

Modeling Simultaneous Shrinkage and Heat and Mass Transfer of a Thin, Nonporous Film During Drying

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ABSTRACT

Thin films of food products have long been dried commercially but the thin film drying process is not well understood. Modeling of a drying system is essential for understanding and improving it. A theoretical model for predicting the drying rate of thin films of nonporous foods was proposed, developed and evaluated. The model simultaneously considered shrinkage and heat and mass transfer within thin films dried on a surface with given boundary conditions. A finite element formulation of the model was used to develop numerical solutions of two governing equations. Starch was selected as a representative material for drying tests. Experimentally determined drying curves of modified corn, potato and rice starch films were compared to model predictions. The technique was useful in explaining the complex relationships of temperature, moisture and thickness profiles of drying films.

Key Words: thin film drying, starch, rice, potato, nonporous films

INTRODUCTION

THIN FILM DEHYDRATION is an important processing technique used to provide low cost, high quality, shelf stable foods. This process has been used commercially for many years. Thin film drying technology has advanced slowly and the process has not been well understood. Improvement of thin film drying could result from speeding up the process, improving the quality of final products, and reducing energy costs. Modeling of the drying system could help achieve such improvements.

Some observed complexities of thin film drying have been ascribed to product shrinkage and the variability of physical properties with changing moisture contents and temperatures (van Arsdel, 1947; Kozempel et al., 1986). Classical thermodynamics and heat transfer theory have been applied to develop mathematical models describing temperature and moisture distributions in films and slabs (Philips and de Vries, 1957; de Vries, 1958; Luikov and Mikhailov, 1965; Mikhailov, 1973; Raats, 1975; Whitaker, 1977, and others). Chirife (1983) and Keey (1990) questioned the use of complex mathematical models unless they could be supported by experimental results. Hougen et al. (1940) and Bruin and Luyben (1990) stated that the solutions to classical equations in their most general forms were not available and they must be solved using numerical techniques. Our objective was to develop a mathematical model to describe heat and mass transfer during thin layer drying of nonporous foods. The model could be used to derive data needed for thin film dryer design and process optimization based on variables such as film thickness, drying time and product temperature and moisture histories.

THEORY

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

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shrinking coordinate system. They successfully simplified the analysis by assuming a constant film temperature. Such is not a valid assumption for thin film drying. The film temperature varies; it is critical to finished product quality; and it also 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 heat and moisture diffusion. Since soybean drying was a relatively slow process (measured in days), Haghighi could assume constant physical properties (specific heat, density, thermal conductivity and moisture diffusivity) with good results. This would not be practical with a starch film, since the physical properties change radically during the short drying process.

Based upon the work of past researchers, a finite element approach could be used to model 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 instantaneous film temperature and moisture content (Fig. 1). We hypothesized this model would add to the theoretical knowledge on thin film drying without becoming so complicated as to have little utility in dryer design.

Model assumptions

Assumptions of the general model were:

1. Shrinkage and gradients in temperature and diffusivity are one dimensional, perpendicular to the surface of the film ("Z" direction, Fig. 1).
2. All moisture movement is by diffusion.
3. Shrinkage is due to moisture migration and 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.

Numbers three through five are from Misra and Young (1980).

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, commonly known as the diffusion equation, (Press et al., 1989) is

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

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/sec .

The diffusion equation does not allow for other phenomena such as capillarity, porous transport and gravity (Hougen et al., 1940). Equation (1), however, is valid for simple materials such as solutions and gels (e.g. starch) when the molecular transport of water takes place by diffusion (Hougen et al., 1940; Bruin and Luyben, 1990).

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

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

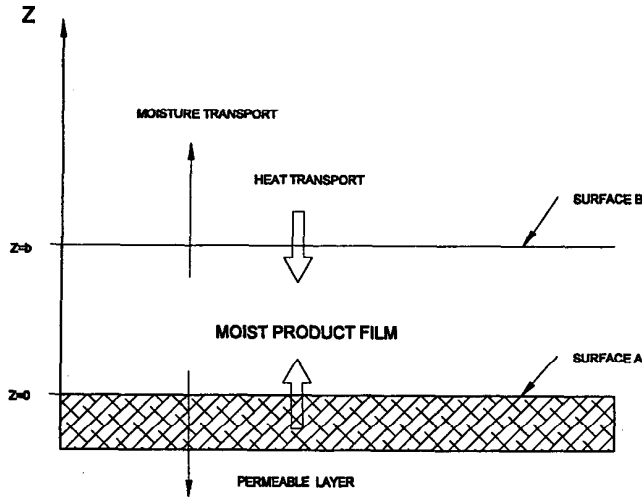


Fig. 1—Cross section of a drying starch film.

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

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 air film nearest surface A, kg/m^3 ; M_B = Moisture concentration of the air film nearest surface B, kg/m^3 ; $M_{\infty A}$ = Moisture content of ambient air over surface A, kg/m^3 ; and $M_{\infty B}$ = Moisture content of ambient air over surface B, kg/m^3 .

Heat diffusion

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

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

where ρ = Density of product film, kg/m^3 ; c_p = Specific heat of product film, $kJ/kg\cdot K$; T = Temperature, K ; and k = Thermal conductivity, $W/m\cdot K$.

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

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

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

where k_A = Thermal conductivity of the film, nearest surface A, $W/m\cdot K$; k_B = Thermal conductivity of the film, nearest surface B, $W/m\cdot K$; h_A = Convective heat transfer coefficient for surface A, $W/m^2\cdot K$; h_B = Convective heat transfer coefficient for surface B, $W/m^2\cdot K$; 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 ; and $T_{\infty B}$ = Temperature of ambient air over surface B, K .

Shrinkage

The shrinkage of a thin film could be modeled using a linear coefficient of hydal shrinkage (Misra and Young, 1980). Empirically determined shrinkage coefficients were reported by Lozano et al. (1983) and Suzuki et al. (1976). The film is regarded as a collection of axial members with individual displacements

$$\mu = L \beta \Delta M \quad (7)$$

where μ = Displacement of member, m ; β = Linear coefficient of hydal shrinkage, dimensionless; ΔM = Change in moisture content, %; and L = Length of member, m .

Finite element equations

The finite element equations are formulated using the direct stiffness method given by Segerlind (1984) (Fig. 1).

Moisture diffusion

The element equations for the moisture diffusion equation are given as

$$[k^{(e)}] = \frac{D}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \quad (8)$$

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

$$[c^{(e)}] = \frac{L}{2} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (9)$$

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

$$f^{(e)} = \begin{bmatrix} 0 \\ h_{MA} M_{\infty A} \end{bmatrix} + \begin{bmatrix} h_{MB} M_{\infty B} \\ 0 \end{bmatrix} \quad (10)$$

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

The first term on the right side of Eq. (10) applies to the surface of the film at $z = 0$. The second term applies to the surface of the film at $z = b$. All other terms in the force vector are zero.

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

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

and again using the lumped formulation, the capacitance matrix is

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

and

$$f^{(e)} = \begin{bmatrix} 0 \\ h_A T_{\infty A} \end{bmatrix} + \begin{bmatrix} h_B T_{\infty B} \\ 0 \end{bmatrix} \quad (13)$$

is the force vector. The first term in Eq. (13) applies only to the surface of the film at $z = 0$. The second term applies to the surface of the film at $z = b$. All other terms in the heat diffusion force vector are set equal to zero.

General finite element solution

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

$$[C] \Phi_b = ([C] - \Delta t [K]) \Phi_a + \Delta t F \quad (14)$$

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, and F = Force vector before time step.

Equation (14) can be solved for Φ_b using a computer and standard matrix manipulation routines Press et al. (1989).

Time step

The time step size must be $> zero$ and satisfy

$$\Delta t < \frac{L^2}{4D} \quad (15)$$

for the moisture diffusion equation and

$$\Delta t < \frac{\rho c_p L^2}{4k} \quad (16)$$

Table 1—Starch(s) and water (w) properties used in the model

Property	Value or equation
Density (kg/m ³) ^a	$\rho_s = 1202 - 148 \times \frac{x}{x_0} + 259 \times \exp \left[-15.507 \times \frac{x}{x_0} \right]$ <p>Where: x = moisture content x_0 = initial moisture content $\rho_w = 1110.4 - 0.49437 \times T$ (°C)</p>
Diffusivity (cm ² /s) ^b	$D = D_L \times \exp \left[\frac{-E}{R \times T} \right] \quad D_L = \frac{D_{25}}{\exp \left[\frac{-E}{R \times 298.15} \right]}$ $E = 9.724 - 1.179 \times \ln \left[\frac{m_c}{\rho} \right] \text{ (kCal)} \quad R = 1.98E-3 \left(\frac{\text{kCal}}{\text{J mol K}} \right)$ <p>For $m_c < 16\%$, $D_{25} = 6.143E-11 \times \exp \left[0.5 \frac{m_c}{\rho} \right]$</p> <p>for $m_c \geq 16\%$, $D_{25} = 5.0 E-11$</p> <p>Where: D_L = diffusivity limit at 25°C; D_{25} = diffusivity at 25°C; E = energy barrier of diffusion; R = universal gas constant; m_c = moisture content, decimal (wb).</p>
Sorption Isotherm ^c	<p>For $m \geq 38$, $a_w = 1.0$</p> <p>For $m < 38$,</p> $a_w = 0.5 \times \left[\frac{m \times C - 2 \times m - C \times V + \sqrt{C} \sqrt{m^2 \times C - 2 \times m \times C \times V + 4 \times m \times V + C \times V^2}}{k \times m \times (C-1)} \right]$ <p>Where: $k = 0.662$; $C = 19.03$; $V = 13.27$; $m = \frac{\text{g H}_2\text{O}}{100\text{g solids}}$</p>
Thermodynamics ^d	$C_{ps} = 1.8608 + 2.4311 E-3 \times T$ (°C) $C_{pw} = 4.1598 + 4.2091 E-4 \times T$ (°C)
k (W/m C)	$k_g = 0.19306 + 8.4997 E-4 \times T$ (°C) $k_w = 0.59075 + 9.8601 E-4 \times T$ (°C)
LHV (kJ/kg)	$h_{fg} = 2502.535 - 2.3858 \times T$ (°C) $i_{hs} = 130.204 \times \exp(-0.098 \times m); \quad m = \frac{\text{kg H}_2\text{O}}{100 \text{ kg starch}}$ <p>LHV = $i_{hs} + h_{fg}$</p> <p>Where: LHV = Latent heat of vaporization, H₂O in starch</p>
Shrinkage ^e	$s_b = \left[k_b \left(\frac{m_i + m_c}{2} \right) + L_b \right]^{2/3}$ $L_b = \frac{\Phi m_i - m_c}{m_i - m_c}; \quad k_b = \frac{1 - \Phi}{m_i - m_c}; \quad \Phi = \frac{(m_i + 1)\rho_i}{(m_o + 1)\rho_o}$ <p>Where: m_i = moisture content, dry basis m_o = previous moisture content, dry basis ρ_i = density, kg/m³ ρ_o = previous density, kg/m³</p>

^a Lozano et al. (1983) (for ρ_s) and Okos (1986) (for ρ_w).

^b Fish (1957).

^c van den Berg et al. (1975).

^d Okos (1986) (for C_p and k); Brooker (1967) (for h_{fg}); and van den Berg et al. (1975) (for i_{hs}).

^e Suzuki et al. (1976).

for the heat diffusion equation. The time step restriction is necessary to insure that the quantity $([C] - \Delta t[K])$, from Eq. (14), remains positive definite (Mohtar and Segerlind, 1992; Haghghi and Segerlind, 1988; Misra and Young, 1979).

Finite element solution

Simultaneous solution of Eq. (1), (4) and (7) will give the instantaneous moisture concentration, temperature and thickness of a drying

film. This is accomplished by numerically solving Equation (1) for a given time step to obtain the moisture profile. Next, the results are used in a numerical solution of Eq. (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, Eq. (10) and (13), respectively. The thermal energy required to evaporate 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 profile can be used in the solution

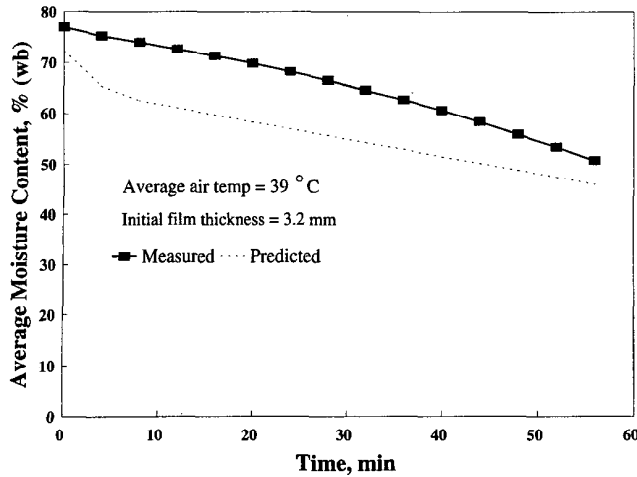


Fig. 2—Predicted and measured drying curves for modified corn starch on a water vapor permeable drying surface.

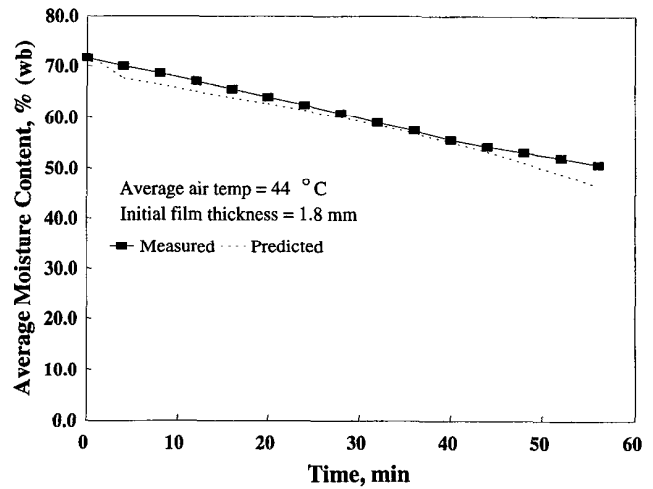


Fig. 5—Predicted and measured drying curves for rice starch on an impermeable drying surface.

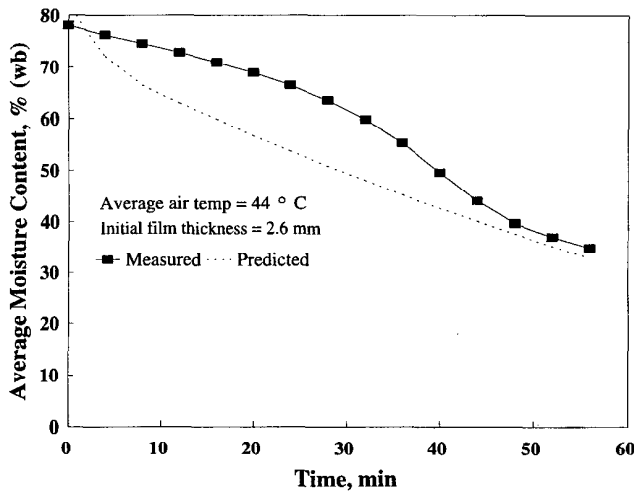


Fig. 3—Predicted and measured drying curves for potato starch on a water vapor permeable drying surface.

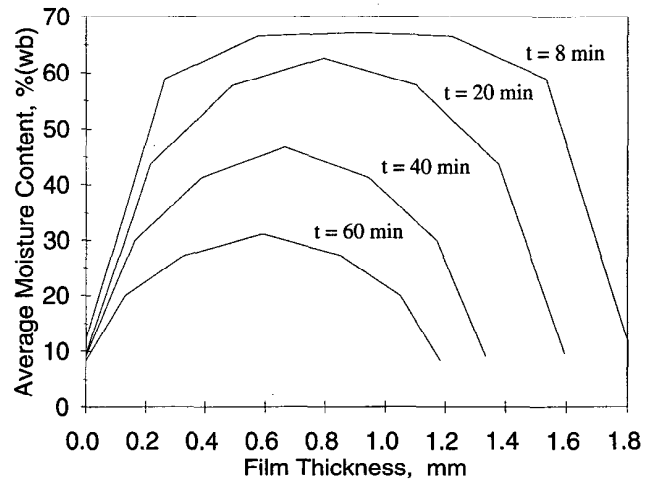


Fig. 6—Predicted moisture distribution and shrinkage of a rice starch film during drying.

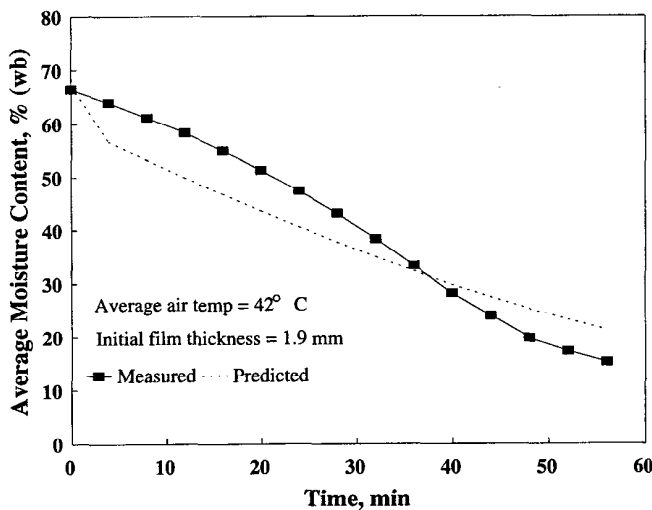


Fig. 4—Predicted and measured drying curves for rice starch on a water vapor permeable drying surface.

of Eq. (7) to find film shrinkage. This procedure is repeated iteratively until the system reaches equilibrium conditions or the desired drying period expires. The described model was implemented using the Pascal programming language. A fully commented program code listing (including references for physical property equations) is available in Bowser (1994).

Satisfactory implementation of the finite element solution required determination of several physical property parameters as the film was heated and dried. Table 1 lists the relationships used for these parameters.

MATERIALS & METHODS

Experimental verification of the model

Experimental verification of the finite element model was performed using data collected by Bowser (1994). The drying chamber was a custom fabricated unit that provided two paths for air flow. The first path permitted air to flow over the surface of the drying film in a conventional drying technique. The drying film rested on a permeable stainless steel fiber media treated with a release agent to prevent product sticking and pore clogging. This media was supported by a macroporous copper material that served as the second path for air flow through the drying chamber. The flow of drying air above the film and below the permeable support of the film permitted approximately equal drying rates from both film surfaces.

Room air was conditioned by dehumidification and heating and directed to the drying chamber. Immediately before entering the chamber,

the flow was divided to provide approximately equal flow rates and air pressures within each flow channel. Air exiting the two channels through the drying chamber was passed through desiccant columns filled with a molecular sieve desiccant. Two desiccant columns were used for each channel. Flow was alternated between the desiccant columns on each channel to permit weighing, at 4 min intervals. The desiccant columns were removed from the system and weighed on a scale to determine moisture removed during the drying process.

Starch gel was a logical selection as the test product since it is a principle constituent of many food materials (Fish, 1957) and is often dried in thin films. Starch materials are readily available and simple to handle. In addition, extensive published information regarding starch properties is readily available (see Table 1). Three starch products were used: corn starch, potato starch, and rice starch. Each product was dried using the same procedure. A starch slurry was prepared and applied to the drying surface in the thinnest layer possible (about 1.9 mm for rice starch and 3.2 mm for others). The drying chamber was sealed, and drying air was forced through the two channels in the chamber. Temperature of drying air was well below that of typical commercial drying. This was necessary to produce a drying period long enough such that the time to manually apply the film to the drying surface and to start the dryer would not significantly affect results. Also, drying rates and other drying parameters could be effectively measured.

RESULTS & DISCUSSION

RESULTS OF THE MODEL'S PREDICTIONS were compared to experimentally determined drying curves of modified corn, potato, and rice starch films (Figs. 2, 3 and 4). Measured and predicted drying curves were compared for corn, potato and rice starch films dried on a water vapor permeable surface. The measured and predicted drying curves for a rice starch film dried was also compared on an impermeable surface (Fig. 5).

While generally tending to overestimate drying rates, the model gave good approximations of experimental drying curves of the starch films. The initial, steep descent of the predicted drying curve was a result of high water vapor pressure (fully wetted conditions) at the surfaces of the film as estimated by the model of van den Berg et al. (1975). The predicted drying curve had a much shallower slope as the water vapor pressure at the surfaces began to drop and the temperature of the film stabilized. The measured curve did not show an initial, steep descent probably because some drying occurred during application of the film and related start up procedures (Bowser, 1994). Removal of the wetted surface component of the model would result in considerably greater agreement between the model and the measured data. Other differences between the model and experimental results may be due to differences in physical properties of specific starches compared to the published values.

Predicted values of moisture concentration and film thickness at indicated times were compared (Fig. 6) for a rice starch film dried on an experimental, water vapor permeable drying surface. The film thickness prediction was based on the verified model of Suzuki et al. (1976). The initial film and boundary conditions for the plot were assumed to be the same as those obtained by measurement during the rice starch drying experiment (Fig. 4). These data (Fig. 6) are based upon output of the mathematical model. They provide a very powerful technique for visualizing complicated relationships between temperature, moisture and thickness of a drying film. While not shown, temperature profiles across the film could also be computed in a similar manner.

The model represents a unique application linking previously developed models to simultaneously solve for heat transfer, mass transfer, and shrinkage in thin film drying. The model requires further testing to compare predictions to thin film drying data obtained over much shorter drying periods (<15 secs). High speed drying is required for industrial applications and may result in steep temperature gradients and radical, physical

property changes. The model provides a convenient and low cost means to predict and investigate such conditions.

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