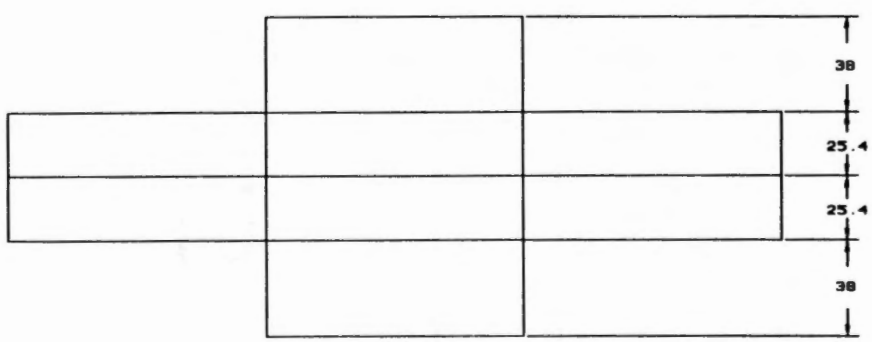


Figure 8. Cross sections A and B of drying chamber from Figure 7

It is used commercially as a fabric softener and thread lubricant, vinyl and auto-polish additive, and release coating.

3.1.3 Support for Drying Surface

A macroporous copper material provided support and allowed air circulation beneath the drying surface. Two, 300 x 300 x 13 mm sheets of reticulated copper battery anode material were donated by the Eltech Co. (Oakland, CA). Pore size of the material is about eight pores per linear cm with a porosity of 90%. Copper is an excellent conductor of heat and the large pore size gave low resistance to air flow. The sheets are flexible, provided adequate support for the drying surface, and were easily cut with a paper cutter or scissors.

3.1.4 Drying Surface Assembly

The two sheets of battery anode were cut identically (285 x 285 mm) to stack snugly inside the drying chamber as shown in Figure 7. The sheets were held in place by two PVC strips (13 x 285 x 3 mm thick) attached to the sides of the chamber, parallel to the direction of air flow. The drying surface was placed directly on top of the porous copper and secured around the perimeter by a bead of silicone-rubber sealant. Areas of battery anode not covered by the drying surface were "air-proofed" by filling the exposed pores with silicone-rubber sealant. Efforts were made to seal any cracks and holes with silicone

sealant to prevent air exchange between the separate air flow paths above and below the drying surface. Air passage through the drying surface was blocked by the product as it dried.

3.1.5 Desiccant Columns

Desiccant columns were developed specifically for this project using available materials. The ideal column would have an adequate water absorption capacity, acceptable head loss, low cost, be simple to build and easy to weigh on an existing, 6,100 gram capacity scale. PVC sewer pipe (type SDR 35) was selected as the construction material since it is light weight, inexpensive, available and easy to handle. A 4A molecular sieve (Catalog no. 33,430-8, Aldrich Chemical Co., Inc., Milwaukee, WI) desiccant was specified with reference to application notes from W.R. Grace and Co. (undated). Molecular sieve can dry air to almost 0 percent moisture. The molecular sieve was provided in 1.6 mm pellets that minimized pressure drop through the column. Repeated handling of the sieve produced very little dust or fines. Each column was packed with 1.0 kilogram of pellets, providing approximately 80 grams of useful water absorption capacity per column. Regeneration of the sieve was accomplished by spreading it in shallow pans and baking it in a convection oven at 260°C for a minimum of two hours.

Figure 9 shows an exploded, side view of a typical desiccant column. The mesh screen was a piece of nylon fabric. The screen material is

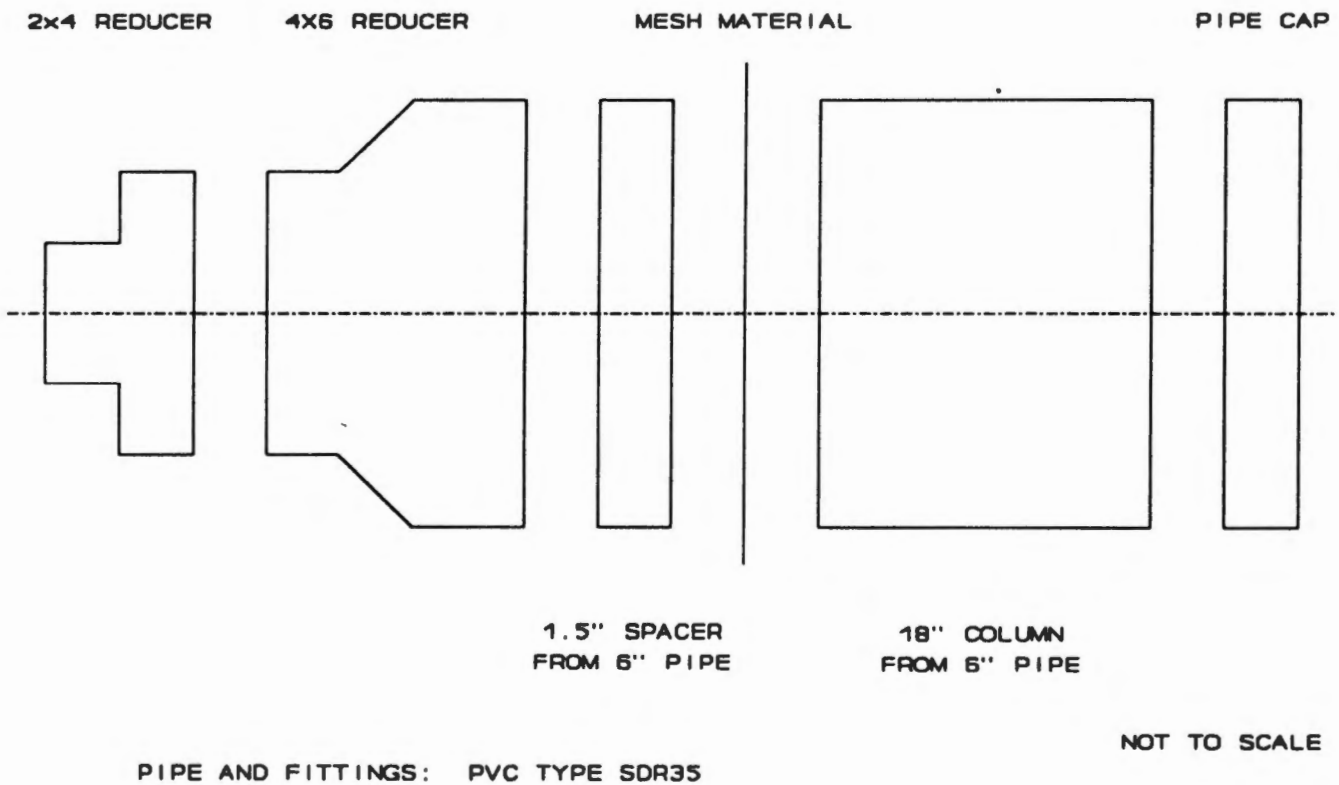


Figure 9. Exploded view of desiccant column

commonly marketed for use in clothing and sporting goods as a mosquito netting. The netting was cut oversized for the pipe diameter and the column components were "force-fit" assembled. Pipe cement was not used, so the mesh screen could be replaced as necessary. The seams were sealed with tape to prevent air leakage. Columns were color and symbol coded to prevent accidental mixup while collecting data. Columns used on the airstream that passed over the drying surface were color coded blue. Those columns used on the airstream that passed below the drying surface were color coded green. Pairs of columns (on-line simultaneously) were identified by large plus or minus symbols on the side of the container. PVC pipe caps (six inch) were placed over the columns when they were not in use and formed an airtight seal.

The desiccant columns were plumbed and coded according to Figure 10. The valves were two-inch, PVC on/off type ball valves (Haywood Industrial Products, Inc., Elizabeth, NJ). Valves to be turned simultaneously were located side by side to facilitate hand actuation. The desiccant chamber's two-inch opening fit snugly into two-inch rubber, Quick Ell's (Part number QL 200, Fernco, Inc.) to form an airtight seal without clamping. Removal, weighing and replacement of columns were simple.

The optimum air-flow rate through the desiccant columns was found by forcing air at varying flow rates through two, three and six inch diameter pipes (PVC type SDR 35), each filled with 1.0 kg of desiccant. The six-inch pipe worked the best for the flow range requirement (0.3-0.5 kg dry air per minure)

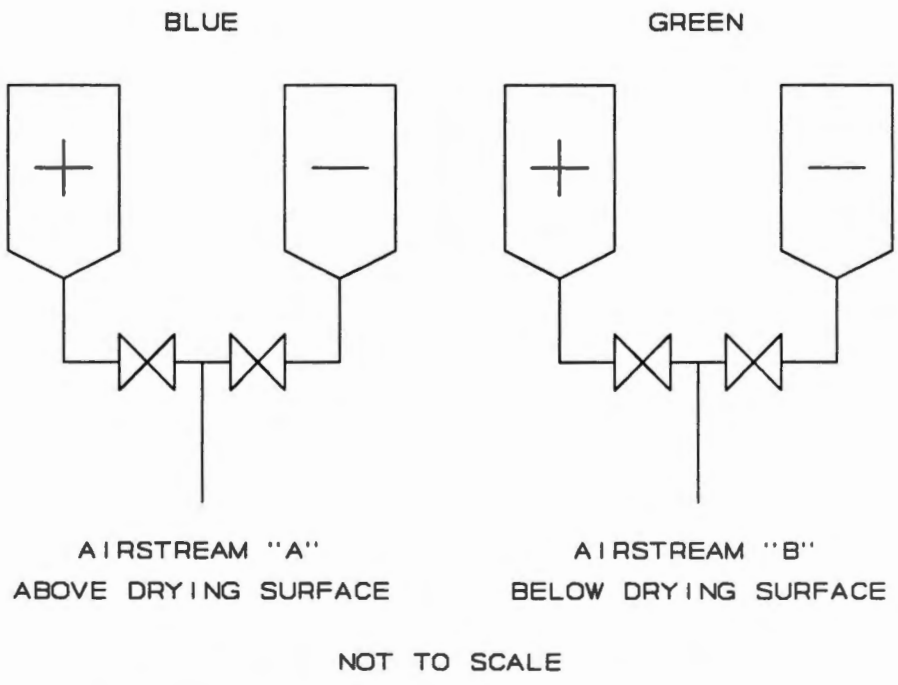


Figure 10. Desiccant column plumbing and coding

and had a fairly low head loss of about 0.25 inches of water. The desiccant beads were slightly fluidized at the highest flow rate, but did not blow out of the container.

A preliminary performance test was conducted to determine if the desiccant could absorb all of the moisture from the air as it was forced through the column in the specified flow range. Warm, humid, room air at known conditions (wet and dry bulb temperatures) was blown through the columns using the previously described fan and a system of PVC piping. The columns were periodically removed from the piping system and weighed to determine

moisture absorption. An orifice plate and differential pressure cell (described earlier in this chapter) were used to measure the air flow rate. Air conditions were measured using a portable psychrometer (model 566, Bendix Environmental and Process Instruments Div., Baltimore, MD). A comparison of the mass rate of moisture accumulation in the columns versus the calculated mass rate of moisture accumulation was made.

3.2 DATA COLLECTION

This section describes the data collection system, instrument usage and location. Data collected during thin film drying experiments consisted of time, temperature, pressure, volume and weight measurements. Most of the temperatures were logged automatically and all other information was recorded by hand. A form was developed to aid in the manual data collection process. A copy of the form is given in Appendix A (Data Collection Procedure).

3.2.1 Temperature Data

Air temperatures (except those measured by the psychrometer) were monitored by type T thermocouples connected to a portable data logger (model 21X, Campbell Scientific, Inc., Logan, UT). Locations of the thermocouples are given in Table 5. The data logger stored temperatures sensed by each

TABLE 5. Thermocouple number and location

THERMOCOUPLE NUMBER	LOCATION
1	Discharge air stream of the dehumidifier
2	Inlet air stream A (above the drying surface) of the drying chamber
3	Inlet air stream B (below the drying surface) of the drying chamber
4	Drying surface
5	Discharge air stream A from the drying chamber
6	Discharge air steam B from the drying chamber

thermocouple at 30 second intervals. A laptop computer (model ZWL-183-93, Zenith Data Systems, Inc.) connected to the data logger displayed the temperatures. After an experiment was completed, the temperature data set was downloaded from the data logger to the laptop computer and copied to a portable diskette for storage and subsequent analysis. The thermocouples were calibrated using ice and boiling water baths and were found to have an accuracy of ± 0.5°C.

Thermocouples sensing air temperatures were positioned at the center of the air stream. A small hole was drilled in the wall of the PVC pipe through which the thermocouple was inserted. Air leaks around the hole were sealed with putty. The tip of the thermocouple number four (used to sense the temperature of the drying surface) was pressed against the drying surface under spring tension to assure good contact. The thermocouple's tip was insulated with a layer of silicone-rubber sealant so that only the terminus was

exposed. During each experimental run, thermocouple number four was positioned after the product film was applied to the drying surface.

The portable psychrometer was positioned near the inlet of the fan to measure room dry and wet bulb temperatures. Distilled water was used to wet the sock covering the wet bulb thermometer. Temperature of the liquid starch slurry was measured with a mercury-filled, partial immersion type thermometer (Ertco model ASTM 1C, Baxter Scientific Products, McGraw Park, IL).

3.2.2 Pressure Data

Absolute pressure and differential pressure were monitored using two manometers (model 400, F.W. Dwyer Mfg. Co., Michigan City, IN), tygon tubing with valves and pressure taps. The pressure taps were threaded into the PVC components of the system. Pressure taps for the orifice plates were installed on the flange connections holding each orifice. Plastic valves attached to the tygon tubing made it convenient to monitor several pressure differentials using the same manometer cell. Table 6 gives the description of each pressure measurement including the location where it was taken.

3.2.3 Product Data

Products dried were corn, rice and potato starch. The corn starch powder (lot number DF27861) was provided by the A.E. Staley Mfg. Co. (Decatur, IL). Rice starch slurry came from the reconstituted flakes of Gerber®

TABLE 6. Description of pressure measurements

MEASUREMENT NUMBER	DESCRIPTION "Pressure difference . . ."
1	across the valve at the inlet air stream A (above the drying surface) of the drying chamber
2	between air stream B (below the drying surface) at the inlet to the drying chamber and the atmosphere
3	between air stream A inside the drying chamber and the atmosphere
4	between the inlet and the outlet of air stream B of the drying chamber
5	across the valve at the discharge of air stream A from the drying chamber
6	across the flow measurement orifice on airstream A
7	across the flow measurement orifice on airstream B

brand rice cereal for babies. The potato starch slurry was similarly made by reconstituting flakes of Hungry Jack® brand mashed potatoes. Acid modified corn starch, rice cereal and mashed potato flakes are examples of products that are commercially dried using thin film techniques.

3.3 PROCEDURE

Step by step instructions for the data collection procedure are given in Appendix A (Data Collection Procedure). Experiments were conducted on relatively cool, dry (below 25°C and 60% relative humidity) occasions to maximize air dehumidification. The system was "warmed up" for not less than

1.5 hours before any run to insure steady-state operating conditions. Desiccant columns were "warmed up" for five minutes by placing them on line just before the application of product slurry to the drying surface. The columns were weighed in four minute intervals determined by a timer that displayed minutes in 100ths (cat. no. 69235, Precision Scientific Company).

Slurries of each product were made by adding hot, distilled water to the dry flakes or powder. Sulfuric acid was used to modify the corn starch by decreasing the pH of a hot slurry to less than 3.0. The pH of the slurry was ascertained using paper indicator strips (catalog no. P1119-5A, Baxter Scientific Products, McGraw Park, IL). Acidified slurry was cooked for a minimum of five minutes before application to the drying surface.

Product application to the drying surface was accomplished by pouring a quantity of the product slurry directly onto the drying surface. A wallcovering smoother (model 498 flex, Warner Mfg. Co., Minneapolis, MN) was used to spread the product into a thin film. Opposite ends of the smoother rested on two stainless steel shims measuring 13 x 280 x 01.6 mm. The shims were positioned along the two edges of the drying surface parallel to the air flow. A smooth, uniform product film was formed. The individual film thicknesses varied from experiment to experiment according to the consistency of the starch film, the presence of lumps and the spreadability of the slurry. The shim thickness could be doubled when necessary to cope with variations in starch.

Moisture content of the product was measured before and after drying. The moisture content (wet basis) was determined using the procedure given by the American Society of Agricultural Engineers (1985) in standard number S358.1. Samples were desiccated in an oven (model Imperial IV, Lab-Line Instruments, Inc., Melrose Park, IL) at 60°C until they reached equilibrium. The density of the liquid material (before drying) was determined by pouring it into a tared, 100 ml graduate. The graduate was then weighed and the result recorded.

A summary of the data collection procedure follows.

1. The system was "warmed up" and prepared for operation.
2. Separate air stream pressures (A and B) through the drying chamber were balanced.
3. Starch slurry was mixed, sampled and prepared for drying.
4. Desiccant columns were warmed for use.
5. The drying system was turned off and a starch film was quickly applied to the drying surface and the lexan cover was installed.
6. The dryer was restarted and the drying sequence initialized.
7. Weights of desiccant columns were recorded every four minutes, for 56 minutes during drying.
8. After completion of step seven, a film sample was immediately removed from the drying surface to find the moisture content.
9. The desiccant was regenerated in preparation for the next run.

3.3.1 Single-Side Drying

Rice starch was used as a representative material for the single-side drying test. Single-side drying means, in the present case, that moisture can only dry from a single face of a thin film. Single-side drying was accomplished experimentally by placing a piece of heavy gauge aluminum foil over the vapor-permeable drying surface and sealing it around the edges with masking tape. The foil prevented moisture from diffusing through the drying surface and the masking tape prevented air leakage. The purpose of the single-side drying test was two-fold: first, it allowed a rough comparison between the traditional, single-sided, thin-film drying methods and the proposed water-vapor permeable drying surface; second, it provided an additional opportunity to check the operation of the desiccant columns.

Now faith is being sure of what we hope for and certain of what we do not see. This is what the ancients were commended for.
Heb 11: 1,2 (NIV)

CHAPTER 4

RESULTS AND DISCUSSION

Results of experiments and a discussion of the results are presented in this chapter. The first section summarizes selected data. The second section presents results of tests conducted to evaluate the usefulness of the desiccant columns and to verify the operation of the thin film drying system. Section three reports the drying behavior of modified corn, potato and rice starch. The final section gives results of the mathematical model with a comparison to experimental drying curves of the same three starches.

4.1 DATA

Three types of starch were dried in a total of four experiments that were carried out during the following four days in September, 1993: 22, 27, ,28 and 29. Statistics describing some of the observed data are given in Table 7 to

Table 7. Statistics describing some of the observed data for all observations

Description of Observation	number of obs.	Value mean	max	min	± std. dev.
1. Ambient air temperature, C					
a. dry bulb	4	24.65	26.50	23.60	1.29
b. wet bulb	4	15.44	17.50	13.25	1.78
2. Air temperature, dryer inlet, C					
a. above dryer surface	452	43.66	47.39	36.19	2.10
b. below dryer surface	452	47.50	52.00	37.60	2.40
3. Air temperature difference between inlet and outlet, C					
a. above dryer surface	452	5.11	7.34	-1.73	1.18
b. below dryer surface	452	9.33	14.29	-3.50	1.94
4. Air flow rate, kg/min					
a. above drying surface	56	0.43	0.51	0.40	0.03
b. below drying surface	56	0.36	0.40	0.33	0.02
5. Measured moisture dried from film, g/ 4 min					
a. above drying surface	56	2.89	6.22	-0.68	1.57
b. below drying surface	42	3.12	5.30	1.20	0.86
6. Calculated moisture in dehumidifier dis. air, g/ 4 min					
a. above drying surface	56	5.87	9.47	3.05	1.56
b. below drying surface	56	4.97	8.22	2.50	1.55
7. Initial moisture content (wb) of starch films	4	74.10	82.00	67.20	6.16
8. Final moisture content (wb) of starch films	4	45.60	66.10	15.30	24.9

provide an overview of the experimental data and conditions.

The air temperature at the dryer chamber inlet below the dryer surface was usually slightly higher than the air temperature at the chamber inlet above the dryer surface. The flexible dryer hose leading to the inlet above the dryer surface was longer than the one leading to the inlet below the dryer surface. Despite insulation, the heat loss from the longer pipe resulted in a lower air temperature at the air inlet above the dryer surface. Air flow rates were normally lower for the air stream that passed below the drying surface. The lower rates were due to the smaller cross-sectional area for the flow path and the resistance of the porous, copper, battery anode.

4.2 DESICCANT COLUMNS

The design of the desiccant columns, which are used to absorb and measure the moisture dried from a thin film, was developed specifically for this study. A complete description of the desiccant columns, their construction, plumbing and use can be found in Chapter 3 (Design) of this work. Performance of the columns was evaluated in stages. Preliminary tests were conducted outside of the thin-film drying system. Final tests were performed with the columns installed as a part of the complete drying system.

4.2.1 Preliminary Desiccant Column Tests

A preliminary performance test was conducted to determine if the desiccant could absorb all of the moisture from air as the air was forced through the column in the specified flow range. The experimental setup is explained in Chapter 3 (Design). A comparison of the calculated and measured mass rate of moisture accumulation in the columns versus time is shown in Figure 11. Results indicated that the calculated and experimental values agreed closely, except for the first measurement set. A "warm up" period was needed before the columns could be used to collect accurate data. As a result of this test, a warm up period became a standard part of the data collection procedure (see Appendix A).

4.2.2 On-Line Desiccant Column Tests

The desiccant columns were tested on-line by using the complete thin-film drying system as described in the Design chapter of this work. The testing procedure was the same as the data collection procedure listed in Appendix A, except that product was not applied to the drying surface. The motions of applying the product to the drying surface were performed so the timing of the process would be the same. The results are given in Figure 12. Figure 12 shows that the results of the on-line desiccant test were excellent, except for the very first measurement set. The percent differences between predicted and measured moisture values were less than 2%. The 40 minute test consumed

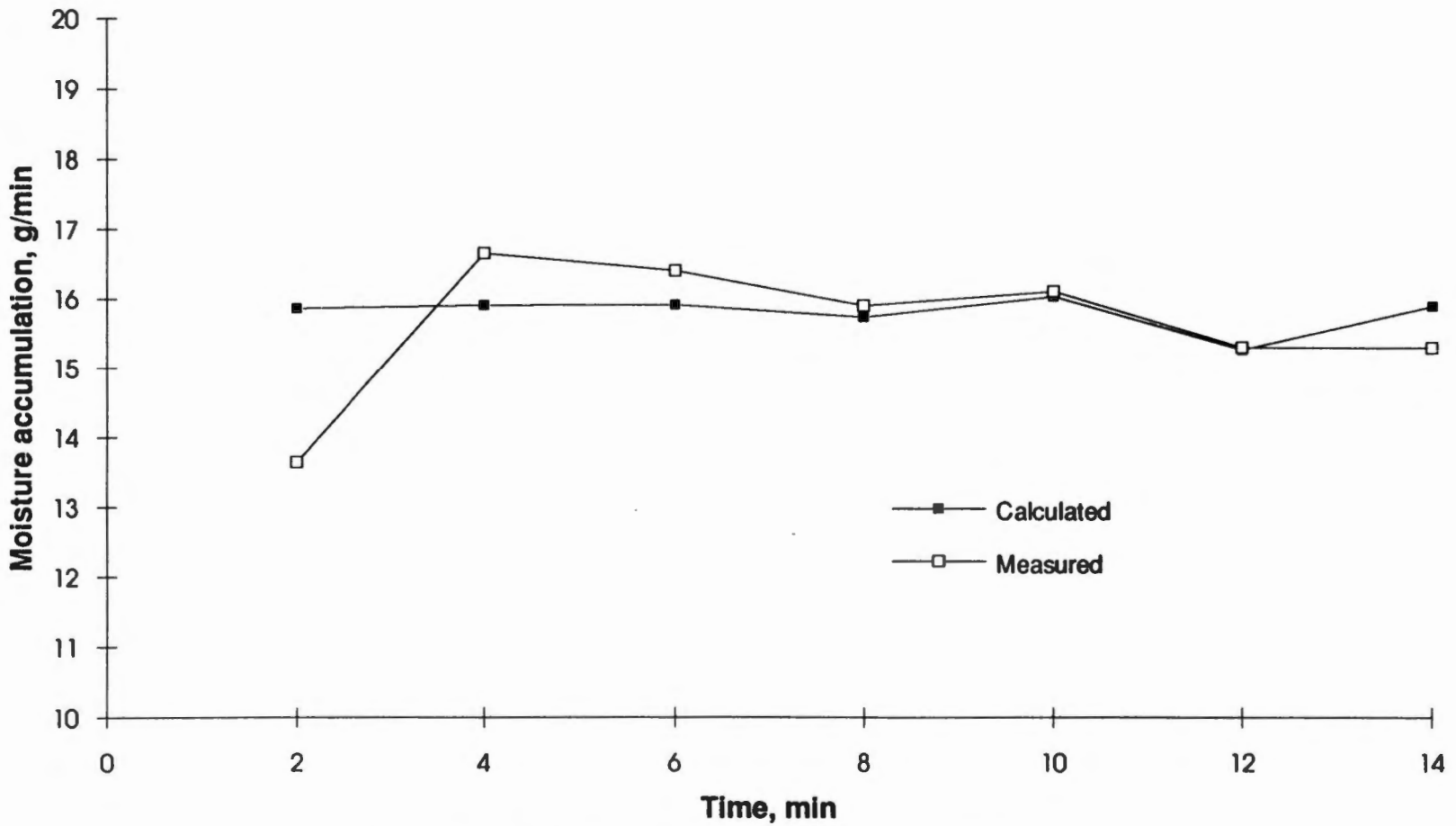


Figure 11. Rate of moisture accumulation in desiccant columns vrs. time for preliminary desiccator test.

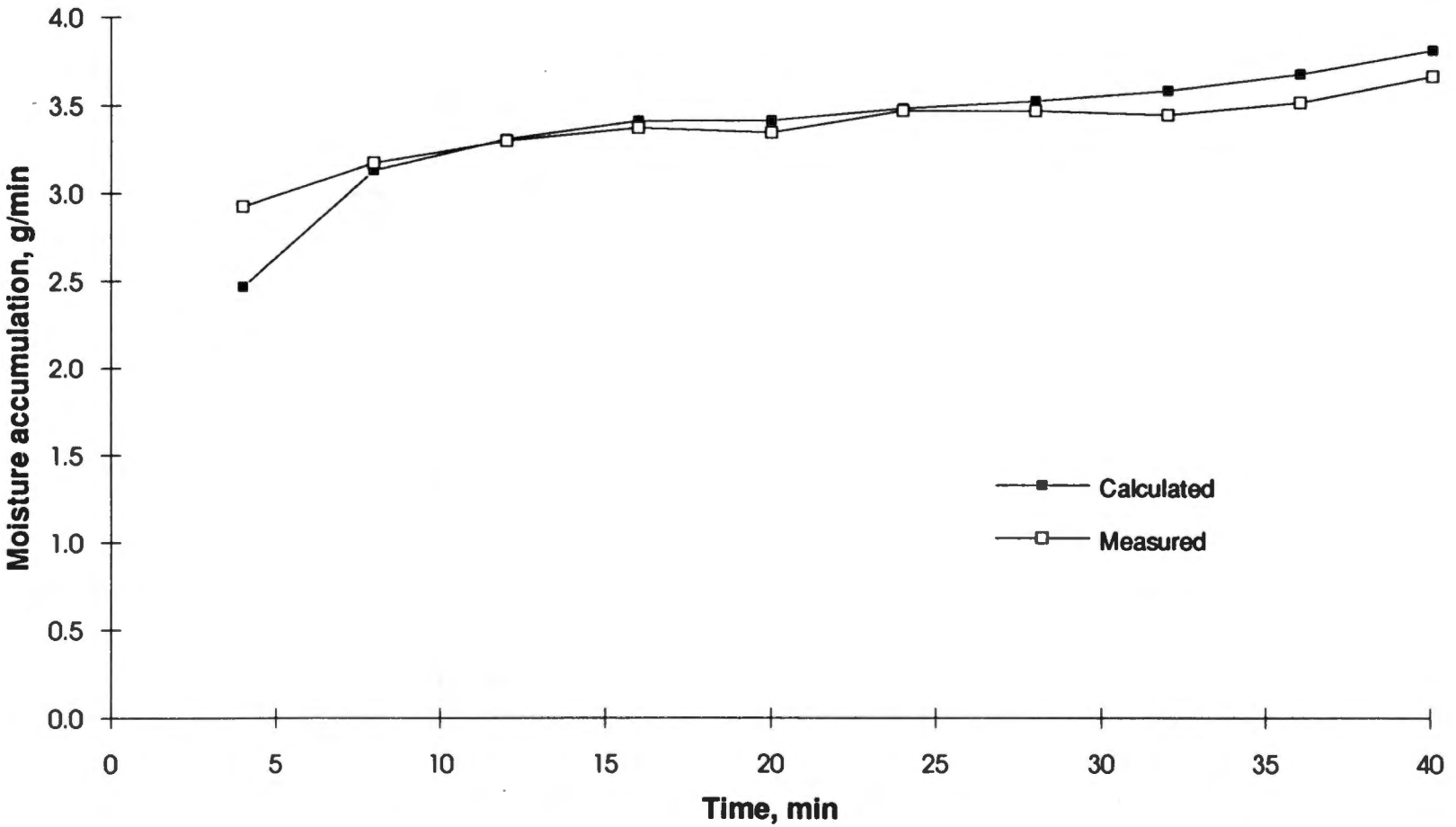


Figure 12. Rate of moisture accumulation in desiccant columns vrs. time for on line desiccator test

the useful moisture capacity of the desiccant columns.

The first measurement set was biased by approximately 1.0 gram of surplus moisture for each desiccant column. The bias probably resulted from the start-up procedure used for the drying system. The two columns selected to go on-line first were given lightweight paper lids during the period when the film was applied to the drying surface. The paper lids blew off the columns when the fan was started, saving the time of removing lids when the drying system was started. Apparently the paper lids are not moisture proof. As a correction for this start-up phenomena, 1.0 gram of water has been subtracted from the first mass measurement sets of all subsequent data collected.

4.3 SINGLE-SIDE DRYING

Rice starch was used as a representative material for the single-side drying test. Results of the test are shown in Figure 13. The three curves represent the moisture accumulated in each of the two individual desiccant columns and the total moisture accumulated in the two desiccant columns. One desiccant column dried the air that flowed above the drying surface and the other dried the air that passed below the drying surface. Figure 13 clearly indicates that the desiccant columns were working properly and that there was no significant mixing between the two air streams. Figure 13 also implies that a

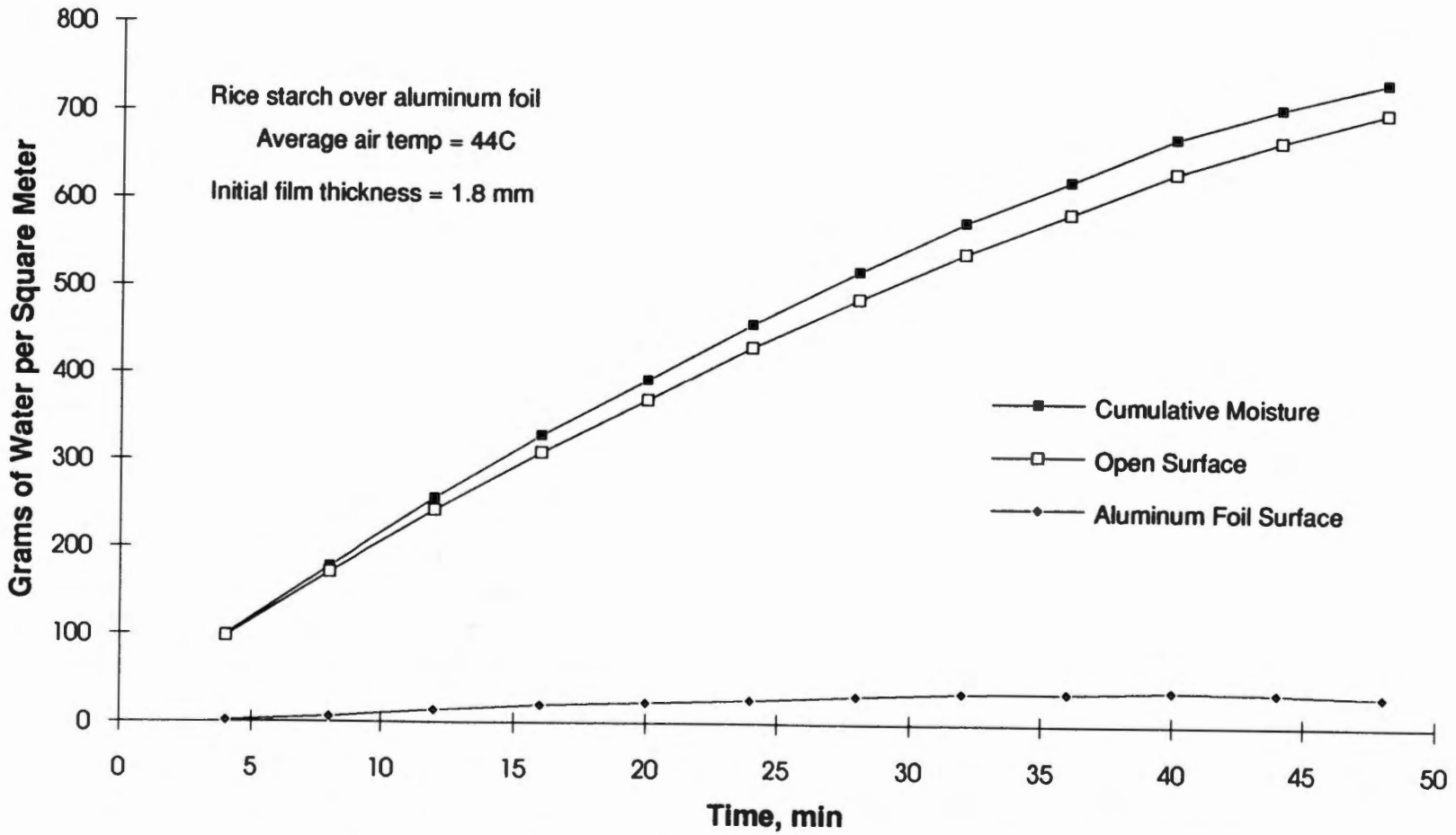


Figure 13. Cumulative moisture dried from a rice starch film during a single side drying test

small amount of moisture was removed from the film through the aluminum foil drying surface. This amount of moisture is considered insignificant and likely results from experimental error, rather than diffusion through the aluminum foil. The average rate of moisture removal for the first twelve minutes of the single-side drying test was 12.3 grams per m^2 and 16.8 grams per m^2 at forty minutes. After forty minutes, the rate of moisture removal was too low to measure with the experimental desiccant system.

4.4 PERMEABLE DRYING SURFACE

Corn, potato and rice starch were dried on a water-vapor permeable drying surface using the materials and procedure outlined in Chapter 3 (Design). Figures 14, 15 and 16 give the cumulative moisture dried per unit surface area per minute for the corn, potato and rice starches respectively. As described in the previous section, the three curves in each figure represent the moisture accumulated in each of the two individual desiccant columns and the sum of the moisture accumulated in the two desiccant columns. One desiccant column dried the air that flowed above the drying surface and the other dried the air that passed below the drying surface. The average, initial starch-film thickness is given in each figure. The film thicknesses were not the same between starch films, due to the initial moisture content and physical

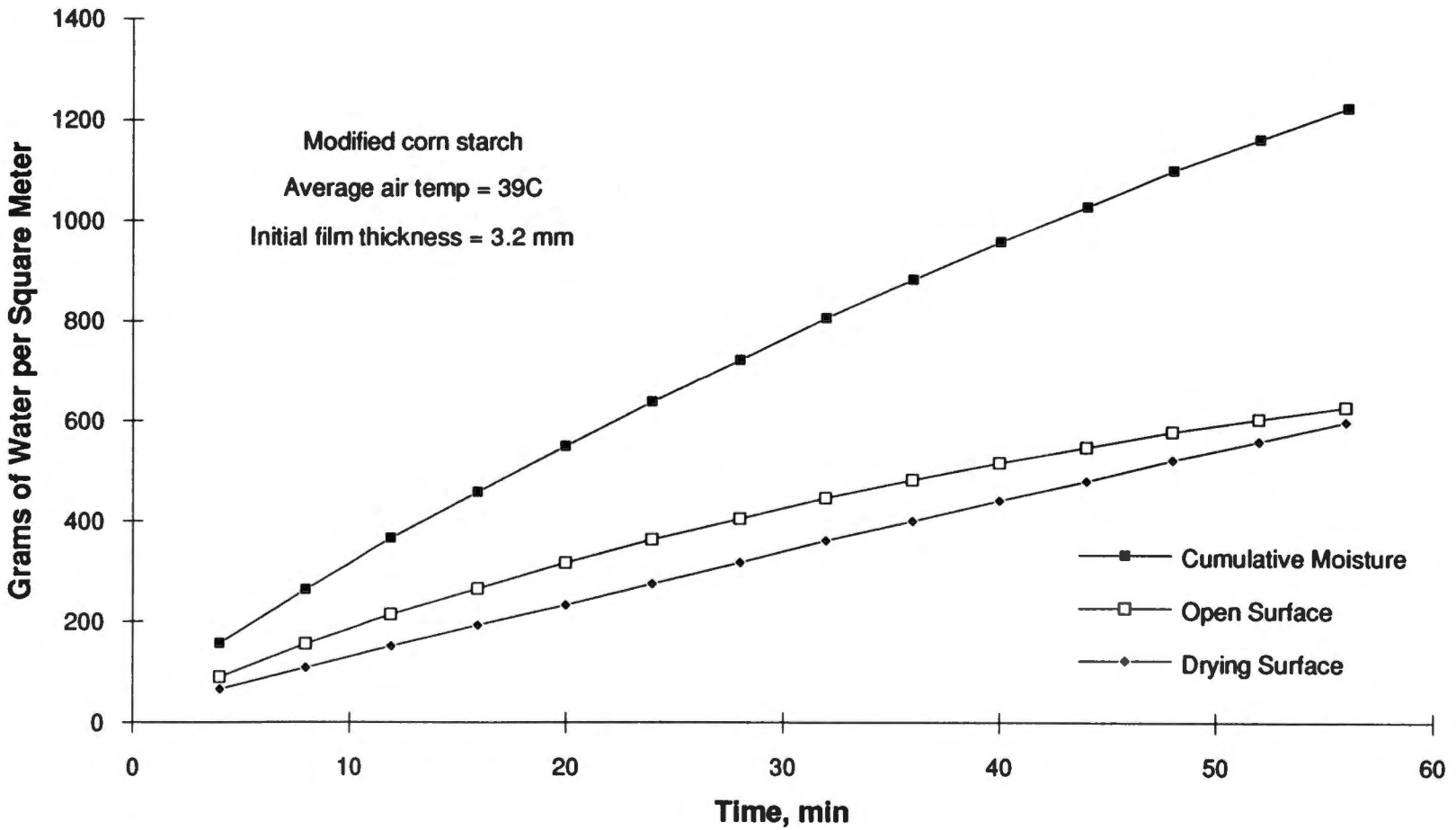


Figure 14. Cumulative moisture dried from a modified corn starch film

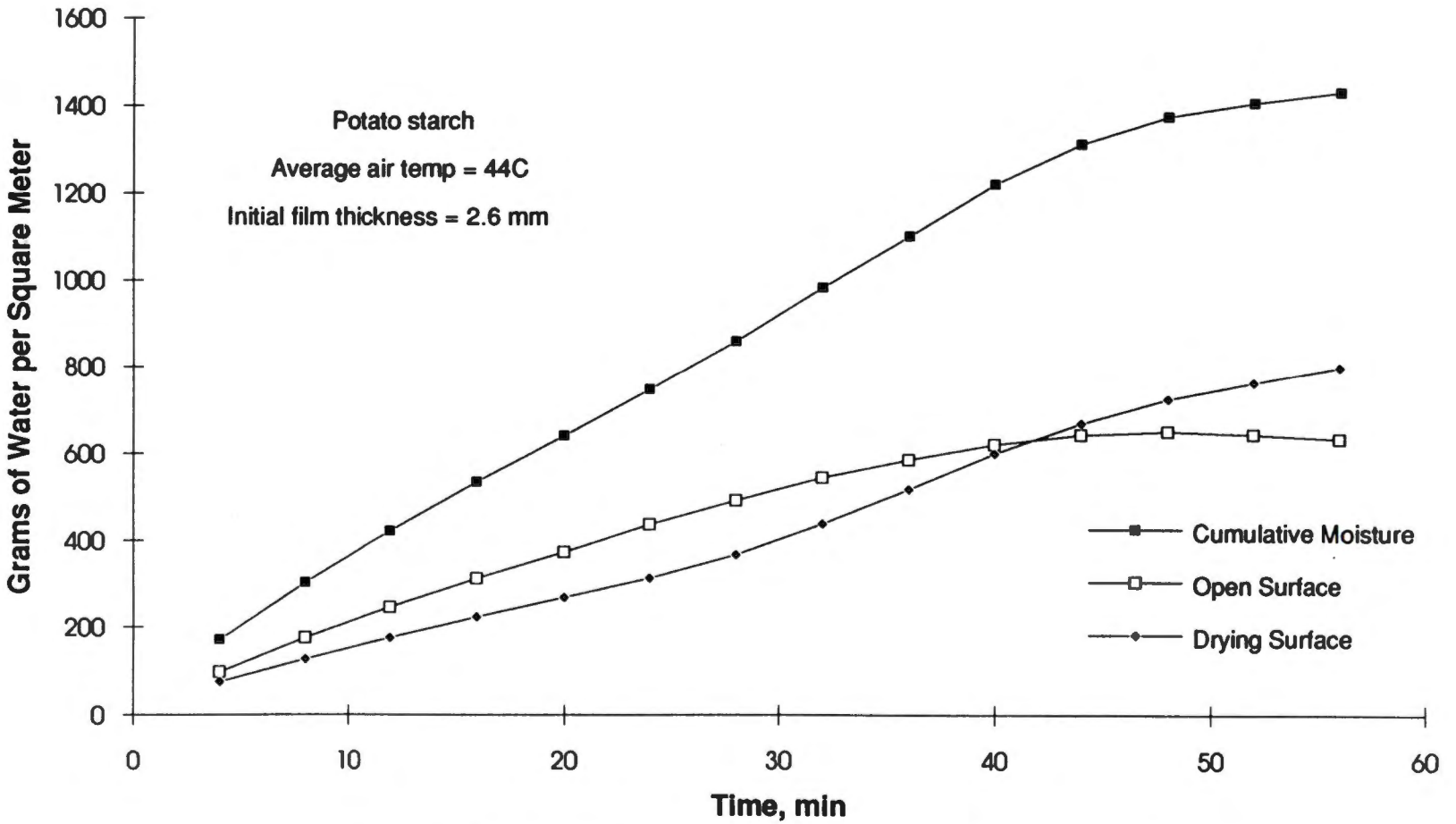


Figure 15. Cumulative moisture dried from a potato starch film

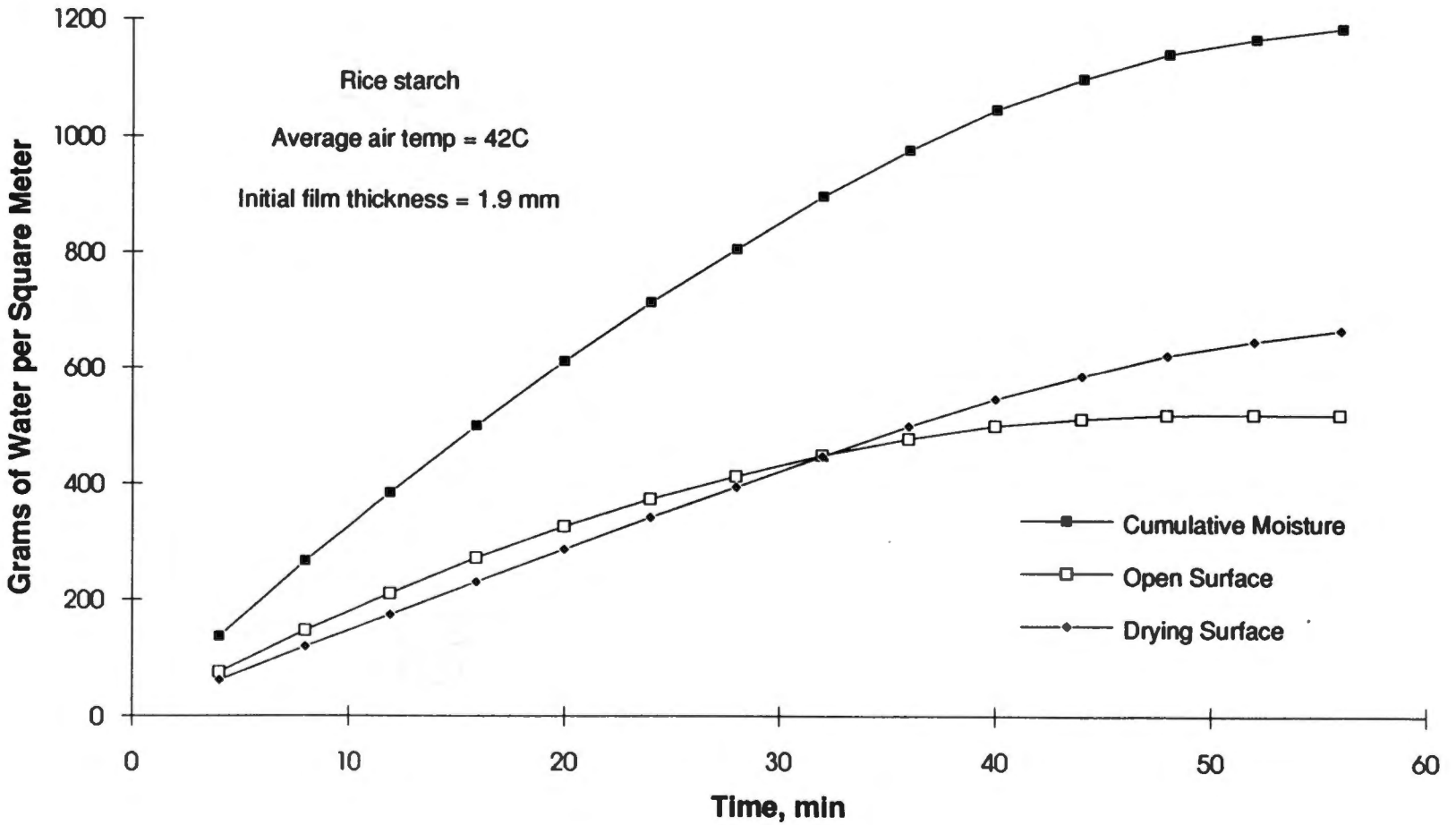


Figure 16. Cumulative moisture dried from a rice starch film

characteristics of each slurry. The average film thickness was determined using the measured density of the starch, the mass applied to the drying surface and the surface area covered by the film.

The individual desiccant column curves of Figures 14-16 indicate that the rates of mass transfer from the faces of each starch film are approximately equivalent. The water vapor permeable drying surface offered insignificant resistance to moisture vapor diffusion. The average rate of drying for the first twelve minutes for a rice starch film on the permeable surface is 32.0 grams per m^2, or a 50% increase over the rate of the single-side drying test. At forty minutes, the average drying rate is 28.6 grams per m^2, or a 70% increase over the rate of the single-side drying test. The comparisons made between the single-side drying test and the water-vapor permeable drying surface tests are not exact. The thickness and initial moisture content of the rice-starch films were slightly different: 1.8 mm and 72.3% for the single-side test and 1.9 mm and 67.2% for the water-vapor permeable drying surface test.

4.5 MATH MODEL

A theoretical model based on the simultaneous solution of partial differential equations for moisture and heat diffusion and an axial force member shrinkage integral was developed in Chapter 2 (Theory). The model was

formulated using the finite element method and implemented in the Pascal programming language (Version 7.0, Borland International, Inc., Scotts Valley, CA). The program was written specifically to run on a microcomputer under the Microsoft® Windows™ system. A complete listing of the program code (including comments and references for equations) can be found in Appendix C. The results of the model's predictions are compared to the experimentally determined drying curves of corn, potato and rice starch in Figures 17, 18 and 19 respectively.

Experimental drying curves were obtained by back calculating using the final measured moisture and solids content of the film (determined immediately after the drying experiment was completed) as a starting point. Moisture data collected from the desiccant columns was "added back" to the film moisture content in reverse order for each time step. Table 8 shows a comparison between the measured end points of the drying curves, the experimentally determined endpoints and the predicted endpoints. Measured data comes from samples of the initial starch slurry and the final film (after the drying period) that were weighed before and after they were dried in the desiccation chamber. The results show good agreement between the measured, experimental and predicted endpoints of the curves.

The mathematical model gives a good approximation of the experimental drying curve for each starch film. Initial, steep descent of the predicted drying curve is a result of high water vapor pressure at the surfaces of the film. The

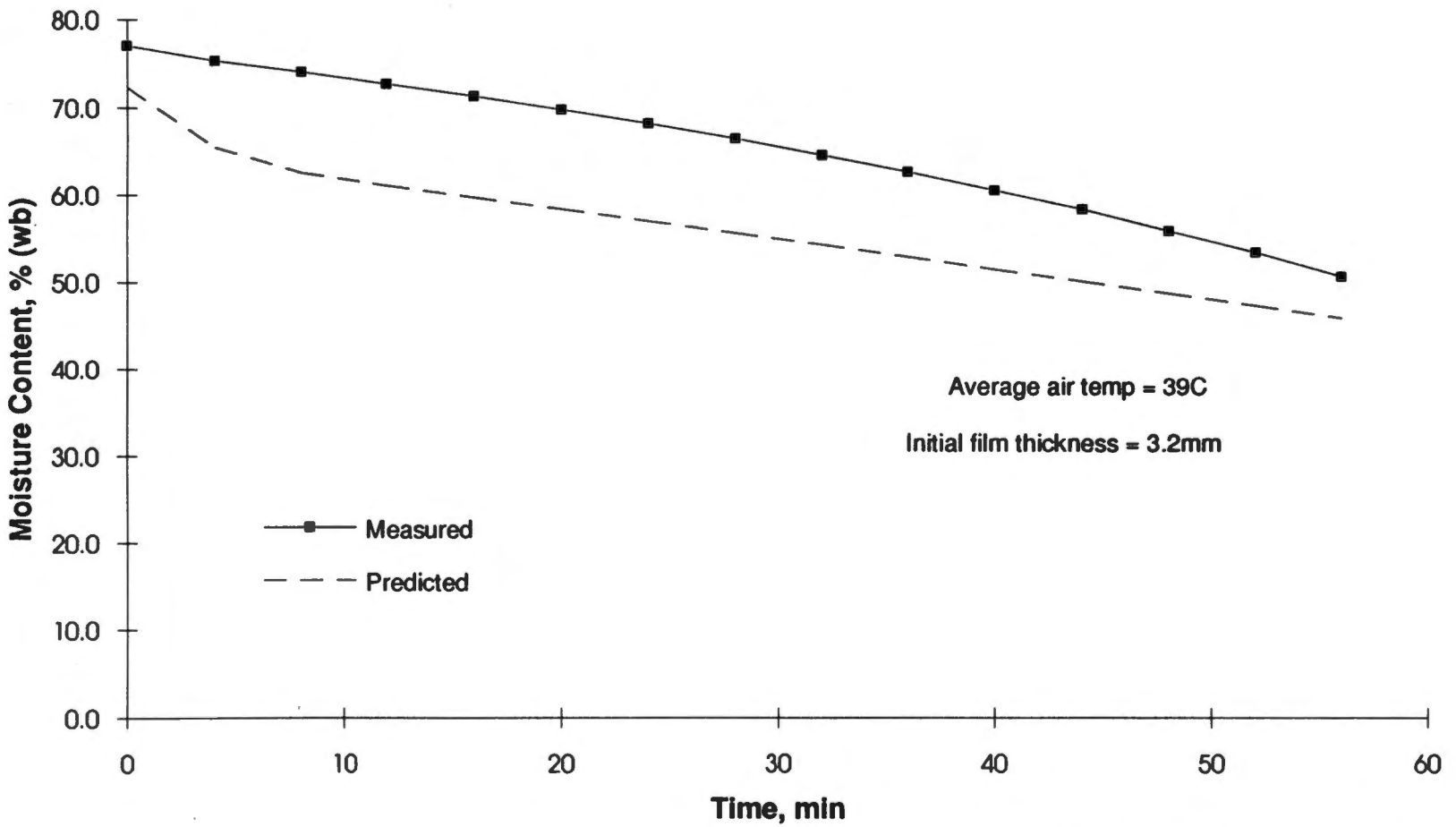


Figure 17. Predicted and measured drying curves for modified corn starch

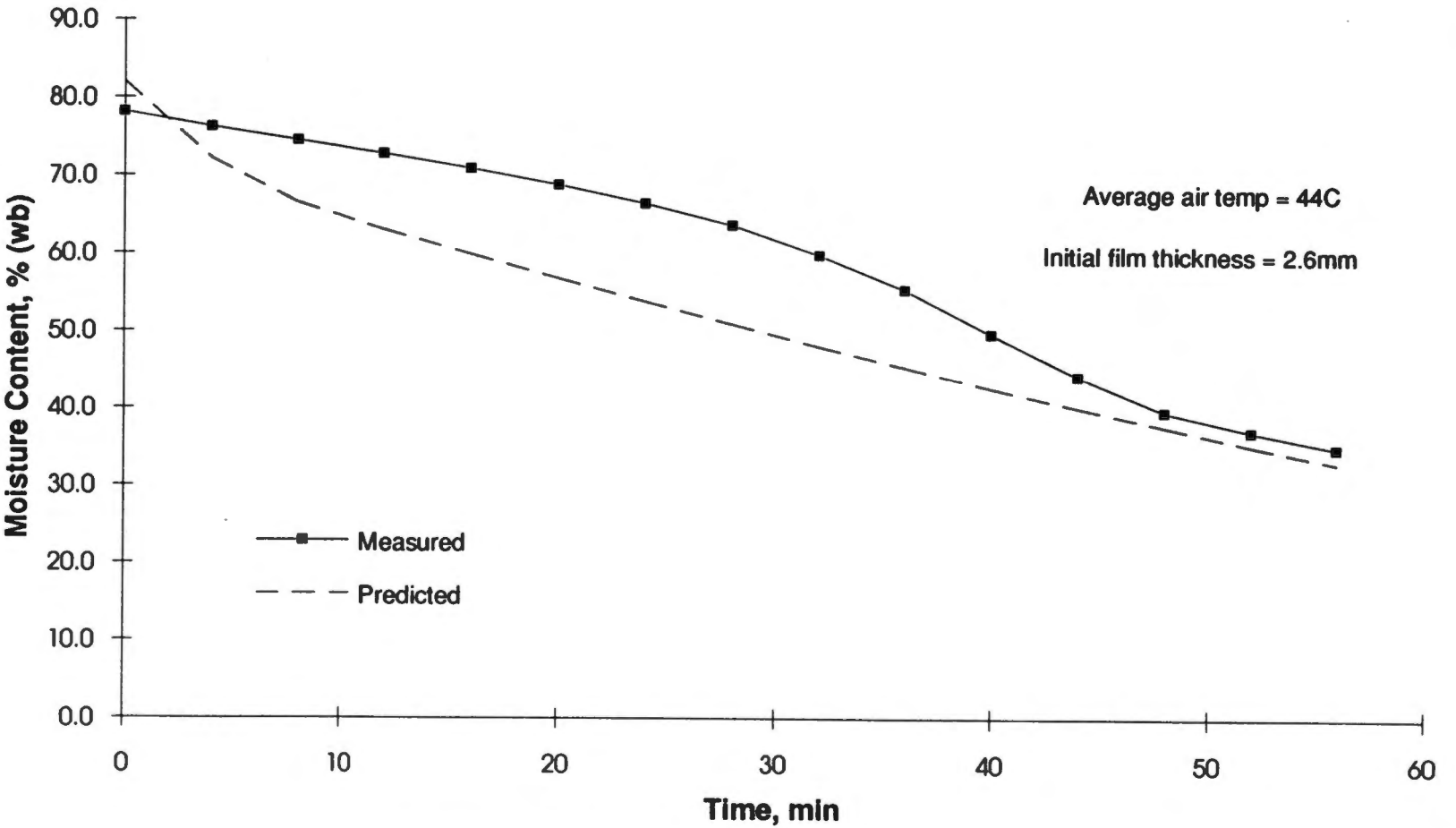


Figure 18. Predicted and measured drying curves for potato starch

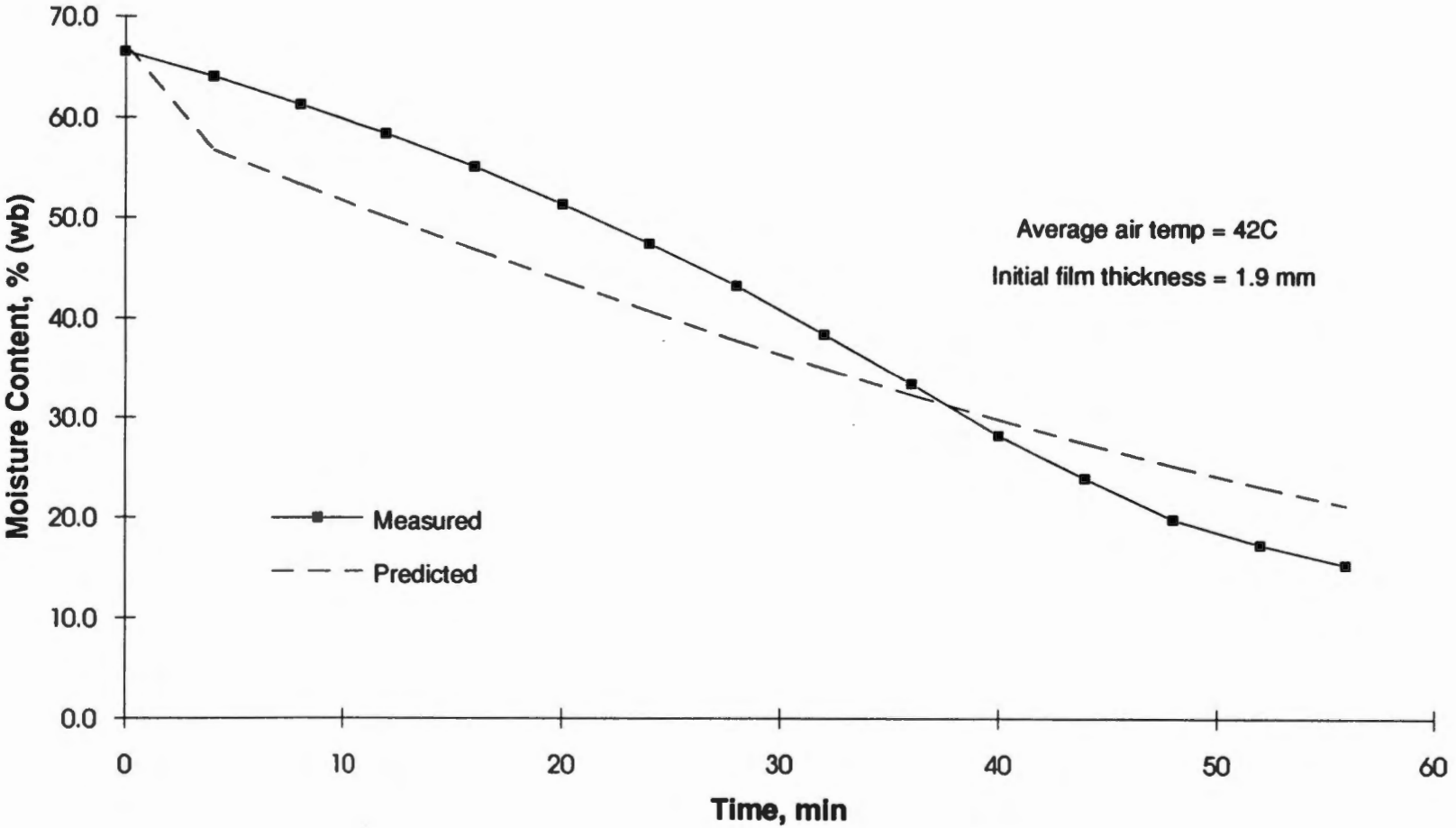


Figure 19. Predicted and measured drying curves for rice starch

Table 8. Comparison between measured, experimental and predicted endpoints of drying curves for three starches.

Starch	Initial moisture content, %(wb)	Final moisture content, %(wb)
modified corn:		
measured[1]	72.3	65.9
experimental[2]	77.0	50.7
predicted[3]	72.3	46.0
potato:		
measured	82.0	34.9
experimental	78.1	34.9
predicted	82.0	33.0
rice:		
measured	67.2	15.3
experimental	66.5	15.3
predicted	67.2	21.2

[1] Values obtained by oven desiccation of starch samples
[2] Obtained by back-calculating using the final measured moisture content of the film as a starting point and "adding back" moisture measured using the desiccant columns.
[3] Predicted by the theoretical model

predicted curve takes on a much shallower slope as the water vapor pressure at the surfaces begins to drop and the temperature of the film stabilizes.

Figure 20 shows the calculated values of moisture concentration and film thickness at indicated times for a rice starch film dried on the experimental, water-vapor permeable drying surface. The initial film and boundary conditions for the plot are taken as those obtained by measurement during the rice starch drying experiment (see Figure 19). Figure 20 is based upon output of the mathematical model.

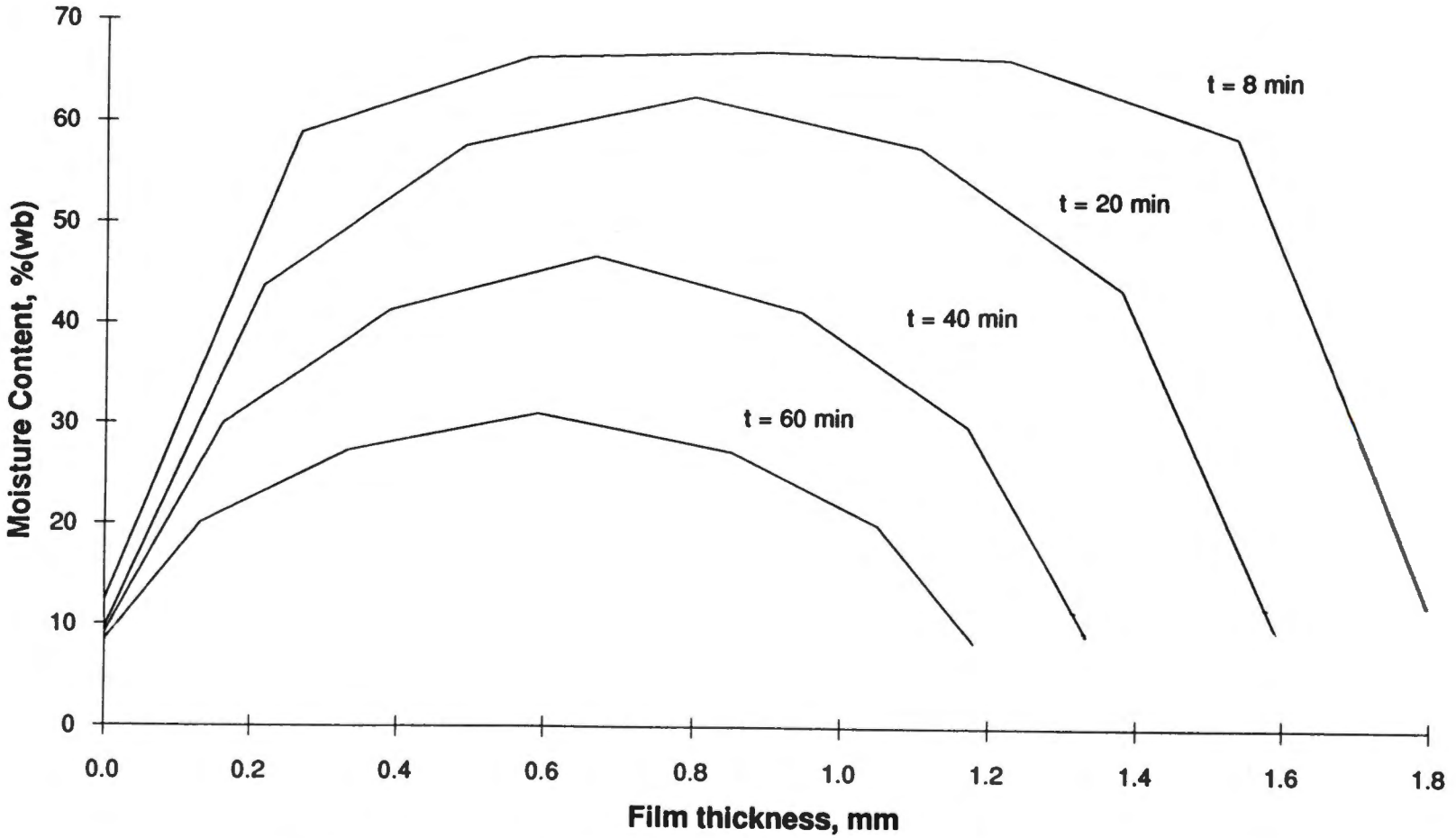


Figure 20. Predicted moisture distribution in a rice starch film during drying

Preach the word; be prepared in season and out of season; correct, rebuke, and encourage --with great patience and careful instruction. 2 Tim 4:2 (NIV)

CHAPTER 5

RECOMMENDATIONS

Feasibility of a water-vapor permeable drying surface (PDS) for thin films of solutions and colloidal slurries of modified corn, potato and rice starch has been evaluated using a bench-top dryer. A mathematical model was developed and tested to predict the drying characteristics of the starch films. This section recommends improvements for the present experimental system and suggestions for follow-up studies. Recommendations are listed numerically, in no particular order, under the topics of "water-vapor permeable drying surface" and "mathematical model."

5.1 WATER-VAPOR PERMEABLE DRYING SURFACE

1. Examine alternate forms and application of heat sources. Steam, gas convection, microwave, radiant and electrical resistance are examples of heat sources that could be applied to evaporate water from a thin film. Some heat sources are not compatible with all PDS materials. For example, steam would not work in direct contact with a porous drying surface and microwaves are not compatible with most metallic drying surfaces.

2. Run tests at high drying temperatures. High drying temperatures were not possible with the experimental drying system, however, they are essential for short time, commercial drying. Film drying experiments at high temperature are necessary to more fully test the mathematical model and to make product quality comparisons between films dried on a PDS and traditional equipment.

3. Develop an energy budget for the PDS system. An energy budget of a drying system using a PDS must be determined for comparison to energy requirements of traditional film dryers.

4. Research opportunities for waste heat recovery. A PDS dryer provides great opportunities to capture waste heat of drying. The heat energy from the water vapor removed through the drying surface should be simple to recover, since the vapor is contained and may be forced through piping.

5. Test additional water-vapor permeable materials for use as drying surfaces. Some possibilities are given Chapter 1 (Literature Review) of this work.

6. Test additional release agents for the drying surface. Food grade release agents should be located and tested on the various drying surfaces as required. Some release agents (lecithin for example) may be added to the product or continuously sprayed on the drying surface and considered as an incidental ingredient or processing aid.

7. Construct and test a pilot size, permeable surface dryer. The pilot sized dryer would facilitate continuous production testing of the drying surface. A pilot dryer, if designed properly, would allow direct comparison to pilot scale, traditional film dryers.

5.2 MATHEMATICAL MODEL

1. Develop the model to conform to more flexible dryer characteristics. Dryer characteristics include: type and application of heat source (constant temperature nodes and heat flux boundaries for example), geometry and type of drying surface material.

2. Improve the shrinkage section of the model. The solution of the film shrinkage equations requires a more generalized method to be compatible with

drying parameters other than those encountered during the experimental tests. The present shrinkage model works only when the film is drying equally from both faces. In the case of equal face drying, the film shrinks evenly towards the center node, or "zero shrinkage node." When an unequal drying rate is present, the zero shrinkage node must be identified in the film profile and the shrinkage calculated around it.

3. Include physical properties of the specific starch in the model. Physical properties of starch obtained from the literature may not accurately describe every type of starch. The critical physical properties of each unique material should be determined and included in the model to achieve optimum results.

4. Improve the format of the model output. Currently the model output is limited to nodal and element values such as temperature, moisture content and length. A selection from a menu of two and three dimensional plots using these values is desirable.

And he said to them, "Therefore every scribe who has been trained for the kingdom of heaven is like a householder who brings out of his treasure what is new and what is old."
Matt 13:52 (RSV)

CHAPTER 6

CONCLUSIONS

Conclusions are arranged in numerical order corresponding to the objectives given in the introduction.

1. A new drying technique for thin films of colloidal slurries and solutions has been proposed and evaluated. Preliminary tests show that a water-vapor permeable drying surface (PDS) may be an attractive alternative to traditional thin film drying methods. A review of the literature has uncovered many materials that may be used as a PDS in commercial applications. The average moisture removal rate for a rice starch film increased over 50% when dried on a PDS compared to a non-permeable surface.

The advantage of the new drying method is twofold. First the process of dehydration is much faster than traditional methods. The faster drying speed allows greater production rates for the same drying surface area. Second, the quality of the final product may be improved since evaporation from both faces of the film reduces the temperature of the film solids. Energy savings, a third possible advantage, remain undetermined in this study.

2. A practical mathematical model has been developed to describe the heat and mass transfer of the proposed system. Physical properties of starch including moisture diffusivity, heat of sorption, modulus of elasticity, bulk shrinkage, water activity, thermal diffusivity and others have been taken directly from the literature and used in the model. A menu driven system allows the user to input film and drying system parameters to the model. The model is written to operate on any computer capable of running Pascal.

3. A bench top representation of the proposed drying system was constructed to test the mathematical model. The bench top dryer was designed and instrumented to collect data used to determine experimental drying curves for starch films. The experimentally determined drying curves were accurate when compared to known endpoints of the curves.

4. Four experiments, using three types of starch films dried on a PDS, were conducted. Feasibility of a PDS for thin films was verified. The porous, stainless steel material, used as the drying surface proved to be rugged, had good heat conduction capability and was low cost and available from stock.

The PDS gave no measurable resistance to water evaporation. When treated with a silicone emulsion, the drying surface gave good product release. The pores of the drying surface did not clog noticeably.

The mathematical model accurately predicted the drying curves for thin films of modified corn, potato and rice starch at varying film thicknesses, initial moisture content and drying temperatures. A graph showing film properties of moisture content and thickness at specific times was generated from model output for discussion purposes. The technique is very powerful for explaining the complicated relationships between temperature, moisture and thickness of the drying film. The model successfully ran on a an IBM compatible, 486-based microcomputer. A math coprocessor is highly desirable to reduce iteration time.

LIST OF REFERENCES

LIST OF REFERENCES

American Society of Agricultural Engineers. 1985. Agricultural engineers yearbook of standards. The American Society of Agricultural Engineers, Michigan.

American Society of Agricultural Engineers. 1990. Agricultural engineers yearbook of standards. The American Society of Agricultural Engineers, Michigan.

American Society of Mechanical Engineers. 1959. Power test codes, chapter 4, flow measurement. The American Society of Mechanical Engineers, New York.

American Society of Mechanical Engineers. 1963. Flowmeter computation handbook. The American Society of Mechanical Engineers, New York.

Asselberys, E.A.M., H.A. Hamilton and P. Saldala. 1961. Preparation of dehydrated, cooked potatoes. Can. Pat. 620541, May 23.

Bekaert Steel Wire Corp. 1989. Bekaert fibre technologies, porous media supplier; sales brochure. Bekaert Steel Wire Corp., Georgia.

Bell, K.J. 1983. Heat exchanger criterion, In: Heat exchanger design handbook, ch. 3.1.3, E.U. Schlunder (editor), Hemisphere Publishing Co., New York.

Bencini, M.C. 1986. Functional properties of drum dried chickpea (Cicerarietinum L.) flours. Journal of Food Science, 51(6): 1518-1521.

Bhave, R.R. and H.L. Fleming (ed.). 1988. Removal of oily contaminants in wastewater with microporous alumina membranes. AIChE Symposium Series. Number 261, Vol. 84. American Institute of Chemical Engineers, New York.

Bhave, R.R. 1991. Inorganic membranes, synthesis, characteristics and applications. Van Nostrand Reinhold, New York.

Bird, R.B., W.E. Stewart and E.N. Lightfoot. 1960. Transport phenomena. John Wiley and Sons, New York.

Boquet, R., J. Chirife and H.A. Iglesias. 1978. Equations for fitting water sorption isotherms of foods II. Evaluation of various two-parameter models. Journal of Food Technology, 13: 319-327.

Braddock, R.J. 1983. Utilization of citrus juice vesicle and peel fiber. Food Technology, 37(12): 85-87.

Brekke, J.E. and W.F. Talburt. 1950. Preparation of fig powder. U.S. Dept. Agr., Bur. Agr. Ind. Chem., AIC-283.

Brooker, D.G. 1967. Mathematical model of the psychrometric chart. Transactions of the American Society of Agricultural Engineers 10(4): 558-560, 563.

Brubaker, D.W. and K. Kammermeyer. 1952. Separation of gases by means of permeable membranes. Industrial Engineering Chemistry, 44: 1465-1467.

Bruin, S. 1969. Calculation of temperature and moisture distributions during contact drying of a sheet of moist material. International Journal of Heat and Mass Tránsfer, 12: 45-59.

Bruin, S. and K.Ch.A.M. Luyben. 1990. Drying of food materials: a review of recent developments. In: Advances in drying, A.S. Mujumdar (editor), Marcell Dekker, Inc., New York.

Callahan, P.T., K.W. Jolley, J. Lelievre and R.B.K. Wong. 1983. Nuclear magnetic resonance studies of wheat starch pastes. Journal of Colloid and Interface Science, 92(2): 332-337.

Chirife, J. 1983. Fundamentals of the drying mechanism during air dehydration of foods. In: Advances of drying, vol. 2 ch. 3, A.S. Mujumdar (editor), Hemisphere Pub., Washington, DC.

Chirife, J., H.A. Iglesias and R.A. Boquet. 1977. Some characteristics of the heat of water vapor sorption in dried foodstuffs. Journal of Food Technology. 12: 605-613.

Cording, J.Jr., M.J. Willaard Jr., R.K.Eskew and P.W. Edwards. 1954. Potato flakes, a new form of dehydrated mashed potatoes I. Pilot plant processes using double drum drier. USDA Agr. Res. Serv. AR 73-2.

Cording, J.Jr., M.J. Willaard Jr., R.K. Eskew and P.W. Edwards. 1955. Potato flakes, a new form of dehydrated mashed potatoes II. Some factors influencing texture. USDA Agr. Res. Serv. ARS 73-9.

Cording, J.Jr., J.F. Sullivan and R.K. Eskew. 1959. Potato flakes --a new form of dehydrated, mashed potatoes. IV. Effects of cooling after precooking. USDA Agr. Res. Serv., ARS 73-25.

Costar Corp. 1992. Life science filtration catalog. Costar Corp, Cambridge, Massachusetts.

Cowan, W.F. 1964. The mechanism of hot-surface drying. Tappi, 47(12): 808.

de Vries, D.A. 1958. Simultaneous transfer of heat and moisture in porous media. Transactions, American Geophysical Union, 39(5): 909-916.

Dreshfield, A.C., Jr. 1957. The mechanism of hot-surface drying of fibrous sheets. Chem. Engr. Progr., 53(4): 174.

Erdman, J.W., Jr., M.P. O'Connor, K.E. Weingartner, L.W. Solomon, and A.I. Nelson. 1977. Production, nutritional value and baking quality of soy-egg flours. Journal of Food Science, 42(4): 964-968.

Eskew, R.K. and F.H. Drazga. 1956. Potato flakes --a new form of dehydrated mashed potatoes III. Estimated commercial costs. USDA Agr. Res. Serv. ARS 73-12.

Eskew, R.K. and F.H. Drazga. 1962. Potato flakelets --a new dense product from flakes. Food Tech. 16(4): 99-101.

Eyraud, C., M. Prettre, Y. Trambouze, J. Lenoir, G. Thomas and P. Plurien. 1962. Metal oxides for gaseous diffusion. U.S. Patent no. 3,022,187.

Fergusson, J.L. 1976. Food Engineering, (48)9: ef27.

Fish, B.P. 1957. Diffusion and equilibrium properties of water in starch. Department of Scientific and Industrial Research, Food Investigation, Technical Paper No. 5. Her Majesty's Stationery Office, London.

Fish, B.P. 1958. Diffusion and thermodynamics of water in potato starch gel. In: Fundamental aspects of the dehydration of foodstuffs. Soc. of Chem. Ind., London.

Fritze, H. 1972. The use of drum driers in the human food industry. Proceedings, International Symposium of Heat and Mass Transfer; Problems in Food Engineering, OCT 24-27, Vol. 2, Wageningen, the Netherlands.

Fritzsche, K.A. and J.E. Kurz. 1990. The separation of gases by membranes. In: Handbook of Industrial Membranes, M.C. Porter (editor), Noyes Pub., New Jersey.

General Electric Co. 1992. GE silicones emulsions selector guide, form number CDS 4456. General Electric Co., Waterford, New York.

Gerber Products Co. 1993. Rice cereal for baby, product label. Fremont, Michigan.

Ginzburg, A.S. 1981. The forms and energy of moisture binding in foods as a basis for choosing rational methods for processing and storage. In: Water Activity: Influences on Food Quality, L.B. Rockland and G.F. Stewart (editors), Academic Press, New York.

Gore, R.W. 1976. U.S. Patent 3,962,153. (Stretched, microporous membrane for use in water-repellent garments)

Görling, P. 1958. Physical phenomena during the drying of foodstuffs. In: Fundamental Aspects of the Dehydration of Foodstuffs, Society of Chemical Industry, London.

Haghighi, K. and L.J. Segerlind. 1988. Modeling simultaneous heat and mass transfer in an isotropic sphere - a finite element approach, Transactions of the American Society of Agricultural Engineers, 31(2): 629-637.

Haghighi, K. 1990. Finite element simulation of the thermo-hydro stresses in a viscoelastic sphere during drying. Drying Technology, 8(3): 451-464.

Harcourt, G.N. 1938. Effective drum drying by present-day methods. Chemical and Metallurgical Engr., 45(4): 179.

Harte, C.H., Jr. 1936. Ind. Engr. Chem., 28: 7.

Hasan, M. and A.S. Mujumdar. 1987. Drying of polymers. In: Handbook of Industrial Drying, A.S. Mujumdar (editor), Marcel Dekker, Inc., New York.

Hayashi, H. 1989. Drying technologies of foods - their history and future. Drying Technology, 7(2): 315-369.

Henis, J.M.S. and M.K. Tripodi. 1980. Sep. Sci. Tech: 59-1068.

Hougen, O.A., H.J. McCauley and W.R. Marshall, Jr. 1940. Limitations of diffusion equations in drying. American Institute of Chemical Engineers, 36: 183-206.

Hsieh, H.P. 1988. Inorganic membranes. In: AIChE Symposium Series, Number 261, V84 K.S. Sirkar and D.R. Lloyd (editors), American Institute of Chemical Engineers, New York.

Hwang, H.J. and R.L. Thomas. 1989. Direct use of apple pomace in bakery products. Journal of Food Science, 54(3): 618-620, 639.

Hwang, S.T., C.K. Choi and K. Kammermeyer. 1974. Review, gaseous transfer coefficients in membranes. Separation Science 9(6): 461-478.

Iglesias, H.A. and J. Chirife. 1976. Prediction of the effect of temperature on water sorption isotherms of food material. Journal of Food Technology, 11: 109-116.

Incropera, F.P. and D.P. DeWitt. 1981. Fundamentals of heat transfer. John Wiley and Sons, Inc., New York.

Johnson, J.S., Jr., R.E. Minturn and P.H. Wadia. 1972. Hyperfiltration. XXI. Dynamically formed hydrous Zr(IV) oxide-polyacrylate membranes. Journal of Electroanalytical Chemistry, 37(6): 267-281.

Karel, M. 1973. Recent research and development in the field of low-moisture and intermediate-moisture foods. Critical Reviews in Food Technology, 2: 329-373.

Keenan, J.H. and F.G. Keyes. 1936. Thermodynamic properties of steam. John Wiley and Sons, Inc., New York.

Keey, R.B. 1990. Theoretical foundations of drying technology. In: Advances in Drying, Vol 1, A.S. Mujumdar (editor), Hemisphere Publishing Co., New York.

Kenrich Petrochemicals, Inc. 1987. Bulletin No. KR-1084L-4. Kenrich Petrochemicals, Inc., Bayonne, New Jersey.

Kesting, R.E. 1985. Synthetic and polymeric membranes, 2nd ed. John Wiley and Sons, Inc., New York.

Kitson, J.A. and D. Britton. 1978. Metamorphosis of fruit trimmings creates sweet alternative to dried fruit. Food Product Development, 12(2): 39,42.

Komanowsky, M., R.K. Eskew and J. Cording,Jr. 1964. Pure pumpkin powder. Food Engineering, 36(5): 107.

Komanowsky, M., J. Cording, Jr. and R.K. Eskew. 1968. Double-drum dries without pretreatment. Food Engineering

Kopelman, I.J. and I. Saguy. 1977. Drum dried beet powder. Journal of Food Technology, 12: 615-621.

Kozempel, M.F., J.F. Sullivan, J.C. Craig and W.K. Hailand. 1986 Lebensm. Wiss. U.-Technol., 19:193.

Kozempel, M.F., P.M. Tomasula, J.C. Craig, Jr. and M.J. Kurantz. 1990. Effect of potato composition on drum dryer capacity. Lebensm.-Wiss. U.-Technol., 23(4): 312-316.

Kröll, K., A.S. Mujumdar and A.S. Menon. 1980. Drying since the millenniums. In: Drying '80 Vol. 2, Proc. of the International Symposium, Hemisphere Pub. Co., New York.

Lazar, M.E. and A.I. Morgan. 1965. Instant fruit flakes. Food Processing, 26(10): 72.

Lazar, M.E. and A.I. Morgan. 1966. Instant applesauce. Food Technology, 20(4): 179-181.

Lazar, M.E. 1968. Modified drum dryer shows versatility. Food Engineering, 2: 95-98.

Lee, K.H. and S.J. Khang. 1987. Physical characteristics of a porous silica material formed by pyroloysis of silicone rubber. Ceram. Engr. Sci. Proc. 8: 85-92.

Leenaars, A.F.M., K. Keizer and A.J. Burggraaf. 1986. Porous alumina membranes. Chemtech, 16: 560-564.

Leslie, R.B., P.J. Carillo, S. Chung, G. Gilbert, K. Hayakawa, S. Marousis, G.D. Saravacos and M. Solberg. 1991. Water diffusivity in starch-based systems. In: Water relationships in foods, advances in experimental

medicine and biology, Vol 302, H. Levine and L. Slade (editors), Plenum Press, New York.

Lozano, J.E., E. Rotstein and M.J. Urbicain. 1983. Shrinkage, porosity and bulk density of foodstuffs at changing moisture contents. Journal of Food Science, 48(5): 1497-1502.

Luikov, A.V. and Y.A. Mikhailov. 1965. Theory of energy and mass transfer. Permagon Press. Oxford.

Lynch, Wilfred. 1978. Handbook of silicone rubber fabrication. Van Nostrand Reinhold Co., New York.

Manlan, M., R.F. Matthews, R.P. Bates and S.K. O'Hair. 1985. Drum drying of tropical sweetpotatoes. Journal of Food Science, 50: 764-768.

Marlow, T.G. 1910. Drying machinery and practice. Van Nostrand. New York.

Maxwell, J.L. and H.F. Zobel. 1978. Model studies on cake staling. Cereal Foods World, 23(3):124-128.

McDermott, J. (editor). 1972. Industrial membranes, design and applications. Noyes Data Corporation, New Jersey.

Menting, L.C., B. Hoogstad and H.A.C. Thijssen. 1970. Diffusion coefficients of water and organic volatiles in carbohydrate-water systems. J. Food Technology, 5(2): 111-126.

Mikhailov, M.D. 1973. General solutions of the diffusion equations coupled at boundary conditions. International Journal of Heat and Mass Transfer, 16: 2155-2167.

Misra, R.N. and J.H. Young. 1979. The finite element approach for solution of transient heat transfer in a sphere. Transactions of the American Society of Agricultural Engineers, 22(4): 944-949.

Misra, R.N. and J.H. Young. 1980. Numerical solution of simultaneous moisture diffusion and shrinkage during soybean drying. Transactions of the American Society of Agricultural Engineers, (23)5: 1277-1282.

Mitchell, W. and V. Studer. 1963. U.S. Patent 3,077,411. To General Foods Corp.

Mohtar, R. and L.J. Segerlind. 1992. Time step criteria for solving unsteady engineering field problems. ASAE Winter Meeting, paper number 92-3523. The American Society of Agricultural Engineers, St. Joseph, Michigan.

Moore, J.G. 1987. Drum driers. In: Handbook of industrial drying, A.S. Mujumdar (editor), Marcel Dekker, Inc., New York.

Mott Metallurgical Corp. 1987. Catalog No. 1000B. Mott Metallurgical Corp., Farmington, Conn.

Mumjumdar, A.S. 1987. Drying of coated webs. In: Handbook of industrial drying, A.S. Mujumdar (editor), Marcel Dekker, Inc., New York.

Nip, W.K. 1979. Development and storage stability of drum-dried guave- and papaya-taro flakes. Journal of Food Science, 44(1): 222-225.

Okaka, J.C. and N. Potter. 1979. Physico-chemical and functional properties of cowpea powders processed to reduce beany flavor. Journal of Food Science, 44: 1235-1239.

Okazaki, M., K. Shoida, K. Masuda and R. Toei. 1974. Drying mechanism of coated film of polymer solution. Journal of Chemical Engineering Japan, 7(2): 99-105.

Okos, M.R. (editor). 1986. Physical and chemical properties of food. American Society of Agricultural Engineers, St. Joseph, Michigan.

Pakowski, Z. and A.S. Mujumdar. 1987. Drying of pharmaceutical products. In: Handbook of industrial drying, A.S. Mujumdar (editor), Marcel Dekker, Inc., New York.

Perry, J.H. (editor). 1950. Chemical engineers handbook, third edition. McGraw-Hill, New York.

Pfeifer, V.F., C. Vojnovich and R.A. Anderson. 1958. Vital wheat gluten by drum drying. Cereal Chemistry, 35: 458.

Philips, J.R. and D.A. de Vries. 1957. Moisture movement in porous materials under temperature gradients, Trans. Amer. Geophys. Union, 38: 222-232.

Popov, E.P. 1976. Mechanics of materials, 2nd ed. Prentice-Hall, New Jersey.

Porex Technologies Corp. 1989. Materials data sheet, ID #661-330-1089. Georgia.

Porter, M.C. (editor). 1990. Handbook of industrial membrane technology. Noyes Publications, New Jersey.

Press, W.H., B.P. Flannery, S.A. Teukolsky and W.T. Vetterling. 1989. Numerical recipes in PASCAL. Cambridge University Press, Cambridge.

Raats, P.A.C. 1975. Transformations of fluxes and forces describing the simultaneous transport of water and heat in unsaturated porous media. Water Resources Research, 11(6): 938-942.

Rautenbach, R. and R. Albrecht. 1989. Membrane processes. John Wiley and Sons, New York.

Rulkens, W.H. and H.A.C. Thijssen. 1969. Numerical solution of diffusion equations with strongly variable diffusion coefficients, calculation of flavour loss in drying food liquids. Transactions of the Institution of Chemical Engineers, 47: T292-T298.

Russel, P.L. and G. Oliver. 1989. The effect of pH and NaCl content on starch gel ageing. A study by differential scanning calorimetery and rheology. Journal of Cereal Science, 10(1): 123-138.

Salunkhe, D.K., J.Y. Do and H.R. Bolin. 1973. Developments in technology and nutritive value of dehydrated fruits, vegetables and their products. Critical Reviews in Food Technology, November: 153-192.

Schmidt, S.J. and Lai, Hsi-Mei. 1991. Use of NMR and MRI to study water relations in foods. In: Water relationships in foods, advances in experimental medicine and biology, Vol. 302, H. Levine and L. Slade, (editors), Plenum Press, New York.

Segerlind, L.J. 1984. Applied finite element analysis, second edition. John Wiley and Sons, New York.

Sherwood, T.K. 1931. Application of theoretical diffusion equations to the drying of solids. American Institute of Chemical Engineers, 27: 190-202.

Soekarto, S.T. and M.P. Steinberg. 1981. Determination of binding energy for the three fractions of bound water. In: Water activity: Influences on food quality, L.B. Rockland and G.F. Stewart (editors). Academic Press, New York.

Sokhansenj, S. 1987. Drying of foodstuffs. In: Handbook of industrial drying, A.S. Mujumdar (editor), Marcel Dekker, Inc., New York.

Spadaro, J.J. and E.L. Patton. 1961. Precooked dehydrated sweet potato flakes. Food Engineering, 33(7): 46.

Spadaro, J.J., J.I. Wadsworth, G.M. Ziegler, A.S. Gallo and S.P. Koltun. 1966. Instant sweetpotato flakes - processing modifications necessitated by varietal differences. Food Technology, 21: 326.

Spadaro, J.J., J.I. Wadsworth and H.L.E. Vix. 1966. Drum drying of foods. ASHRAE Journal, 8(9): 55-63.

Strathmann, H. 1985. Production of microporous media by phase inversion processes. In: Material science of synthetic membranes, D.R. Lloyd (editor), ACS Symp. Series 269, American Chemical Society, Washington, D.C.

Strathmann, H. 1990. Synthetic membranes and their preparation. In: Handbook of industrial membrane technology, M.C. Porter (editor), Noyes Publications, New Jersey.

Sullivan, J.F., M.F. Kozempel, M.J. Egoville, and E.A. Talley. 1985. Losses of amino acids and water soluble vitamins during potato processing. Journal of Food Engineering, 50: 1249-1253.

Suzuki, K., Kubota, K., Hasegawa, T. and H. Hosaka. 1976. Shrinkage in dehydration of root vegetables. Journal of Food Science, 41(5): 1189-1193.

Toles, G.E. 1964. Instant fish flakes roll of drum. Canner Packer, 133(7): 27.

Tressler, D.K. and M.A. Joslyn. 1961. Fruit and vegetable juice processing technology. AVI Publishing Co., Inc., Connecticut.

van den Berg, C. 1991. Food-water relations: progress and integration, comments and thoughts. In: Water relationships in foods, advances in experimental medicine and biology, Volume 302, H. Levine and L. Slade (editors), Plenum Press, New York.

van den Berg, C., F.S. Kaper, J.A.G. Weldring and I. Wolters. 1975. Water binding by potato starch. Journal of Food Technology, 10: 589-602.

van Arsdel, W.B., M.J. Copley, and A.I. Morgan, Jr. (editors). 1973a. Food dehydration, 2nd ed., Vol.1, drying methods and phenomena. AVI Pub. Co., Inc., Connecticut.

van Arsdel, W.B., M.J. Copley, and A.I. Morgan, Jr. (editors). 1973b. Food dehydration, 2nd ed., Vol. 2, practices and applications. AVI Pub. Co., Inc., Connecticut.

van Arsdel, W.B. 1947. Approximate diffusion calculations for the falling-rate phase of drying. Transactions American Institute Chemical Engineers, 43(1): 13-24.

von Loesecke, H.W. 1943. Drying and dehydration of foods. Reinhold Pub. Corp., New York.

van Marle, D.J. 1938. Drum drying. Industrial and Engineering Chemistry 30(9): 1006-1008.

Wadsworth, J.I., A.S. Gallo, G.M. Ziegler, Jr. and J.J. Spadaro. 1967. Controlling bulk density of high sugar products during drum drying. Food Technology, 21(7): 100-103.

Wang, H.J. and R.L. Thomas. 1989. Direct use of apple pomace in bakery products. Journal of Food Science, 54(3): 618-620.

Whitaker, S. 1977. Toward a diffusion theory of drying. Industrial Engineering Chemistry, Fundamentals, 16(4): 408-414.

Whitney, J.D. and J.G. Porterfield. 1968. Moisture movement in porous, hygroscopic solids. Transactions of the American Society of Agricultural Engineers, 11(5):716-719.

Willard, M.J., Jr. 1959. Potato flour. In: Potato processing. W.F. Talburt and O. Smith (editors), AVI Publ. Co., Connecticut.

Willard, M.J. and J. Cording, Jr. 1957. Dehydration of cooked potato. U.S. Patent 2,780,552, Feb 5.

Williams-Gardner, A. 1977. Industrial drying. Gulf Publishing Co., Texas.

W.R. Grace and Co. (undated). Technical brochure, Davidson molecular sieve. Baltimore, Maryland.

Zhou, L., V.M. Puri, R.C. Anantheswaran and S. Roy. 1992. Material property measurement for simultaneous heat and mass transfer in food products, paper no. 926594. American Society of Agricultural Engineers, 1992 International Winter Meeting, St. Joseph, Michigan.

Zobel, H.F. 1984. Gelatinization of starch and mechanical properties of starch pastes. In: Starch chemistry and technology, 2nd ed., R.L. Whistler, J.N. Bemiller and E.F. Paschall (editors), Academic Press, Inc., New York.

Zsigmondy, R., W. Bachmann. 1918. Z. Anorg. Allg. Chem. 103-119.

APPENDICES

APPENDIX A

DATA COLLECTION PROCEDURE

APPENDIX A

DATA COLLECTION PROCEDURE

The following data collection procedure was followed closely during the starch film drying experiments run on 22, 27, 28 and 29 September, 1993. An exception was made for the single-side drying test, ran on the 22nd. A piece of heavy gauge aluminum foil was taped over the drying surface to prevent moisture flow through the surface. The moisture content of the starch film after the drying period (see step 14) was obtained by removing the entire piece of aluminum foil with the starch film intact and placing it in the desiccation chamber. A sample of the form used for data collection is given following the procedure.

1. Plug in and/or turn on the various appliances in the following order and allow a minimum of 1.5 hours for the system to reach equilibrium.
    a. Fan. Make sure that the desiccant columns are removed from the system and the valves are positioned to discharge air to the room.
    b. Dehumidifier.
    c. Air heater controller (turn set-point to desired temperature).
    d. Computer data collection system (initialize but do not start).
    e. Scales.
    f. Hot plate.
    g. Table-top desiccation chamber (setpoint 60°C).

2. Place a beaker filled with about 500 ml of distilled water on the hot plate. The heated water will be used later to prepare the starch slurry.

3. Fill the desiccant columns with about 1.0 kg each of dry, molecular sieve.

4. Balance the air flows in the blue (above) and green (below) ducts of the drying chamber and record air pressures.

a. Place a metal plate (285 x 285 mm) over the drying surface and seal around the edges with masking tape. The plate will prevent air exchange between the air flows above and below the drying surface during the balancing period.
b. Replace the clear, lexan cover on the drying chamber.
c. Check and record the absolute pressure of upper chamber and the average absolute pressure of lower chamber.
d. Equalize the upper chamber pressure to the average lower chamber pressure by adjusting the hand wheels on upper chamber air valves. The pressure loss across both valves should be equal.
e. Check the chamber pressure equalization by comparing the orifice pressure loss of the blue and green ducts. They should be approximately equal.

5. Mix the starch slurry.
   a. Mix hot water (about 60°C) into the dry starch until a smooth paste is formed. For rice starch, use about 50 grams of water per every 10 grams of flakes.
   b. Place the starch slurry on a stirred hot plate and maintain the temperature as given in (a).
   c. If you a preparing a modified corn starch slurry, add sulfuric acid to the slurry to reduce the pH to less than 3.0. Check the pH using paper indicator strips. Cook the acidified slurry at 80°C for at least 5.0 minutes.
   d. Find the density of the slurry: Tare a graduated cylinder, pour in a sample of slurry, and record the weight and volume.
   e. Tare and label two sample trays to be used for desiccation of starch samples and record their mass.
   f. Weigh the wall covering smoother and record the value.

6. Measure the room dry and wet bulb temperatures and record.

7. Meter out starch slurry and sample.
   a. Measure out about 400 grams of slurry into an insulated beaker and record the mass.
   b. Cover the bottom of a tared, labeled sample tray (from step five) with slurry, record mass and place in the desiccation chamber.
   c. Cover and place the insulated beaker near the drying surface.

8. Prewarm the desiccant columns.
   a. Remove the covers from the "+" columns and warm them up by installing them into the system and valving air through them for about five minutes.
   b. Install the "-" columns and warm them up for about five minutes

immediately after the "+" columns are warmed.
c. Tare the "+" columns and place them back in the system with a paper cover over their discharge ends.

9. Quickly apply the starch slurry to the drying surface.
   a. Turn off the heater and fan (in that order).
   b. Switch the air flow valves to allow air to pass through the "+" columns when the fan is restarted.
   c. Remove the clear, lexan dryer cover and remove the metal plate from the chamber.
   d. Apply the starch slurry to the drying surface by pouring it from the insulated beaker.
   e. Use the wall covering smoother to spread the paste into a thin, even film that completely covers the drying surface. Rest the ends of the smoother on the shims while spreading to get an even film thickness.
   f. Set the smoother aside without disturbing any slurry remaining on the edge.
   g. Position the spring-loaded thermocouple on the drying surface.
   h. Replace the lexan cover onto the drying chamber.

10. Begin the drying sequence.
   a. Turn on the fan and then the air heater.
   b. Start the timer.
   c. Start the data collection system.
   d. Observe that the paper cover has blown off of the "+" columns.
   e. Observe the air temperature controller for steady state conditions.
   f. Weigh and record the mass of the insulated beaker and remaining starch slurry.
   g. Weigh and record the mass of the wall covering smoother and slurry left on the blade.

11. Measure the moisture evaporated from the starch film.
   a. Weigh the "-" columns and record the value at time "zero" then place them back into the system. Rotate each column (about its vertical axis) about 1/4 turn from its previous position.
   b. Record the pressure loss across each orifice.
   c. After an elapsed time of four minutes switch the air valves to the "-" columns.
   d. Weigh the "+" columns, record mass and time, then place them back into the system. Rotate the column about 1/4 turn (about its vertical axis) from its previous position.
   e. Record the pressure loss across each orifice.
   f. After an elapsed time of four minutes switch the air valves back to the "+" columns.

g. Continue to weigh and record mass and time and replace the columns, alternating between "+" and "-" columns for 56 minutes. Record the pressure difference across each orifice for every time interval.

12. Periodically check and record the following while the film is drying.
    a. Room relative humidity.
    b. Condition of film (visual).

13. At the end of the drying period turn off the air heater and then the fan.

14. Sample the thin film.
    a. Remove the cover from the drying chamber.
    b. Collect a sample of the dried film and place it into the tared, labeled sample tray (from step five).
    c. Place the tray in the desiccation chamber.

15. Dry the desiccant for the next run.
    a. Preheat the convection oven to 260°C.
    b. Pour the desiccant from each column into one of four 230 x 300 mm, baking trays.
    c. Spread the desiccant evenly in the baking trays and place in the oven.
    d. Bake for one hour, remove briefly and stir the desiccant.
    e. Bake for an additional hour and remove and pour desiccant into a sealed container for cooling and subsequent use.

DATA COLLECTION FORM
PDS EXPERIMENTS

A. Starch slurry description:

B. Dryer temperature setpoint:

C. Starch sample:

tare, foil tray A (g):

tray and moist starch (g):

dried sample (g):

temperature (C):

tare foil tray B (g):

film and tray B (g):

dry film and tray B (g):

D. Starch Film:

specific volume (g/ml):

tare, styrofoam cup (g):

cup and slurry (g):

cup and remaining slurry (g):

Spatula tare (g):

Spatula and slurry (g):

E. Air Pressures (inches of water):

Time	Chamber		
	upper	lower (in)	lower dP

Experimenter:

Date:

F. Room air conditions:

Time	Temperature, C	
	wet bulb	dry bulb

G. Molecular Sieve column mass (grams):

Time	Mass (+)		Mass (-)		Delta P	
	blue +	green+	blue -	green -	blue	green

APPENDIX B

RAW DATA

APPENDIX B

RAW DATA

Appendix B contains the raw data collected during the drying experiments conducted on September 22, 27, 28 and 29 of 1993. Data is organized by collection date. Individual datum are described with units specified. Columns of data are identified by the column heading. A key for the column headings, including comments, follows.

Time	The first recorded time for each experimental run is zero. Each subsequent time is found by adding the elapsed number of minutes to the first time.
Column mass	Desiccant columns were removed from the system piping and weighed every four minutes. The first recorded value is given at time zero. Individual column labels correspond to the labeling arrangement described in the Design chapter. Blank spaces indicate a time period when the desiccant column was off-line.
Pressure drop	Pressure loss across the two orifice plates was recorded every four minute period, corresponding to the column mass measurements.
Dehum	The temperature of the air discharged from the dehumidifier was recorded every thirty seconds.

Blue in Air temperature at the inlet to the drying chamber above the drying surface. Recorded every thirty seconds, beginning with time zero.

Green in Air temperature at the inlet to the drying chamber below the drying surface. Recorded every thirty seconds, beginning with time zero.

Drying Surface Temperature of the drying surface, recorded every thirty seconds, beginning with time zero.

Blue out Air temperature at the outlet of the drying chamber above the drying surface. Recorded every thirty seconds, beginning with time zero.

Green out Air temperature at the outlet of the drying chamber below the drying surface. Recorded every thirty seconds, beginning with time zero.

RICE STARCH OVER ALUMINUM FOIL

22SEP93

Dryer setpoint temp., C	52	Starch slurry temp. (initial), C	65
Starch sample and tray, g	18.68	Film sample and tray, g	55.00
Dry sample and tray, g	5.18	Dryed film sample and tray, g	18.76
Beaker and slurry, g	260.50	Spatula tare, g	67.70
Beaker and rem. slurry, g	138.80	Spatula and slurry, g	68.60
Graduate tare, g	137.69		
Volume in graduate, ml	100		
Graduate and slurry, g	241.70		

Chamber air pressure, in H2O		Room temperature, C	
upper	2.3	wet bulb	16.0
lower	3.3	dry bulb	24.0
lower dP	3.0		

	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
0	2564.6	2558.6	2582.5	2550.6		
4	2576.7	2564.0			0.182	0.141
8			2593.2	2556.1	0.175	0.129
12	2587.5	2570.0			0.172	0.133
16			2604.1	2562.2	0.175	0.128
20	2598.2	2576.2			0.168	0.130
24			2615.2	2568.6	0.167	0.124
28	2608.5	2582.5			0.170	0.130
32			2626.0	2575.3	0.162	0.124
36	2619.5	2589.7			0.163	0.128
40			2637.4	2582.7	0.168	0.124
44	2630.3	2597.1			0.162	0.128
48			2648.4	2590.2	0.165	0.123
52	2641.1	2604.9			0.161	0.126
56			2659.9	2598.3	0.162	0.122

	TEMPERATURES, C					
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
0.0	-6.67	38.49	42.44	35.79	37.70	39.56
0.5	-5.27	40.42	45.56	34.84	37.76	40.01
1.0	-4.26	41.83	47.59	34.48	37.81	39.99
1.5	-3.24	42.09	48.08	34.30	37.80	39.89
2.0	-2.35	41.79	47.17	34.21	37.67	39.78
2.5	-2.06	42.50	47.24	34.31	37.80	39.68
3.0	-1.75	43.21	48.60	34.38	37.85	39.68
3.5	-1.05	42.59	47.67	34.60	37.79	39.74
4.0	-0.86	42.97	47.28	34.72	37.90	39.70
4.5	-0.88	43.35	48.37	34.72	37.87	39.62
5.0	-0.69	43.06	48.47	34.88	37.91	39.66
5.5	-0.53	43.68	48.30	35.23	38.09	39.77
6.0	-0.56	43.58	48.81	35.23	38.00	39.77
6.5	-0.46	42.96	47.63	35.16	38.01	39.76
7.0	-0.38	43.85	48.73	35.23	38.17	39.83

		TEMPERATURES, C				
TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
7.5	0.26	43.57	48.38	35.47	38.05	39.80
8.0	-0.03	43.24	48.37	35.55	38.03	39.80
8.5	-0.19	42.60	47.15	35.54	37.91	39.74
9.0	0.11	43.48	47.89	35.88	38.16	39.81
9.5	-0.03	44.32	49.71	36.07	38.33	39.90
10.0	0.31	43.45	48.44	36.11	38.21	39.99
10.5	0.19	43.24	47.39	36.05	38.25	39.95
11.0	0.41	43.57	47.95	36.23	38.33	39.93
11.5	0.64	43.99	48.70	36.10	38.44	39.93
12.0	1.19	43.54	48.52	36.09	38.36	39.99
12.5	0.50	43.07	47.85	36.10	38.30	39.98
13.0	0.88	43.91	48.49	36.65	38.48	40.09
13.5	0.84	43.90	49.21	36.67	38.45	40.16
14.0	0.71	43.97	48.82	37.01	38.60	40.24
14.5	0.96	44.37	49.21	37.11	38.71	40.37
15.0	0.80	43.88	48.95	36.91	38.64	40.32
15.5	1.37	43.83	48.51	37.06	38.74	40.39
16.0	1.13	44.44	49.42	37.19	38.84	40.59
16.5	1.07	43.96	48.92	37.07	38.77	40.48
17.0	0.95	43.36	48.02	37.14	38.67	40.46
17.5	1.22	43.35	47.47	37.26	38.71	40.47
18.0	1.65	44.12	48.63	37.50	38.88	40.48
18.5	1.86	44.36	50.11	37.56	38.92	40.57
19.0	2.10	43.57	47.83	37.66	38.89	40.59
19.5	1.84	43.93	48.18	37.75	38.93	40.57
20.0	2.63	44.14	48.69	37.80	38.98	40.47
20.5	2.29	44.42	49.24	37.90	39.02	40.48
21.0	1.96	43.71	48.53	37.88	38.92	40.53
21.5	2.42	44.45	49.21	38.11	39.21	40.41
22.0	1.53	43.97	49.15	38.05	39.07	40.54
22.5	2.95	44.33	48.88	38.23	39.21	40.59
23.0	3.17	44.46	49.14	38.29	39.24	40.74
23.5	0.89	43.64	48.76	37.98	39.06	40.71
24.0	0.73	43.82	48.50	38.25	39.17	40.77
24.5	0.67	44.07	48.81	38.28	39.19	40.92
25.0	1.19	43.68	48.58	38.15	39.06	40.83
25.5	1.43	43.76	48.47	38.16	39.05	40.76
26.0	1.31	43.74	48.63	38.22	39.07	40.81
26.5	1.89	43.77	48.85	38.18	39.06	40.78
27.0	1.98	43.00	48.00	38.12	38.89	40.76
27.5	1.94	42.97	47.80	38.16	38.95	40.80
28.0	2.04	43.13	47.31	38.24	38.98	40.72
28.5	2.60	43.25	47.76	38.24	39.01	40.63
29.0	2.48	43.72	48.62	38.24	39.05	40.46
29.5	3.06	43.11	48.48	38.23	38.91	40.59
30.0	2.92	42.92	48.15	38.26	38.92	40.58
30.5	3.06	42.84	47.46	38.27	38.94	40.61
31.0	3.60	43.12	47.64	38.35	38.98	40.69
31.5	3.06	43.93	49.26	38.51	39.14	40.67

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
32.0	3.15	43.91	49.64	38.61	39.20	40.93
32.5	3.86	43.56	49.20	38.60	39.08	40.98
33.0	4.02	43.21	48.48	38.66	39.09	40.98
33.5	3.86	43.12	48.03	38.71	39.14	41.03
34.0	4.05	43.23	47.87	38.73	39.18	41.04
34.5	4.43	43.78	48.79	38.81	39.24	41.07
35.0	4.32	43.72	48.95	38.84	39.25	41.14
35.5	4.36	43.47	49.15	38.80	39.24	41.12
36.0	3.99	43.17	48.25	38.87	39.18	41.11
36.5	4.46	43.38	47.98	38.97	39.25	41.10
37.0	4.54	43.50	48.28	39.00	39.29	41.15
37.5	4.64	43.95	49.15	39.02	39.42	41.14
38.0	4.50	43.72	49.35	39.03	39.29	41.17
38.5	4.41	43.29	48.62	39.02	39.25	41.20
39.0	3.75	43.21	48.31	39.08	39.33	41.18
39.5	5.01	43.39	47.99	39.19	39.36	41.19
40.0	4.83	43.53	48.18	39.20	39.37	41.30
40.5	4.75	43.96	49.34	39.21	39.44	41.34
41.0	5.14	43.55	49.08	39.26	39.49	41.37
41.5	4.77	43.48	48.92	39.28	39.52	41.43
42.0	4.49	43.39	48.34	39.34	39.50	41.45
42.5	4.56	43.39	47.94	39.43	39.55	41.44
43.0	4.80	43.85	48.67	39.46	39.64	41.48
43.5	4.82	43.99	49.37	39.41	39.64	41.54
44.0	4.91	44.08	49.30	39.51	39.66	41.50
44.5	5.43	43.36	48.67	39.44	39.53	41.28
45.0	5.27	43.29	47.91	39.52	39.64	41.07
45.5	5.60	43.53	47.98	39.58	39.65	41.02
46.0	5.38	43.74	48.51	39.54	39.69	41.41
46.5	5.36	43.81	48.88	39.58	39.65	41.41
47.0	5.63	43.30	48.35	39.50	39.54	41.09
47.5	5.41	42.87	47.66	39.46	39.45	40.98
48.0	5.49	43.58	48.14	39.65	39.64	41.43
48.5	5.86	43.45	48.10	39.69	39.65	41.56
49.0	5.40	44.02	49.29	39.77	39.74	41.64
49.5	5.73	43.82	49.10	39.74	39.72	41.64
50.0	5.68	43.30	48.63	39.63	39.57	41.61
50.5	5.64	42.91	47.90	39.58	39.51	41.56
51.0	6.15	43.12	47.75	39.68	39.61	41.50
51.5	5.89	43.54	48.21	39.73	39.69	41.60
52.0	6.38	43.71	48.59	39.75	39.71	41.27
52.5	6.31	43.60	48.56	39.70	39.68	41.05
53.0	6.22	43.11	48.19	39.66	39.63	41.01
53.5	6.08	43.08	47.84	39.71	39.66	40.98
54.0	7.00	44.09	49.36	39.89	39.83	41.05
54.5	6.13	43.25	48.51	39.76	39.62	41.03
55.0	6.47	43.29	47.83	39.83	39.77	41.00
55.5	6.36	44.01	49.53	39.96	39.82	41.09
56.0	6.87	43.72	48.70	40.06	39.86	41.78

RICE STARCH
27SEP93

Dryer setpoint temp., C	52	Starch slurry temp. (initial), C	50
Starch sample and tray, g	15.51	Film sample and tray, g	8.34
Dry sample and tray, g	5.09	Dryed film sample and tray, g	7.06
Beaker and slurry, g	246.60	Spatula tare, g	67.80
Beaker and rem. slurry, g	118.40	Spatula and slurry, g	68.71
Graduate tare, g	137.68		
Volume in graduate, ml	100		
Graduate and slurry, g	241.00		

Chamber air pressure, in H2O		Room temperature, C	
upper	1.9	wet bulb	15.0
lower	3.1	dry bulb	24.5
lower dP	2.6		

	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
0	2563.2	2561.9	2598.2	2551.4		
4	2573.3	2570.0			0.261	0.143
8			2608.0	2559.0	0.252	0.142
12	2582.7	2577.4			0.250	0.135
16			2617.2	2566.7	0.239	0.144
20	2591.6	2585.2			0.239	0.142
24			2625.8	2574.4	0.253	0.141
28	2599.6	2592.7			0.240	0.140
32			2633.5	2582.1	0.230	0.146
36	2606.8	2600.2			0.230	0.140
40			2640.4	2589.5	0.233	0.148
44	2613.1	2607.1			0.231	0.147
48			2646.4	2596.3	0.231	0.150
52	2618.7	2613.1			0.235	0.148
56			2651.9	2602.1	0.225	0.158

	TEMPERATURES, C					
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
0.0	-11.14	39.77	42.52	33.16	36.68	36.88
0.5	-8.93	40.70	43.87	33.43	36.73	37.01
1.0	-7.48	41.72	44.95	33.72	36.89	36.68
1.5	-6.44	42.63	46.25	33.99	36.92	36.45
2.0	-5.88	42.39	45.75	34.16	36.98	36.28
2.5	-5.07	42.80	46.19	34.47	37.02	36.26
3.0	-5.10	42.71	45.83	34.70	37.07	36.15
3.5	-4.80	43.50	46.42	35.09	37.32	36.23
4.0	-4.76	43.89	46.83	35.21	37.49	36.23
4.5	-4.39	44.56	47.99	35.43	37.53	36.23
5.0	-4.59	44.08	47.34	35.54	37.47	36.25
5.5	-4.54	44.18	47.46	35.80	37.66	36.30

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
6.0	-4.28	43.88	46.85	35.90	37.59	36.29
6.5	-4.08	44.37	47.25	36.08	37.85	36.38
7.0	-4.12	44.98	48.04	36.30	38.07	36.42
7.5	-4.14	44.93	47.70	36.28	37.95	36.42
8.0	-4.36	43.87	46.62	36.30	37.91	36.38
8.5	-4.25	44.74	47.49	36.39	37.91	36.38
9.0	-4.06	44.17	46.77	36.39	37.88	36.36
9.5	-3.99	44.20	46.72	36.22	37.80	36.27
10.0	-4.13	43.16	45.72	36.22	37.62	36.29
10.5	-3.86	43.23	45.83	36.31	37.61	36.28
11.0	-3.83	43.70	46.27	36.48	37.83	36.31
11.5	-4.11	44.47	47.18	36.55	37.84	36.33
12.0	-3.72	44.71	47.91	36.66	38.04	36.39
12.5	-3.87	44.31	47.35	36.64	37.98	36.42
13.0	-3.81	44.81	47.62	36.80	38.11	36.37
13.5	-3.92	44.86	48.03	36.95	38.12	36.48
14.0	-3.56	44.65	47.69	37.05	38.14	36.50
14.5	-3.72	44.34	47.07	37.14	38.19	36.56
15.0	-4.17	44.60	47.28	37.35	38.38	36.62
15.5	-3.77	45.08	47.78	37.40	38.54	36.64
16.0	-3.56	45.21	48.06	37.44	38.38	36.71
16.5	-3.86	44.44	47.26	37.25	38.31	36.57
17.0	-4.11	44.28	47.24	37.26	38.25	36.62
17.5	-4.00	44.13	47.02	37.45	38.28	36.65
18.0	-3.46	44.56	47.30	37.68	38.54	36.74
18.5	-3.59	45.15	48.02	37.84	38.75	36.81
19.0	-3.77	45.55	48.46	37.97	38.77	36.89
19.5	-3.55	45.55	48.52	37.99	38.75	36.94
20.0	-3.67	45.07	47.72	38.08	38.78	37.00
20.5	-4.02	44.04	46.40	37.68	38.47	36.79
21.0	-3.58	43.72	46.34	37.69	38.34	36.79
21.5	-3.59	43.59	45.83	37.78	38.40	36.78
22.0	-3.72	43.58	45.74	37.73	38.41	36.75
22.5	-3.49	44.01	46.44	37.90	38.55	36.81
23.0	-3.07	44.69	47.28	38.16	38.67	36.88
23.5	-3.43	45.32	48.14	38.28	38.92	36.92
24.0	-3.80	45.00	47.78	38.36	38.94	36.97
24.5	-3.37	44.30	46.80	38.15	38.63	36.93
25.0	-3.97	43.74	46.27	38.05	38.48	36.86
25.5	-3.70	43.65	46.09	38.17	38.49	36.80
26.0	-3.49	44.81	47.45	38.56	38.82	36.94
26.5	-3.43	43.91	46.52	38.56	38.70	37.01
27.0	-3.53	44.00	46.52	38.60	38.79	36.97
27.5	-3.72	44.74	47.40	38.88	38.95	37.12
28.0	-3.49	44.74	47.28	38.88	38.89	37.17
28.5	-3.47	44.61	47.58	38.79	38.85	37.16
29.0	-3.59	43.96	46.76	38.86	38.87	37.22
29.5	-3.58	44.46	47.29	39.20	39.04	37.30
30.0	-3.45	44.18	46.75	39.21	39.07	37.37

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
30.5	-3.61	44.73	47.29	39.26	39.16	37.39
31.0	-3.93	43.71	46.26	39.04	38.98	37.35
31.5	-3.41	44.36	46.91	39.20	39.13	37.36
32.0	-3.40	44.47	47.40	39.34	39.15	37.39
32.5	-3.48	43.84	46.57	39.23	38.95	37.48
33.0	-3.57	43.58	46.13	39.15	38.97	37.36
33.5	-3.52	44.15	46.95	39.22	39.05	37.44
34.0	-3.23	44.35	47.28	39.32	39.16	37.50
34.5	-3.64	44.45	47.42	39.47	39.18	37.62
35.0	-3.72	44.57	47.51	39.73	39.37	37.75
35.5	-3.70	44.35	47.13	39.84	39.36	37.84
36.0	-3.53	44.77	47.34	40.19	39.56	37.97
36.5	-3.57	45.41	48.26	40.32	39.83	38.11
37.0	-3.28	45.68	48.66	40.57	39.91	38.25
37.5	-3.58	45.25	47.98	40.63	39.94	38.35
38.0	-3.79	45.22	47.80	40.62	39.96	38.35
38.5	-3.34	45.36	48.02	40.77	40.03	38.46
39.0	-3.36	45.12	48.02	40.87	40.02	38.55
39.5	-3.33	44.94	47.79	41.02	40.16	38.67
40.0	-3.14	44.87	47.51	41.01	40.06	38.76
40.5	-3.35	44.45	47.11	40.98	40.08	38.74
41.0	-2.87	44.14	46.55	41.10	40.13	38.79
41.5	-3.68	44.19	46.30	40.94	39.99	38.82
42.0	-3.09	44.30	46.59	40.97	40.12	38.79
42.5	-3.25	44.46	46.84	41.05	40.24	38.83
43.0	-3.33	45.27	48.03	41.31	40.33	39.00
43.5	-3.65	44.83	47.16	41.27	40.28	39.00
44.0	-3.16	44.48	46.78	41.15	40.15	39.02
44.5	-3.22	45.13	47.93	41.38	40.47	39.08
45.0	-3.39	45.02	47.90	41.60	40.50	39.30
45.5	-3.12	44.87	47.67	41.73	40.67	39.36
46.0	-3.22	44.53	47.19	41.89	40.64	39.55
46.5	-3.38	44.12	46.72	41.79	40.56	39.61
47.0	-3.18	43.82	46.04	41.70	40.48	39.56
47.5	-3.20	44.40	46.52	41.62	40.60	39.57
48.0	-3.27	44.44	46.60	41.62	40.56	39.54
48.5	-3.55	44.45	46.90	41.73	40.63	39.69
49.0	-3.02	44.55	46.83	41.84	40.77	39.76
49.5	-3.07	44.56	46.69	41.75	40.64	39.70
50.0	-3.41	44.51	46.67	41.92	40.84	39.86
50.5	-2.94	45.20	47.74	42.18	41.01	39.98
51.0	-3.43	44.93	47.75	42.29	40.98	40.15
51.5	-3.36	44.77	47.33	42.50	41.29	40.34
52.0	-3.28	44.80	47.13	42.66	41.37	40.49
52.5	-3.21	45.33	47.71	42.72	41.42	40.56
53.0	-3.08	45.79	48.38	42.75	41.65	40.65
53.5	-3.44	44.33	46.67	42.50	41.21	40.71
54.0	-3.16	43.95	46.07	42.39	41.17	40.71
54.5	-3.09	44.79	46.74	42.42	41.33	40.72

TEMPERATURES, C

TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
55.0	-3.24	44.68	46.83	42.63	41.51	40.88
55.5	-3.09	45.47	47.87	42.76	41.59	41.01
56.0	-2.51	46.39	48.21	43.51	42.41	41.60

POTATO STARCH
28SEP93

Dryer setpoint temp., C	52	Starch slurry temp. (initial), C	55
Starch sample and tray, g	35.16	Film sample and tray, g	13.96
Dry sample and tray, g	6.35	Dryed film sample and tray, g	9.10
Beaker and slurry, g	532.50	Spatula tare, g	67.69
Beaker and rem. slurry, g	359.92	Spatula and slurry, g	73.50
Graduate tare, g	138.10		
Volume in graduate, ml	100		
Graduate and slurry, g	239.73		

Chamber air pressure, in H2O		Room temperature, C	
upper	2.2	wet bulb	17.5
lower	3.4	dry bulb	26.5
lower dP	2.2		

	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
0	2567.2	2562.8	2592.4	2558.9		
4	2578.5	2571.9			0.189	0.123
8			2602.9	2566.6	0.190	0.120
12	2588.9	2579.8			0.181	0.118
16			2613.4	2574.8	0.180	0.120
20	2599.3	2587.8			0.179	0.113
	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
24			2624.2	2583.1	0.181	0.118
28	2609.8	2597.0			0.174	0.121
32			2634.3	2593.5	0.180	0.136
36	2618.5	2607.6			0.169	0.141
40			2643.2	2605.1	0.172	0.157
44	2627.0	2618.7			0.171	0.150
48			2651.4	2616.2	0.172	0.162
	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
52	2634.6	2628.9			0.168	0.159
56			2659.0	2626.4	0.169	0.155

TEMPERATURES, C

TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
0.0	-9.87	36.19	37.60	33.39	37.92	41.10
0.5	-7.96	41.66	47.71	33.30	38.57	40.80
1.0	-6.74	42.55	48.33	33.12	38.48	40.31
1.5	-5.37	43.59	48.89	33.26	38.59	39.99

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
2.0	-4.28	44.51	49.75	33.35	38.69	39.74
2.5	-3.89	44.87	50.23	33.78	38.58	39.56
3.0	-3.36	45.33	51.08	34.07	38.64	39.39
3.5	-2.72	45.26	50.68	34.37	38.75	39.36
4.0	-2.75	45.37	50.12	34.62	38.87	39.34
4.5	-2.56	45.64	50.08	34.96	38.91	39.27
5.0	-2.44	45.82	50.00	35.02	39.02	39.22
5.5	-1.82	46.44	51.52	35.22	39.11	39.20
6.0	-2.13	45.65	50.28	35.43	38.97	39.19
6.5	-1.56	45.72	50.01	35.39	39.08	39.11
7.0	-1.64	45.83	49.88	35.56	39.11	39.05
7.5	-1.80	46.52	50.92	35.86	39.18	39.11
8.0	-1.12	45.74	50.13	35.78	39.04	39.06
8.5	-1.15	45.13	48.67	35.64	38.91	38.90
9.0	-1.02	45.33	48.52	35.71	39.02	38.86
9.5	-1.06	46.33	50.54	35.78	39.22	38.88
10.0	-1.01	46.24	50.77	35.93	39.12	38.88
10.5	-0.40	45.74	50.04	36.06	38.99	38.91
11.0	-0.59	45.82	49.84	36.14	39.23	38.90
11.5	-0.66	46.56	50.65	36.24	39.34	39.01
12.0	-0.09	45.61	49.69	36.10	39.22	38.92
12.5	-0.08	45.78	49.51	36.40	39.28	38.93
13.0	-0.29	46.51	50.64	36.56	39.28	39.00
13.5	-0.28	45.70	49.68	36.35	39.29	38.91
14.0	-0.60	46.45	50.18	36.55	39.54	38.99
14.5	-0.26	46.60	50.67	36.31	39.53	39.06
15.0	-0.26	45.43	49.05	36.48	39.34	38.93
15.5	0.21	46.70	50.69	36.36	39.68	39.01
16.0	0.15	46.35	50.55	36.22	39.50	39.04
16.5	0.22	45.84	49.86	36.12	39.45	38.94
17.0	0.22	45.55	48.64	36.12	39.44	38.88
17.5	0.55	46.78	51.07	36.23	39.66	38.97
18.0	0.63	46.68	51.40	36.27	39.62	39.04
18.5	0.64	45.99	49.81	36.34	39.59	39.06
19.0	0.06	46.54	50.31	36.34	39.53	38.99
19.5	0.52	46.85	51.68	36.41	39.60	39.07
20.0	0.79	46.63	51.18	36.50	39.63	39.13
20.5	0.64	46.75	50.39	36.79	39.64	39.15
21.0	0.69	46.70	50.46	36.71	39.47	39.06
21.5	0.74	46.17	50.18	36.42	39.46	38.94
22.0	0.84	45.89	49.60	36.61	39.37	38.91
22.5	0.89	46.75	50.41	36.59	39.55	38.93
23.0	0.77	46.37	50.58	36.41	39.63	38.91
23.5	1.18	45.92	49.53	36.53	39.51	38.80
24.0	1.13	46.98	50.86	36.67	39.75	38.84
24.5	1.59	46.67	50.95	36.53	39.67	38.77
25.0	1.21	45.83	49.56	36.44	39.53	38.55
25.5	1.53	46.04	49.04	36.37	39.53	38.46
26.0	1.54	46.95	51.23	36.59	39.73	38.44

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
26.5	1.45	45.99	49.92	36.62	39.57	38.32
27.0	1.90	46.23	49.37	36.26	39.79	37.84
27.5	1.42	46.38	49.82	36.11	39.72	37.71
28.0	1.76	46.60	50.47	35.90	39.73	37.94
28.5	1.55	46.14	50.25	36.08	39.67	37.74
29.0	2.15	46.20	49.75	36.46	39.72	37.48
29.5	2.46	47.01	51.20	36.50	40.00	37.75
30.0	1.23	45.99	49.82	36.51	39.69	37.81
30.5	-0.68	46.13	49.64	36.54	39.88	37.74
31.0	-0.74	46.82	51.13	35.99	40.04	37.72
31.5	-0.58	45.82	49.93	35.61	39.91	37.61
32.0	-0.59	45.04	48.31	35.81	39.82	37.43
32.5	-0.47	46.31	50.44	36.96	39.88	37.33
33.0	-0.51	46.76	51.60	35.93	40.21	37.31
33.5	-0.06	45.86	50.22	35.82	40.19	37.31
34.0	-0.13	45.95	50.04	36.11	40.27	37.33
34.5	0.33	46.14	49.83	36.03	40.45	37.29
35.0	0.04	46.54	50.72	36.71	40.17	36.91
35.5	0.28	45.54	49.59	37.15	40.03	36.76
36.0	0.04	45.31	49.27	36.76	40.02	36.83
36.5	0.63	45.15	48.57	36.58	40.24	36.82
37.0	0.90	45.67	49.20	36.46	40.52	37.08
37.5	1.01	46.12	50.13	36.54	40.57	37.08
38.0	1.25	45.83	50.13	36.44	40.59	37.10
38.5	0.71	45.74	50.19	37.03	40.48	37.09
39.0	0.89	45.36	49.63	37.32	40.64	37.20
39.5	1.27	45.43	49.48	37.56	40.70	37.31
40.0	1.38	45.82	49.70	37.64	41.00	37.42
40.5	1.41	46.06	50.09	38.20	41.22	37.57
41.0	1.88	45.75	49.65	38.03	41.32	37.59
41.5	2.03	46.31	50.59	38.78	41.31	37.74
42.0	2.16	46.15	49.94	38.86	41.60	37.89
42.5	2.39	46.46	50.70	38.86	41.80	37.94
43.0	1.90	46.32	50.76	38.76	41.91	38.06
43.5	2.26	46.58	51.08	39.19	42.02	38.14
44.0	2.41	46.90	51.87	39.87	42.20	38.39
44.5	2.82	46.70	52.00	40.49	42.37	38.63
45.0	2.84	46.53	51.42	40.47	42.56	38.78
45.5	3.17	46.57	51.37	40.77	42.51	38.89
46.0	3.17	46.61	51.64	41.12	42.67	39.05
46.5	3.26	46.90	51.70	41.64	42.75	39.20
47.0	3.33	46.88	51.75	42.87	42.79	39.42
47.5	3.52	46.77	51.34	42.19	42.89	39.48
48.0	3.21	46.13	50.68	42.14	42.99	39.59
48.5	3.78	46.20	51.07	42.28	42.91	39.61
49.0	3.46	46.39	51.11	42.77	43.34	39.86
49.5	3.72	46.40	50.98	43.28	43.44	40.08
50.0	4.04	46.65	51.59	43.37	43.59	40.21
50.5	3.53	46.33	50.40	43.69	43.64	40.32

TEMPERATURES, C

TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
51.0	4.04	46.57	50.89	43.76	43.84	40.46
51.5	3.90	46.85	50.97	44.23	43.99	40.67
52.0	3.90	46.47	50.11	44.42	43.93	40.78
52.5	4.06	46.65	50.68	44.18	43.93	40.73
53.0	4.39	46.71	51.15	44.30	43.67	40.83
53.5	4.07	46.44	51.00	44.42	43.77	40.84
54.0	4.23	46.13	50.88	44.59	43.94	40.96
54.5	4.12	46.18	50.85	45.02	43.93	41.13
55.0	4.25	46.48	51.32	45.47	44.23	41.31
55.5	4.31	47.10	51.63	45.85	44.55	41.50
56.0	4.88	47.39	51.74	46.29	44.67	41.92

CORN STARCH
29SEP93

Dryer setpoint temp., C	52	Starch slurry temp. (initial), C	55
Starch sample and tray, g	20.55	Film sample and tray, g	36.45
Dry sample and tray, g	5.16	Dryed film sample and tray, g	12.34
Beaker and slurry, g	546.62	Spatula tare, g	67.74
Beaker and rem. slurry, g	314.73	Spatula and slurry, g	81.04
Graduate tare, g	138.05		
Volume in graduate, ml	103		
Graduate and slurry, g	247.45		

Chamber air pressure, in H2O		Room temperature, C	
upper	1.8	wet bulb	13.3
lower	3.3	dry bulb	23.6
lower dP	2.8		

	COLUMN MASS, g				PRESSURE DROP, in H2O	
TIME, min	BLUE +	GREEN +	BLUE -	GREEN -	BLUE	GREEN
0	2568.4	2572.3	2605.6	2566.3		
4	2578.2	2580.0			0.176	0.118
8			2613.4	2572.1	0.169	0.119
12	2585.9	2585.9			0.177	0.114
16			2620.6	2578.0	0.168	0.117
20	2593.3	2591.8			0.179	0.115
24			2627.6	2584.1	0.165	0.120
28	2600.1	2597.8			0.174	0.112
32			2634.2	2590.3	0.164	0.120
36	2606.6	2603.7			0.170	0.113
40			2640.5	2596.4	0.166	0.122
44	2612.8	2609.7			0.170	0.115
48			2646.6	2602.6	0.165	0.120
52	2618.7	2615.6			0.170	0.119
56			2652.4	2608.7	0.170	0.121

		TEMPERATURES, C				
	Dehum	Blue	Green	Drying	Blue	Green
TIME, min		in	in	Surface	out	out
0.0	-12.10	36.78	40.99	33.50	35.54	37.66
0.5	-10.74	37.61	42.42	32.38	35.21	37.36
1.0	-9.40	38.45	42.83	31.63	35.00	36.76
1.5	-8.25	39.31	43.92	31.31	34.94	36.36
2.0	-7.98	39.08	43.53	31.11	34.72	36.05
2.5	-7.10	39.01	42.52	30.96	34.66	35.77
3.0	-6.61	39.55	43.46	31.05	34.64	35.50
3.5	-6.34	39.67	43.54	31.15	34.58	35.37
4.0	-6.37	39.69	43.51	31.35	34.28	35.17
4.5	-6.55	39.17	42.88	31.29	34.03	34.98
5.0	-6.24	39.58	42.71	31.40	34.16	34.78
5.5	-6.18	40.12	43.92	31.53	34.33	34.80
6.0	-5.98	40.39	43.88	31.37	34.46	34.71
6.5	-5.84	40.33	44.55	31.45	34.48	34.66
7.0	-5.97	40.14	43.88	31.61	34.40	34.66
7.5	-5.59	40.45	44.23	31.82	34.61	34.73
8.0	-5.61	41.18	44.81	32.36	34.54	34.81
8.5	-5.62	40.99	44.79	32.33	34.62	34.79
9.0	-5.68	41.10	44.77	32.47	34.61	34.77
9.5	-5.54	40.90	44.51	32.54	34.48	34.73
10.0	-5.63	41.04	44.84	32.34	34.67	34.67
10.5	-5.76	40.85	44.93	32.35	34.75	34.70
11.0	-5.64	41.08	44.63	32.43	34.82	34.76
11.5	-5.60	40.19	43.68	32.42	34.60	34.62
12.0	-5.03	40.06	43.60	32.67	34.36	34.61
12.5	-5.33	40.22	43.33	32.52	34.72	34.59
13.0	-5.63	40.79	44.00	32.54	34.85	34.59
13.5	-5.51	40.83	44.24	32.54	34.80	34.60
14.0	-5.36	40.59	44.27	32.59	34.70	34.59
14.5	-5.29	40.59	44.49	32.62	34.71	34.55
15.0	-5.25	39.68	42.62	32.60	34.59	34.50
15.5	-5.18	40.27	43.11	32.69	34.76	34.50
16.0	-5.41	40.36	43.48	32.92	34.83	34.63
16.5	-5.17	41.05	44.44	33.15	35.04	34.70
17.0	-5.15	41.08	44.53	33.23	35.15	34.85
17.5	-5.44	40.90	44.51	33.42	35.17	34.89
18.0	-5.13	41.69	45.15	33.72	35.32	35.00
18.5	-5.06	41.90	45.70	33.94	35.32	35.04
19.0	-4.91	41.85	45.69	34.15	35.24	34.99
19.5	-4.89	41.85	46.00	34.02	35.57	35.12
20.0	-5.22	41.64	45.50	33.97	35.58	35.16
20.5	-4.98	40.87	44.39	33.97	35.32	35.04
21.0	-5.13	40.66	43.93	34.04	35.33	35.02
21.5	-4.83	40.79	43.85	34.15	35.28	34.97
22.0	-5.36	41.12	44.21	33.92	35.48	35.02
22.5	-4.90	41.31	44.58	33.90	35.50	35.01
23.0	-4.94	41.95	45.73	34.14	35.69	35.08
23.5	-5.21	41.74	45.97	34.24	35.64	35.21
24.0	-5.05	41.97	46.19	34.43	35.82	35.29

		TEMPERATURES, C				
TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
24.5	-4.93	41.24	45.01	34.28	35.73	35.28
25.0	-4.99	41.40	45.22	34.53	35.84	35.33
25.5	-5.43	40.76	43.92	34.41	35.75	35.28
26.0	-4.94	41.44	44.35	34.44	35.87	35.26
26.5	-4.74	41.40	44.39	34.46	35.88	35.30
27.0	-4.94	41.35	44.56	34.40	35.81	35.27
27.5	-4.92	41.67	45.24	35.02	35.80	35.32
28.0	-5.06	41.32	44.36	35.05	35.74	35.40
28.5	-5.11	41.63	45.14	34.73	35.85	35.34
29.0	-4.89	41.31	45.03	34.67	35.79	35.36
29.5	-5.28	40.58	43.93	34.52	35.70	35.31
30.0	-5.30	40.34	43.16	34.38	35.65	35.25
30.5	-4.64	40.95	44.04	34.60	35.79	35.34
31.0	-4.93	41.05	44.31	34.62	35.82	35.32
31.5	-5.09	41.13	44.47	34.50	35.75	35.30
32.0	-5.26	40.79	44.49	34.45	35.66	35.22
32.5	-4.73	40.33	43.71	34.57	35.59	35.24
33.0	-4.80	40.29	43.12	34.62	35.66	35.22
33.5	-4.93	40.35	43.11	35.02	35.53	35.22
34.0	-4.64	41.10	44.27	34.91	35.79	35.27
34.5	-4.56	41.09	44.47	35.00	35.67	35.26
35.0	-4.64	40.99	44.96	35.19	35.64	35.29
35.5	-5.11	40.48	43.75	35.25	35.61	35.28
36.0	-4.94	40.22	43.07	35.26	35.60	35.34
36.5	-4.78	41.02	44.02	34.83	35.83	35.33
37.0	-5.23	41.04	44.91	34.86	35.85	35.44
37.5	-4.89	40.32	43.46	34.84	35.77	35.41
38.0	-4.65	40.76	43.55	34.90	35.89	35.43
38.5	-4.85	41.23	44.43	35.44	35.86	35.48
39.0	-4.96	41.24	44.68	35.52	35.83	35.46
39.5	-4.48	40.65	44.24	35.17	35.78	35.45
40.0	-4.87	40.42	43.80	35.09	35.80	35.40
40.5	-4.76	40.25	43.03	35.21	35.75	35.38
41.0	-4.74	40.71	43.56	35.49	35.75	35.38
41.5	-4.50	41.36	45.01	35.64	35.90	35.48
42.0	-4.35	41.09	45.12	35.69	35.86	35.52
42.5	-4.64	40.85	44.52	35.82	35.92	35.58
43.0	-4.47	40.99	44.53	35.71	36.11	35.69
43.5	-4.71	40.93	44.30	35.77	36.10	35.73
44.0	-4.76	41.35	44.98	35.78	36.26	35.78
44.5	-4.64	41.88	45.89	35.59	36.40	35.89
45.0	-4.28	41.36	45.17	35.59	36.35	35.92
45.5	-4.51	41.69	45.62	35.79	36.54	36.00
46.0	-4.86	41.02	44.12	35.89	36.43	36.01
46.5	-4.55	40.90	43.72	35.80	36.39	35.99
47.0	-4.58	41.15	43.80	36.16	36.33	35.96
47.5	-4.76	41.27	44.54	36.22	36.27	35.92
48.0	-4.83	41.23	44.93	36.22	36.26	35.92
48.5	-4.50	40.96	44.60	36.38	36.27	35.98

	TEMPERATURES, C					
TIME, min	Dehum	Blue in	Green in	Drying Surface	Blue out	Green out
49.0	-3.92	41.27	44.28	36.01	36.55	36.04
49.5	-4.69	41.96	45.47	36.17	36.73	36.17
50.0	-4.49	41.88	45.71	36.52	36.60	36.21
50.5	-4.81	40.95	44.10	36.71	36.50	36.19
51.0	-4.36	41.07	43.88	36.75	36.52	36.18
51.5	-4.49	41.21	44.02	36.29	36.63	36.17
52.0	-4.36	41.45	44.57	36.12	36.67	36.20
52.5	-4.54	41.47	44.75	36.12	36.60	36.17
53.0	-4.49	40.78	44.23	36.22	36.48	36.11
53.5	-4.18	40.74	43.75	36.63	36.46	36.13
54.0	-4.71	41.77	45.41	36.89	36.69	36.30
54.5	-4.13	42.39	46.60	36.84	36.90	36.45
55.0	-4.38	42.14	46.45	37.24	36.89	36.55
55.5	-4.38	42.13	46.06	36.93	37.04	36.61
56.0	-3.63	43.27	46.68	37.29	37.65	37.09

APPENDIX C

THIN FILM DRYING MODEL

PASCAL PROGRAM

APPENDIX C

THIN FILM DRYING MODEL

PASCAL PROGRAM

```
{*****************************************************************************}
{                                                                             }
{  Transient heat and mass transfer in a thin, shrinking film                 }
{  Copyright (c) 1993 by Todd and Tim Bowser                                  }
{                                                                             }
{  Version 3.0    10NOV93      Japan/USA                                      }
{*****************************************************************************}

program htfilma;

uses
  WinCrt, WinApi;  { Allows Golbal memory calls}
{
  This program demonstrates heat and mass transfer in a thin film over  a specified time period
and includes shrinkage.  A one-dimensional  finite element grid is generated and analyzed over
time in an iterative  fashion using the FE methods given by Segerlind (1984).

}
const
    A : real = 1;                          {Surface area of film, m2}
    R : real = 8.31434;                    {universal gas constant, J/mol*K}
    Rcal : real = 1.98E-3;                 {Universal gas constant,kcal/J*mol*K}
    MolecA : real = 18;                    {Molecular weight of water 18 g/mol}
    Tinf: real = 312.15;                   {temperature of air surrounding heating
                                           surface, K}
     {Constants for the saturation pressure equation (Keenan and Keyes, 1936)}
    RR : real = 22105649.25;               DD : real = 0.12558E-3;
    AA : real = -27405.526;                EE : real = -0.48502E-7;
    BB : real = 97.5413;                    FF : real = 4.34903;
    CC : real = -0.146244;                  GG : real = 0.39381E-2;
     {Potato starch constants used in water activity calculatin (van Den Berg et al., 1975}
    Cps : real = 19.03;                Vm : real = 13.27;
    kps : real = 0.662;
    hm : real = 0.014;                     {mass transfer coeff., m/sec}
    hconvsur : real = 140;                 {exper conv heat trans coeff for drying
                                           surface, W/m2*K}
    hconvinf : real = 140;                 {exper conv heat trans coeff for open starch
                                           surf, W/m2*K}
        {conv and mass trans coeffs check with experimental data for rice}
        {constants used in bulk density equation for potato from Lozano et al. (1983)}
    h : real = 1.202;
    l : real = -0.148;
    p : real = 0.259;
    q : real = 15.507;
```

```
type

   bigmatrix = array [1..100,1..100] of real;
   bigvector = array [1..100] of real;
   extndvector = array [1..100] of extended;
   bigpointer = ^bigmatrix;
   RealArrayNPbyNP = array [1..100,1..100] of real;
   RealArrayNP = array [1..100] of real;
   integerArrayNP = array [1..100] of integer;

var
        { declare all matrix and vector arrays as pointers,
        (expand integer arrays normally) }

   mcap:   bigpointer;          {moisture capacitance matrix}
   mstiff: bigpointer;          {moisture stiffness matrix}
   hcap:   bigpointer;          {heat capacitance matrix}
   hstiff: bigpointer;          {heat stiffness matrix}
   sstiff: bigpointer;          {shrinkage stiffness matrix

   {inverse calculation variables}
   inverse: bigpointer;   {storage space for inverse calc}
   mattem:  bigpointer;  {storage matrice for temporary math}
   pivot_flag: array[1..100] of integer;
   swap_row: array[1..100] of integer;
   swap_col: array[1..100] of integer;
   big, pivot_inverse, itemp, abs_element: real;
   n, row, col, swap, irow, icol: integer;
   {end of inverse calculation variables}

   diff:   ^bigvector;      {diffusion coefficient at node temp, m2/sec}
   cond:   ^bigvector;      {conduction coefficient for each node}
   length: ^extndvector;    {length between nodes, mm}
   mforce: ^bigvector;      {moisture force}
   hforce: ^bigvector;      {heat force}
   sforce: ^bigvector;      {shrinkage force}
   atemp:  ^bigvector;      {initial temperature of film}
   btemp:  ^bigvector;      {temperature of film after time step}
   ctemp:  ^bigvector;      {temporay temp storage vector}
   amois:  ^bigvector;      {initial moisture content of film, g/m3}
   tamois: ^bigvector;      {element storage}
   bmois:  ^bigvector;      {moisture of film after time step, g/m3}
   cmois:  ^bigvector;      {saves amois vector for shrinkage calcs, g/m3}
   tcmois: ^bigvector;      {element storage}
   Mc:     ^bigvector;      {Moisture content of film g H20/gdm}
   rhocarbo:   ^bigvector;          {density of carbohydrate, kg/m3}
   brhocarbo:  ^bigvector;          {density of carbohydrate after time step, kg/m3}
   tbrhocarbo: ^bigvector;          {element storage}
   rhowa:   ^bigvector;             {density of water, kg/m3}
   rhostarch:  ^bigvector;          {density of starch (increases on drying), kg/m3}
   trhostarch: ^bigvector;          {element storage}
```

```
shrinkv: ^bigvector;   {displacement vector for shrinkage, m}
Elast:  ^bigvector;    {Youngs modulus for starch elements, Pa}
tElast:  ^bigvector;   {element storage}
sbf: ^bigvector;       {final bulk shrinkage coeff}
lambda:  ^bigvector;   {thermal heat coefficient}
nnn: integer;                  {for LU decomposition routine}
ddd: real;
indx: integerArrayNP;
bbb: RealArrayNP;
aaa: RealArrayNPbyNP;

delta: real;                           {time step, seconds}
hinfevap: real;                {mass trans coeff. at interface }
hsurevap: real;                {mass trans coeff. at drying surface}
temp, temp4: real;
tsurf: real;
Mps, Mpa: real;                {moisture content of film at drying surface and air
                               interface, gH20/100g solids}
aws, awa: real;                {water activity of the film at drying surface and air
                               interface}
po: real;  {saturation vapor pressure of pure water in air at given Temp, Pa}
Ps: real;  {saturation vapor pressure of pure water in air at starch temp, Pa}
Pw: real; {vapor pressure of water at starch surface as a function of temp,          Pa}
phi: real; {shrinkage parameter}
kbulk: real;           {bulk shrinkage factor}
lbulk: real;                   {bulk shrinkage factor}
Ebarrier : real;       {Internal energy barrier for diffusion, Fish, B.P 1957}
D25 : real;                    {Diffusion coeff for starch gel desorption at 25C, Fish, B.P.
                       1957, cm2/sec}
Dlimit : real;                 {Limiting value of the diffusion coefficient, Fish, B.P. 1957}
kwater : real;                 {thermal conductivity of water, W/m*C}
kcarbo : real;         {thermal conductivity of carbohydrate, W/m*C}
cpwater : real;        {specific heat of water, kJ/kg*C}
cpcarbo : real;        {specific heat of carbohydrate, kJ/kg*C}
cpstarch : real;       {specific heat of starch, kJ/kg*C}
hfg : real;                    {latent heat of vaporization at saturation temp, J/g}
lhs : real;                    {integral heat of sorption for water in potato starch, J/g}
Qconv : real;                  {heat transfer by convection, W}
initmc: real;                  {initial moisture content, g H20/g dm}

nnodes: integer;       {number of nodes}
loop,k: longint;       {temporary program index}
i,j,element: integer;

F: text;
```

```
{-------------------------------------------------------------------------}
{                          PROCEDURES                                     }
{-------------------------------------------------------------------------}

procedure Grabmem;

begin
  Writeln('Grabbing memory and Initializing constants');
  mcap := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if mcap <> nil then     {check to see if memory was allocated}
    Writeln('1 got mcap...');

  mstiff := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if mstiff <> nil then     {check to see if memory was allocated}
    Writeln('2 got mstiff...');

  hcap := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if hcap <> nil then     {check to see if memory was allocated}
    Writeln('3 got hcap...');

  hstiff := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if hstiff <> nil then     {check to see if memory was allocated}
    Writeln('4 got hstiff...');

  sstiff := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if sstiff <> nil then     {check to see if memory was allocated}
    Writeln('5 got sstiff...');

  inverse := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if inverse <> nil then   {check to see if memory was allocated}
    Writeln('6 got inverse...');

  mattem := GlobalAllocPtr(gmem_Moveable, SizeOf(bigmatrix));
  if mattem <> nil then   {check to see if memory was allocated}
    Writeln('7 got mattem...   NOW TRYING VECTORS   ...');

  diff := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if diff <> nil then       {check to see if memory was allocated}
    Writeln('8 got diff...');

  cond := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if cond <> nil then     {check to see if memory was allocated}
    Writeln('8 got cond...');

  length := GlobalAllocPtr(gmem_Moveable, SizeOf(extndvector));
  if length <> nil then    {check to see if memory was allocated}
    Writeln('9 got length...');

  mforce := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if mforce <> nil then   {check to see if memory was allocated}
    Writeln('10 got mforce...');
```

```
hforce := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if hforce <> nil then    {check to see if memory was allocated}
  Writeln('11 got hforce...');

sforce := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if sforce <> nil then    {check to see if memory was allocated}
  Writeln('12 got sforce...');

atemp := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if atemp <> nil then    {check to see if memory was allocated}
  Writeln('13 got atemp...');

btemp := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if btemp <> nil then    {check to see if memory was allocated}
  Writeln('14 got btemp...');

ctemp := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if btemp <> nil then    {check to see if memory was allocated}
  Writeln('15 got ctemp...');

amois := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if amois <> nil then    {check to see if memory was allocated}
  Writeln('16 got amois...');

tamois := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if tamois <> nil then    {check to see if memory was allocated}
  Writeln('17 got tamois...');

bmois := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if bmois <> nil then    {check to see if memory was allocated}
  Writeln('18 got bmois...');

cmois := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if cmois <> nil then    {check to see if memory was allocated}
  Writeln('19 got cmois...');

tcmois := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if tcmois <> nil then    {check to see if memory was allocated}
  Writeln('20 got tcmois...');

Mc := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if Mc <> nil then        {check to see if memory was allocated}
  Writeln('21 got Mc...');

rhocarbo := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if rhocarbo <> nil then          {check to see if memory was allocated}
  Writeln('22 got rhcarbo...');

brhocarbo := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
if brhocarbo <> nil then         {check to see if memory was allocated}
  Writeln('23 got brhocarbo...');
```

```
  tbrhocarbo := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if tbrhocarbo <> nil then        {check to see if memory was allocated}
    Writeln('24 got tbrhocarbo...');

  rhowa := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if rhowa <> nil then    {check to see if memory was allocated}
    Writeln('25 got rhowa...');

  rhostarch := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if rhostarch <> nil then         {check to see if memory was allocated}
    Writeln('26 got rhostarch...');

  trhostarch := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if trhostarch <> nil then        {check to see if memory was allocated}
    Writeln('27 got trhostarch...');

  shrinkv := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if shrinkv <> nil then   {check to see if memory was allocated}
    Writeln('28 got shrinkv...');

  Elast := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if Elast <> nil then     {check to see if memory was allocated}
    Writeln('29 got Elast...');

  tElast := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if tElast <> nil then    {check to see if memory was allocated}
    Writeln('30 got tElast...');

  sbf := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if sbf <> nil then               {check to see if memory was allocated}
    Writeln('31 got sbf...');

  lambda := GlobalAllocPtr(gmem_Moveable, SizeOf(bigvector));
  if lambda <> nil then   {check to see if memory was allocated}
    Writeln('32 got lambda...    *****INITIALIZING*****');

end; { procedure Grabmem }

{-------------------------------------------------------------------------}

procedure Givebackmem;

begin

  GlobalFreePtr(mcap); {moisture capacitance matrix}
  GlobalFreePtr(mstiff); {moisture stiffness matrix}
  GlobalFreePtr(hcap); {heat capacitance matrix}
  GlobalFreePtr(hstiff); {heat stiffness matrix}
  GlobalFreePtr(sstiff); {shrinkage stiffness matrix

   {inverse calculation variables}
```

```
  GlobalFreePtr(inverse);          {storage space for inverse calc}
  GlobalFreePtr(mattem);           {storage matrice for temporary}
  GlobalFreePtr(diff);             {diffusion coefficient at node temp, m2/sec}
  GlobalFreePtr(cond);             {conduction coefficient for each node}
  GlobalFreePtr(length);           {length between nodes, mm}
  GlobalFreePtr(mforce);           {moisture force}
  GlobalFreePtr(hforce);           {heat force}
  GlobalFreePtr(sforce);           {shrinkage force}
  GlobalFreePtr(atemp);            {initial temperature of film}
  GlobalFreePtr(btemp);            {temperature of film after time step}
  GlobalFreePtr(ctemp);            {original temperature of film (saved)}
  GlobalFreePtr(amois);            {initial moisture content of film, g/m3}
  GlobalFreePtr(tamois);           {element storage}
  GlobalFreePtr(bmois);            {moisture of film after time step, g/m3}
  GlobalFreePtr(cmois);                  {saves amois vector for shrinkage calcs, g/m3}
  GlobalFreePtr(tcmois);           {element storage}
  GlobalFreePtr(Mc);               {Moisture content of film g H20/gdm}
  GlobalFreePtr(rhocarbo);         {density of carbohydrate, kg/m3}
  GlobalFreePtr(brhocarbo);        {density of carbohydrate after time step,
                                         kg/m3}
  GlobalFreePtr(tbrhocarbo);       {element storage}
  GlobalFreePtr(rhowa);            {density of water, kg/m3}
  GlobalFreePtr(rhostarch);        {density of starch, kg/m3}
  GlobalFreePtr(trhostarch);       {element storage}
  GlobalFreePtr(shrinkv);          {displacement vector for shrinkage, m}
  GlobalFreePtr(Elast);            {Youngs modulus for starch elements, Pa}
  GlobalFreePtr(tElast);           {element storage}
  GlobalFreePtr(sbf);              {bulk shrinkage coeff.}
  GlobalFreePtr(lambda);           {thermal heat coefficient}

end; { procedure Givebackmem; }

{-------------------------------------------------------------------------}

procedure matinverse(inmatrix : bigpointer);

var
  ii, jj : integer;

begin
  {find inverse of matrix pointed to by inmatrix (result placed in inverse^[r,c]) }
  n := nnodes;                     {single dimension (size) of square matrix}
  for ii := 1 to n do       {copy hcap into inverse and zero out index arrays}
  begin
    pivot_flag[ii] := 0;
    swap_row[ii] := 0;
    swap_col[ii] := 0;
    for jj := 1 to n do
    begin
      inverse^[ii,jj] := inmatrix^[ii,jj];
    end;
```

```
end;
for ii := 1 to n do   {n iterations of pivoting}
begin
  {find the biggest pivot element}
  big := 0.0;
  for row := 1 to n do begin
    if pivot_flag[row] = 0 then begin
      for col := 1 to n do begin
        if pivot_flag[col] = 0 then
        begin
          abs_element := Abs(inverse^[row,col]);
          if abs_element >= big then
          begin
            big := abs_element;
            irow := row;
            icol := col;
          end;
        end;
      end;
    end;
  end;
  pivot_flag[icol] := pivot_flag[icol] + 1;
  {swap rows to make this diagonal the biggest absolute pivot}
  if irow <> icol then begin
    for col := 1 to n do begin
      itemp := inverse^[irow,col];
      inverse^[irow,col] := inverse^[icol,col];
      inverse^[icol,col] := itemp;
    end;
  end;
  {store what's been swapped}
  swap_row[ii] := irow;
  swap_col[ii] := icol;
  {Look out! if pivot is zero!}
  if inverse^[icol,icol] = 0.0 then begin
    Writeln('ERROR:  SINGULAR MATRIX   press return');
    Readln;
    Halt(1);
  end;
  {divide the row by the pivot}
  pivot_inverse := 1.0/inverse^[icol,icol];
  inverse^[icol,icol] := 1.0; {pivot = 1 to avoid roundoff }
  for col := 1 to n do
    inverse^[icol,col] := inverse^[icol,col]*pivot_inverse;
  {fix the other rows by subtracting}
  for row := 1 to n do begin
    if row <> icol then begin
      temp := inverse^[row,icol];
      inverse^[row,icol] := 0.0;
      for col := 1 to n do
        inverse^[row,col] := inverse^[row,col] - inverse^[icol,col]*temp;
```

```
      end;
    end;
  end; {end n iterations of pivoting}
  {fix the affect of all the swaps for the final answer}
  for swap := n downto 1 do begin
    if swap_row[swap] <> swap_col[swap] then begin
      for row := 1 to n do begin
        temp := inverse^[row, swap_row[swap]];
        inverse^[row, swap_row[swap]] := inverse^[row, swap_col[swap]];
        inverse^[row, swap_col[swap]] := temp;
      end;
    end;
  end;   {inverse matrix of mcap now exists in inverse^[r,c] }
end; { procedure inverse( inmatrix : bigpointer ) }
{-------------------------------------------------------------------------}


procedure ludcmp(VAR aaa:          RealArrayNPbyNP;
                           nnn:    integer;
                 VAR indx:         IntegerArrayNP;
                 VAR ddd:          real);

const
  tiny = 1.0e-20;

var
  k,j,imax,i: integer;
  sum, dum, big: real;
  vv: ^RealArrayNP;     {vv stores the implicit scaling of each row}

begin
  {Find the LU decomposition of a matrix.  Used in combination with lubksb
  to solve linear equations or invert a matrix}
  new(vv);
  ddd:= 1.0;              {no row interchanges yet}
  for i := 1 to nnn do begin
    big := 0.0;
    for j := 1 to nnn do
      if abs(aaa[i,j]) > big then big := abs(aaa[i,j]);
    if big = 0.0 then begin     {No nonzero largest element}
      writeln('pause in LUDCMP - singular matrix');
      readln
    end;
    vv^[i] := 1.0/big           {save the scaling}
  end;
  for j := 1 to nnn do begin {this is the loop over columns of Crout's method}
    for i := 1 to j-1 do begin {this is equation 2.3.12 (but i=j) of Press et al., 1989}
      sum := aaa[i,j];
      for k := 1 to i-1 do
        sum := sum - aaa[i,k] * aaa[k,j];
      aaa[i,j] := sum
```

```
    end;
    big := 0.0;          {initialize the search for largest pivot element}
    for i := j to nnn do begin
      sum := aaa[i,j];
      for k := 1 to j-1 do
        sum := sum - aaa[i,k] * aaa[k,j];
      aaa[i,j] := sum;
      dum := vv^[i] * abs(sum); {is the figure of merit for the pivot better than the
                                          best so far?}
      if dum >= big then begin
        big := dum;
        imax := i
      end
    end;
    if j <> imax then begin     {do we need to interchange rows?}
      for k := 1 to nnn do begin  {yes, do so . . .}
        dum := aaa[imax,k];
        aaa[imax,k] := aaa[j,k];
        aaa[j,k] := dum
      end;
      ddd := -ddd;                {and change the parity of ddd}
      vv^[imax] := vv^[j]         {also interchange the scale factor}
    end;
    indx[j] := imax;
    if aaa[j,j] = 0.0 then aaa[j,j] := tiny;
    {if the pivot element is zero the matrix is singular.  For some applications
    on singular matrices, it is desirable to substitute tiny for zero}
    if j <> nnn then begin
      dum := 1.0 / aaa[j,j];      {now finally divide by the pivot element}
      for i := j + 1 to nnn do
        aaa[i,j] := aaa[i,j] * dum
      end
    end;                          {go back for the next column in the reduction}
    dispose(vv)
  end;                            {end procedure ludcmp}
{-------------------------------------------------------------------------}

procedure lubksb (VAR aaa:    RealArrayNPbyNP;
                      nnn:    integer;
                  VAR indx:   IntegerArrayNP;
                  VAR bbb:    RealArrayNP);

var
  j,ip,ii,i: integer;
  sum: real;

begin
  {solves the set of linear equations A*X=B with an LU decomposition as input.
  The result is with the solution vector X}
  ii := 0;
  {when ii is set to a positive value, it will become the index of the first
```

```
  nonvanishing element of b. We now do the forward substitution. The only new wrinkle is to
  unscramble the permutation as we go.}
  for i:= 1 to nnn do begin
    ip := indx[i];
    sum := bbb[ip];
    bbb[ip] := bbb[i];
    if ii <> 0 then
      for j := ii to i-1 do
        sum := sum - aaa[i,j] * bbb[j]
      else if sum <> 0.0 then  {A nonzero element was encountered, so from }
        ii := i;                {now on we will have to do sums in the loop above}
      bbb[i] := sum
    end;
    for i := nnn downto 1 do begin    {now we do backsubstitution}
      sum := bbb[i];
      for j:= i + 1 to nnn do
          sum := sum - aaa[i,j] * bbb[j];
      bbb[i] := sum / aaa[i,i]        {store a component of the solution in vector X}
    end
  end;                                {all done for lubksb }


{-------------------------------------------------------------------------}

begin {body of program}

  Writeln('Transient Heat and Mass Transfer in a Thin, Shrinking Film ');

  {-------------------------------------------------------------------------}
  { MEMORY GRABBING CODE ADDED BY TSB.  Note that all memory allocated must be
de-allocated at the end of the program or Windows might crash after program execution. For
safety, de-allocation should occur in reverse order of allocation shown here.}

  { ALL newly expanded variables have been converted to pointers, so access must be modified
to include a (^); ie, mcap[x,y] is now mcap^[x,y], and so on...     }

  Grabmem;

  {-------------------------------------------------------------------------}

  {matrix initialization}
  for i := 1 to 100 do begin
    shrinkv^[i]:= 0.0;
    length^[i]:= 0.0;
    for j := 1 to 100 do begin
      hcap^[i,j]:= 0.0;
      mcap^[i,j] := 0.0;
      hstiff^[i,j]:=0.0;
      mstiff^[i,j] := 0.0;
      sstiff^[i,j] := 0.0;
    end; {for j}
```

```
end; {for i}

Writeln('Enter the number of nodes (odd number)');
Readln(nnodes);

Writeln('Enter the initial film temperature, C');
Readln(temp);

Writeln('Enter the initial film moisture content, g H20/m3');
Readln(amois^[1]);
for i := 1 to nnodes do begin
   amois^[i] := amois^[1];
   cmois^[i] := amois^[1];
end;

for i := 1 to nnodes do
begin
  atemp^[i]:= temp;                {loads initial temp into atemp and btemp}
  btemp^[i]:= temp;
  ctemp^[i]:= temp;
      {initialize physical properties of starch system}
  rhostarch^[i]:= (h + (l * 1) + p * exp(-q * 1)) * 1000;    {starch density from Lozano et al.
                          (1983), for initial conditions x/xo = 1.0, kg/m3}
  rhocarbo^[i]:= rhostarch^[i] - amois^[i]/1000;   {density of carbohydrate in starch film (will
                          increase as starch drys), kg/m3}
  brhocarbo^[i]:= rhostarch^[i] - amois^[i]/1000;          {initialize variable}
  rhowa^[i]:= 1.1104E3 - 0.49437 * atemp^[i];              {density of water, kg/m3 (Okos, 1986)}
  Mc^[i] := amois^[i]/rhocarbo^[i]/1000;  {Moisture content of node, g H2O/gdm}
     {thermal conductivity equations Okos, 1986}
     {concentration of water (%) is amois^[i]/(rhowa^[i]*1000)}
  kwater := 0.59075 + 9.8601E-4 * atemp^[i];  {conductivity of water, W/m*C}
  kcarbo := 0.19306 + 8.4997E-4 * atemp^[i];   {conductivity of carbohydrate, W/m*C}
       {thermal conductivity of starch, W/m*C}
  cond^[i] := kwater * amois^[i]/1000/rhostarch^[i] +
          kcarbo * (1 - (amois^[i]/1000/rhostarch^[i]));
       {Specific heat from Okos, 199?}
  cpwater := 4.1598 + 4.2091E-4 * atemp^[i];  {specific heat of water, kJ/kg*C}
  cpcarbo := 1.8608 + 2.4311E-3 * atemp^[i];  {specific heat of carbohydrate, kJ/kg*C}
  cpstarch:= cpwater * amois^[i]/1000/rhostarch^[i] +
           cpcarbo *( 1 - (amois^[i]/1000/rhostarch^[i]));
  lambda^[i] := rhostarch^[i] * cpstarch * 1000;  {thermal diffusivity of starch, J/kg*C}
end;
initmc := Mc^[1];

Writeln('Enter the initial thickness of the film, mm');
Readln(temp);
temp := temp / 1000.0;                  {convert to meters}
temp := temp / (nnodes - 1);            {find thickness (length) of each element}
for element:= 1 to (nnodes - 1) do
begin
  length^[element] := temp;             {load initial thickness for each element}
```

```
end;

Writeln('Enter the time step, seconds');
Readln(delta);

Writeln('Enter the number of time steps');
Readln(loop);

{write useful information to disk, file on c:\ directory}
assign(F, 'c:\MOIS.TXT');
rewrite(F);
for i := 1 to nnodes do begin
  Writeln(F, Mc^[i],' , ',amois^[i],' , ', atemp^[i],' , ', length^[i]);
end;
close(F);

for k := 1 to loop do begin      {main loop for time differential}

 {calculate physical properties of starch film for each element}
  for i := 1 to nnodes do begin
    rhostarch^[i] := (h + (l * Mc^[i]/initmc) + p * exp(-q * Mc^[i]/initmc)) * 1000;
        {density of carbohydrate, kg/m3 from Lozano et al. 1983)}
    rhowa^[i] := 1.1104E3 - 0.49437 * atemp^[i];  {density of water, kg/m3}
    rhocarbo^[i] := rhostarch^[i] - amois^[i]/1000;
    Mc^[i] := amois^[i]/rhocarbo^[i]/1000;          {Moisture content of node, g H2O/gdm}
        {thermal conductivity equations in Okos, 1986}
        {concentration of water (decimal %) is amois^[i]/(rhowa^[i]*1000)}
    kwater := 0.59075 + 9.8601E-4 * atemp^[i]; {conductivity of water,W/m*C}
    kcarbo := 0.19306 + 8.4997E-4 * atemp^[i]; {conductivity of carbohydrate, W/m*C}
        {thermal conductivity of starch, W/m*C}
    cond^[i] := kwater * amois^[i]/ 1000 / rhostarch^[i] +
            kcarbo * (1 - amois^[i]/ 1000 / rhostarch^[i]);
        {Specific heat from Okos, 199?}
    cpwater := 4.1598 + 4.2091E-4 * atemp^[i];          {specific heat of water,kJ/kg*C}
    cpcarbo := 1.8608 + 2.4311E-3 * atemp^[i];          {specific heat of carbohydrate, kJ/kg*C}
    cpstarch:= cpwater * amois^[i] / 1000 / rhostarch^[i] +
          cpcarbo * (1 - amois^[i] / 1000/ rhostarch^[i]); {kJ/kg*C}
    lambda^[i] := rhostarch^[i] * cpstarch * 1000;          {thermal diffusivity of starch, J/kg*C}
  end;

  {code to build matrices and computed vectors}
  for element:= 1 to (nnodes - 1) do
  begin
   {build hstiff and hcap, hforce}
   {use average of adjacent node properties to get element properties }
    temp := (cond^[element] + cond^[element +1])/2 * A / length^[element];
    temp4 := (lambda^[element] + lambda^[element +1]) /2 * length^[element] / 2.0;
    {11}
    if element = 1 then
    begin
      hstiff^[element, element]:= temp;
```

```
      hcap^[element, element]:= temp4;
    end
    else
    begin
    hstiff^[element, element]:= hstiff^[element, element] +  temp;
    hcap^[element, element]:= hcap^[element, element] +  temp4;
  end;
  {12}
  hstiff^[element, element + 1] := temp * -1.0;
  {21}
  hstiff^[element + 1, element] := temp * -1.0;
  {22}
  if element = (nnodes - 1) then
  begin
    hstiff^[element + 1, element + 1]:= temp;
  end
  else
  begin
    hstiff^[element + 1, element + 1]:= temp;
  end;
  hcap^[element + 1, element + 1] := temp4;  {does not need conditional set}
end;

{build hforce vector}
for i := 1 to nnodes do begin
  hforce^[i] := 0.0;
  if i = 1 then
  begin
    Qconv := hconvsur * A * (Tinf - 273 - atemp^[i]);     {convective heat
        transfer between air and drying surface (Incropera and DeWitt, 1981)}
    hfg := (2502535.259 - 2385.764 * atemp^[i]) / 1000;          {latent heat of
        vaporization of water, J/g, (Brooker 1967)}
    temp := amois^[i]/1000/rhocarbo^[i]*100;     {g H20/100 g starch}
    if temp < 25 then begin
      ihs := 130.204 * exp(-0.098 * temp);        {integral heat of
        sorption of water in potato starch, J/g, (van den Berg et al., 1975)}
      hfg := hfg + ihs;
      hforce^[1] := hsurevap * hfg + Qconv;
    end
    else begin
      hforce^[1] := hsurevap * hfg + Qconv;
    end;
  end;
  if i = nnodes then begin
    Qconv := hconvinf * A * (Tinf - 273 - atemp^[i]);   {convective heat transfer
        between air and the open starch surface (Incropera and DeWitt, 1981)}
    hfg := (2502535.259 - 2385.764 * atemp^[i]) / 1000;   {latent heat of
        vaporization of water, J/g, (Brooker 1967)}
    temp := amois^[i]/1000/rhocarbo^[i]*100;     {g H20/100 g starch}
    if temp < 25 then begin
      ihs := 130.204 * exp(-0.098 * temp);        {integral heat of
```

```
        sorption of water in potato starch, J/g, (van den Berg et al., 1975)}
      hfg := hfg + ihs;
      hforce^[nnodes] := hinfevap * hfg + Qconv;
    end
    else begin
      hforce^[nnodes] := hinfevap * hfg + Qconv;
    end;
  end;
end;

{find inverse of hcap matrix (result placed in inverse^[r,c] matrix)}
matinverse(hcap);
{inverse matrix of hcap now exists in inverse^[r,c] }
{display output of inverse calculation for check}

{Modify the system equation since the drying surface temperature is a known constant}
{
for j:= 1 to nnodes do begin
  hforce^[j] := hstiff^[j,1]*tsurf + hforce^[j];
  hstiff^[1,j] := 0.0;        {node 1 is on the drying surface}
{  hstiff^[j,1] := 0.0;
end;
hforce^[1] := 0.0;

{solve the equation for btemp:
  hcap^[r,c]*btemp^[c] = (hcap^[r,c]-delta*hstiff^[r,c])*atemp^[] + delta*hforce^[] }
{1.  multiply delta through and leave results in hforce and hstiff }
for i := 1 to nnodes do begin
  hforce^[i] := hforce^[i] * delta;
  for j:= 1 to nnodes do
    hstiff^[i,j] := hcap^[i,j] - hstiff^[i,j] * delta;      {include subtraction}
end;
{2.  matrix multiply using atemp and leave results in hcap^[r,1]}
for i:= 1 to nnodes do begin
  hcap^[i,1] := 0.0;                {only first column of hcap carries answer}
  for j:= 1 to nnodes do begin {mXn * nXp = mXp; or result is nnodesX1}
    hcap^[i,1] := hcap^[i,1] +  (hstiff^[i,j] * atemp^[j]);
  end;
end;
{3.  do vector addition, element by element, and leave results in hforce}
for i:= 1 to nnodes do
  hforce^[i] := hforce^[i] + hcap^[i,1];
{4.  multiply inverse matrix by contents of hforce for btemp}
for i:= 1 to nnodes do begin
  btemp^[i] := 0.0;                 {initialize btemp to all zero}
  for j:= 1 to nnodes do begin {mXn * nXp = mXp; or result is nnodesX1}
    btemp^[i] := btemp^[i] +  (inverse^[i,j] * hforce^[j]);
  end;
end;
for i:= 1 to nnodes do
  atemp^[i] := btemp^[i];
```

```
{moisture matrix routine}

{Determine diffusivity of starch gel at each node, considering temperature and moisture
dependancy, from data from B.P. Fish (1957).}
for i := 1 to nnodes do begin
  if (amois^[i]/rhostarch^[i]/10 < 16) then begin   {Moisture content less than 16%}
  Ebarrier := 9.724 - 1.179 * ln(amois^[i]/rhostarch^[i]/10);  {Energy barrier of diffusion, kcal}
  D25 := 6.143E-11 * exp(0.5 * amois^[i]/rhostarch^[i]/10);  {Diffusivity at 25 C, cm2/sec}
  Dlimit := D25/exp(- Ebarrier/(Rcal * 298.15));          {diffusivity limit at 25C}
  diff^[i] := Dlimit * exp(- Ebarrier/(Rcal * (atemp^[i] + 273.15)))/10000*1.25;
          {diffusivity of starch gel at node temp, m2/sec}
  end
  else begin
  D25 := 5E-7;
  Ebarrier := 9.724 - 1.179 * ln(amois^[i]/rhostarch^[i]/10);  {Energy barrier of diffusion, kcal}
  Dlimit := D25/exp(- Ebarrier/(Rcal * 298.15));          {diffusivity limit at 25C}
  diff^[i] := Dlimit * exp(- Ebarrier/(Rcal * (atemp^[i] + 273.15)))/10000*1.25;
          {diffusivity of starch gel at node temp, m2/sec}
  end
end;

{determine water flux at surfaces of film}
      {water activity of film at the air surface}
Mpa := amois^[nnodes]/rhocarbo^[i]/10;        {g H2O/100 g solids}
if (Mpa < 38) then
  awa := 0.5*(Mpa*Cps - 2*Mpa - Cps*Vm + sqrt(Cps)*sqrt(sqr(Mpa)*Cps -
       2*Mpa*Cps*Vm + 4*Mpa*Vm + Cps*sqr(Vm))) / (kps*Mpa*(Cps - 1))
else awa := 1.0;
      {water activity of film at the dryer surface}
Mps := amois^[1]/rhocarbo^[1]/10;             {g H20/100 g solids}
if (Mps < 38) then
aws := 0.5*(Mps*Cps - 2*Mps - Cps*Vm + sqrt(Cps)*sqrt(sqr(Mps)*Cps -
      2*Mps*Cps*Vm + 4*Mps*Vm + Cps*sqr(Vm))) / (kps*Mps*(Cps - 1))
else aws := 1.0;
      {vapor pressure in the bulk gas, Pa}
Po := RR * exp((AA+BB*Tinf+CC*sqr(Tinf) + DD*sqr(Tinf)*Tinf + EE*sqr(Tinf)*sqr(Tinf)) /
      (FF*Tinf-GG*sqr(Tinf)));
Po := 0.05 * Po;  {relative humididy in bulk stream is about 5%}
      {vapor pressure at the drying surface, Pa}
temp:= atemp^[1] + 273.15;
Ps := RR * exp((AA+BB*temp+CC*sqr(temp) + DD*sqr(temp)*temp +
      EE*sqr(temp)*sqr(temp)) / (FF*temp-GG*sqr(temp)));
      {evaporation rate at the drying surface, g/sec}
hinfevap := hm*A*(Po/(R*Tinf)-aws*Ps/(R*(atemp^[1]+273)))*MolecA;
      {vapor pressure at the air interface, Pa}
temp:= atemp^[nnodes] + 273.15;
Ps := RR * exp((AA+BB*temp+CC*sqr(temp) + DD*sqr(temp)*temp +
      EE*sqr(temp)*sqr(temp)) / (FF*temp-GG*sqr(temp)));
      {evaporation rate at the air interface, g/sec}
hsurevap := hconvinf/hconvsur * hm * A *(Po/(R*Tinf) - aws *
      Ps/(R*(atemp^[nnodes] + 273))) * MolecA;
```

```
        {code to build matrices and computed vectors}
  for element:= 1 to (nnodes - 1) do
  begin
   {build mstiff and mcap, mforce}
   {use the average value of adjacent nodes to get element property values}
    temp := (diff^[element] + diff^[element + 1])/2 * A / length^[element];
    temp4 := length^[element] / 2.0;
    {11}
    if element = 1 then
    begin
    mstiff^[element, element]:= temp;
    mcap^[element, element]:= temp4;
  end
  else
  begin
    mstiff^[element, element]:= mstiff^[element, element] +  temp;
    mcap^[element, element]:= mcap^[element, element] +  temp4;
  end;
  {12}
  mstiff^[element, element + 1] := temp * -1.0;
  {21}
  mstiff^[element + 1, element] := temp * -1.0;
  {22}
  if element = (nnodes - 1) then
  begin
    mstiff^[element + 1, element + 1]:= temp;
  end
  else
  begin
    mstiff^[element + 1, element + 1]:= temp;
  end;
  mcap^[element + 1, element + 1] := temp4;  {does not need conditional set}
end;

 {build mforce vector}

for i := 1 to nnodes do begin
  if i = 1 then
    mforce^[1] := hsurevap                          {drying surface evap, g/sec}
  else if i = nnodes then mforce^[i] := hinfevap    {open surface evap, g/sec}
  else mforce^[i] := 0.0;                           {all interior nodes, no evap}
end;

{find inverse of mcap matrix (result placed in inverse^[r,c] matrix)}
matinverse(mcap);
{inverse matrix of mcap now exists in inverse^[r,c] }

{solve the equation for bmois: mcap^[r,c]*bmois^[c] = (mcap^[r,c] -
        delta*mstiff^[r,c])*amois^[] + delta*mforce^[] }
{1.  multiply delta through and leave results in mforce and mstiff^ }
for i := 1 to nnodes do begin
```

```
  mforce^[i] := mforce^[i] * delta;
  for j:= 1 to nnodes do
    mstiff^[i,j] := mcap^[i,j] - mstiff^[i,j] * delta;   {include subtraction}
end;
{2.  matrix multiply using amois and leave results in mcap^[r,1]}
for i:= 1 to nnodes do begin
  mcap^[i,1] := 0.0;              {only first column of mcap carries answer}
  for j:= 1 to nnodes do begin {mXn * nXp = mXp; or result is nnodesX1}
    mcap^[i,1] := mcap^[i,1] +  (mstiff^[i,j] * amois^[j]);
  end;
end;
{3.  do vector addition, element by element, and leave results in mforce}
for i:= 1 to nnodes do
  mforce^[i] := mforce^[i] + mcap^[i,1];
{4.  multiply inverse matrix by contents of mforce for bmois}
for i:= 1 to nnodes do begin
  bmois^[i] := 0.0;       {initialize bmois to all zero}
  for j:= 1 to nnodes do begin {mXn * nXp = mXp; or result is nnodesX1}
    bmois^[i] := bmois^[i] +  (inverse^[i,j] * mforce^[j]);
  end;
end;
for i:= 1 to nnodes do begin
  amois^[i] := bmois^[i];
end;

{reset all reused matrices to zero}
for i := 1 to 10 do
  for j := 1 to 10 do
begin
  hcap^[i,j]:= 0.0;
  mcap^[i,j] := 0.0;
  hstiff^[i,j]:=0.0;
  mstiff^[i,j] := 0.0;
end;
hforce^[i] := 0.0;
mforce^[i] :=0.0;

{Begin shrinkage section, complete every 100th iteration}
if k mod 100 = 0.0 then begin
for i := 1 to nnodes do  begin
      {Moisture content, g H20/g dm}
  temp := cmois^[i]/brhocarbo^[i]/1000; {old moisture content, g H20/g dm}
      {Shrinkage calculations from core model of Suzuki et al. 1976}
  if temp > Mc^[i] then begin
    phi := ((Mc^[i] + 1) * rhostarch^[i]) / ((temp + 1) * (brhocarbo^[i] + cmois^[i]/1000));
    kbulk := (1 - phi) / (Mc^[i] - temp);
    lbulk := (phi * Mc^[i] - temp) / (Mc^[i] - temp);
    sbf^[i] := exp(2/3 * ln(kbulk * (Mc^[i] + temp)/2 + lbulk));
      {linear coeff of shrinkage}
  end
  else begin
```

```
    sbf^[i] := 1.0
  end;
     {Modulus of Elasticity as a function of moisture content, Pa}
  temp := (bmois^[i]/(bmois^[i] + rhocarbo^[i]*1000))*100;
          {temporary variable for moisture content, % (wb) --> 100 factor since we are
          working with %'s    }
  if temp < 24 then begin
    Elast^[i] := 7.234 * exp(-0.044 * temp)*1E-7;  {Modulus of Elasticity, Pa
                                                    data from B.P. Fish (1957)}
  end
  else begin
    Elast^[i] := 2.5E-7;
  end;
end;

 {shrinkage force vector calculation from element force vectors}
 {average properties for elements in shrink force vector using nodal values and place into
temporary variables (start with "t") and use to calculate shrink force vector        }
 for i:= 1 to (nnodes - 1) do begin
  tElast^[i] := (Elast^[i] + Elast^[i+1])/2;
  end;
  for i := 1 to nnodes do begin
    if i = 1 then
    begin
      sforce^[1] := - A * tElast^[1] * (1 - (sbf^[1] + sbf^[2])/2);
        {use the average bulk shrinkage for the first two nodes in determining the bulk
        shrinkage of the first element}
    end
    else if i = nnodes then
    begin
    sforce^[nnodes] := A * tElast^[nnodes-1] * (1 - (sbf^[nnodes] + sbf^[nnodes-1])/2);
     {use average bulk shrinkage for  the last two nodes in determining sforce of last element}
    end
    else begin
      sforce^[i] := A * tElast^[i-1] * (1 - (sbf^[i-1]+ sbf^[i])/2) - A * tElast^[i] * (1 - (sbf^[i] +
            sbf^[i+1])/2);
       {use average bulk shrinkage for adjacent nodes in determining sforce of each element}
    end;
  end;
    for i := 1 to nnodes do begin   {set new initial values for next shrinkage iteration}
      cmois^[i] := amois^[i];
      brhocarbo^[i] := rhocarbo^[i];
    end;

    {code to build stiffness matrix for shrinkage}
  for element:= 1 to (nnodes - 1) do
  begin
  {build sstiff }
    temp := tElast^[element] * A / length^[element];
    {11}
    if element = 1 then
```

```
    begin
      sstiff^[element, element]:= temp;
    end
    else
    begin
      sstiff^[element, element]:= sstiff^[element, element] +  temp;
    end;
    {12}
    sstiff^[element, element + 1] := temp * -1.0;
    {21}
    sstiff^[element + 1, element] := temp * -1.0;
    {22}
    if element = (nnodes - 1) then
    begin
      sstiff^[element + 1, element + 1]:= temp;
    end
    else
    begin
      sstiff^[element + 1, element + 1]:= temp;
    end;
  end;

{1. Solve the equation:  sstiff^[i,j] * shrinkv^[j] = sforce^[j]; for the displacement vector shrinkv^[]
  a. get LU decomposition of sstiff^[i,j] via procedure ludcmp}

  for i := 1 to nnodes do begin          {places sstiff[i,j] into a[i,j]          }
    bbb[i] := sforce^[i];                {and sforce[i] into bbb[i]               }
    for j := 1 to nnodes do begin
      aaa[i,j] := sstiff^[i,j];
      sstiff^[i,j] := 0.0                {reset sstiff[i,j] to zero for next iteration}
    end; {for j}
  end; {for i}

  {modify the system of equations to account for the known displacement (zero) of the middle
node of the shrinking system.  Note that this routine is only valid if the shrinkage is symmetric
about the middle node.  The drying rate must be equal on both faces of the film (this is true for
experimental results of this work).                }

  {1.  All the coefficients of the stiffness matrix in the middle row are set =0 except for the
diagonal term.}
  for i := 1 to nnodes do
    if i <> succ(trunc(nnodes/2)) then aaa[succ(trunc(nnodes/2)),i] := 0.0;
  {2.  The middle term in the force vector is replaced by the product of
sstiff[mid,mid]*shrinkv[mid] (zero)  }
  bbb[succ(trunc(nnodes/2))] := 0.0;
  {3.  Eliminate the column of coefficients in the stiffness matrix that multiply shrinkv[mid]   }
  for i := 1 to nnodes do
    if i <> succ(trunc(nnodes/2)) then aaa[i,succ(trunc(nnodes/2))] := 0.0;
  {end system modification }

  nnn := nnodes;        {input for ludcmp and lubksb; gives dimension of A matrix}
```

```
    ludcmp(aaa,nnn,indx,ddd);

    {b. solve the linear equation A*x = b }

    lubksb(aaa,nnn,indx,bbb);    {places result in bbb[i] and the original aaa[i,j] is destroyed}

{2. Subtract the displacement vector from the element length vector given above }
    for i:=1 to (nnodes -1) do     { bbb[mid] is not used! (fixed surface) }
    begin
      if i <= trunc(nnodes/2) then length^[i] := length^[i] + bbb[i];
      if i >= trunc(nnodes/2) then length^[i] := length^[i] - bbb[i+1];
    end;
    end;   {end of loop to calculate shrinkage every 100th iteration}

  {Output data to disk}
    if (k=2400) or (k=4800) or (k=7200) or (k=9600) or (k=12000) or (k=14400)   or (k=16800) or
(k=19200) or (k=21600) or (k=24000) or (k=26400) or              (k=28800) or (k=31200) or
(k=33600) then begin
      Writeln('k = ',k);
      for i := 1 to nnodes do begin
        Append(F);
        Writeln(F, mc^[i], ' , ', amois^[i], ' , ', atemp^[i], ' , ', length^[i]);
      end;
      close(F);
    end;
  end;   {end of for k}

    {-------------------------------------------------------------}

    { RETURN GRABBED MEMORY TO OPERATING SYSTEM          }

    Givebackmem;

    {-------------------------------------------------------------}

    Writeln('Press <enter> to exit');
    Readln;
end.
```

VITA

Tim Bowser was born in New Kensington, Pennsylvania on September 17, 1962. He graduated from Kiski Area High School, Vandergrift, Pennsylvania, in May, 1980. Tim enlisted in the U.S. Army Reserve and was trained as a Combat Engineer at Fort Leonard Wood, Missouri, graduating in September, 1980. He was an active reservist at the 318th Light Equipment Maintenance Co., State College, Pennsylvania. He attended the Pennsylvania State University, University Park, Pennsylvania, and received a Bachelor of Science degree in Agricultural Engineering in May, 1984 and a Masters of Science degree in Agricultural Engineering in December, 1986. Tim joined the Gerber Products Company, Fremont, Michigan, as a Food Process Engineer from November, 1986 to August, 1991. He was awarded a National Needs Fellowship in Food Engineering at the University of Tennessee, Knoxville and completed the requirements for a Doctorate of Philosophy degree in Agricultural Engineering in December, 1993.

Tim is a member of the American Society of Agricultural Engineers and the Institute of Food Technologists. He is also a member of Tau Beta Pi and Gamma Sigma Delta honor societies.