x = distance
X = dimensionless distance, x/a or $(a - x)/a$
y = temperature difference defined by Eq. 24
z = temperature difference defined by Eq. 24

Greek Letters

$\alpha_j = \kappa_j/\kappa_1$
$\beta_j = K_{j+1}/K_j$
κ = thermal diffusivity
ρ = average density of the system
ϕ = volume fraction

Subscripts

o = initial
a = ambient
c = at the center
fj = jth moving front of phase change
i = ith isotherm
j = jth region
m = isotherm closest to $X = 1$

Superscripts

n = nth time step

Kinetics of the Approach to Sorptional Equilibrium by a Foodstuff

The kinetics of equilibration of a vegetable foodstuff with moist air are studied on the basis of its cellular structure. The problem is modelled as a coupled heat and mass transfer phenomenon; since there is a significant shrinkage as moisture decreases, the model takes the effect into account by changing the basis for the mass and energy balances. The resulting nonlinear second-order partial differencial equations are solved numerically; predicted values of moisture decrease and temperature gain with time are compared with experimental data. A sensitivity analysis of the solution to values of the transport properties shows that the value of effective diffusivity and heat and mass transfer coefficient may alter significantly the predicted equilibration kinetics and center temperature. The adopted value for heat of sorption has less influence. Changes in effective thermal conductivity and porosity bear little influence on predictions.

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SCOPE

Many practical design problems, such as dehydration, packaging and storage, arise when a foodstuff is removed from an equilibrium situation and is required to attain a new one. Much attention has been given to experimental determinations and theoretical predictions of the equilibrium values for the system moist air-foodstuff. The latter were based on adapting theoretical expressions developed for the sorption of gas molecules on nonvolatile solid surfaces or were empirical correlations (Labuza, 1974). An alternative approach was to recognize the actual cellular tissue structure of the foodstuff and to develop a predictive equation on the basis of equal chemical potential at the intervening phases (Rotstein and Cornish, 1978b).

Much less attention has been given to the kinetics of the phenomenon by which equilibration is attained (Román et al., 1979), although the subject is of interest because of many practical situations in packaging as well as in storing, be it cold, room temperature or controlled atmosphere conservation. In such cases it is required to model the kinetics to approach the problem in a sound engineering fashion. If the understanding of the kinetics is based on recognizing the actual cellular tissue structure of the foodstuff, it has the potential of providing useful insight as to the relationship between structure and behavior. In addition, the parallel between the situation of moisture equilibration and drying provides insight useful for the latter process.

In this paper, a model is built on the basis of the cellular structure of a typical fruit and the fact that moisture equilibration is a coupled heat and mass transfer phenomenon. This is done paying due attention to the shrinkage that characterizes the loss of moisture by a foodstuff. The resulting predictions of moisture loss and internal temperature change as a function of time are compared with experimental data. The sensitivity of the solution to the values of the transport properties is then tested.

CONCLUSIONS AND SIGNIFICANCE

It is shown that the model built provides acceptable predictions of moisture loss and internal temperature change with time, when shrinkage is taken into consideration. This is not the case when the predictions are made disregarding shrinkage. The sensitivity analysis indicates that the predictions change significantly when the effective mass diffusivity, heat transfer coefficient, or mass transfer coefficient are modified. They are much less sensitive to the values of effective thermal conductivity, heat of sorption and porosity.

The information obtained provides insight as to what is controlling the process from an internal and external standpoint. The structure of the subject matter should be helpful in designs and as a tool of innovation.

The equilibration of the water–foodstuff system involves a

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process of coupled heat and mass transfer, which can be modelled in mathematical terms. The mass transfer process has been described (Rotstein and Cornish, 1978 a,c) as a series of diffusional steps from the main water reservoirs, the cellular vacuoles, through the enveloping structure made of the cellular membrane and cell wall, the intercellular spaces, and the outside boundary layer.

It is possible to modelate the process by considering vapor-phase diffusion through the voids as the controlling step for internal mass diffusion. The reasonability of the assumption has been proven (Rotstein and Cornish, 1978a). Although the process does not differ from drying and other similar operations, the low temperature and low external turbulences result in a matching of internal and external resistances which give interest to the problem and precludes the use of the traditional simplified approach of total internal mass transfer control. In this sense the problem is an extreme case of King's (1968) analysis of a food drying problem, as shown by Román et al. (1979) in an earlier simplified analysis.

THEORY

The process is thought of as diffusion of water vapor through a porous-like open structure. The equivalent to a solid matrix is provided by cellular tissue, the voids being the intercellular spaces. These spaces are large (average 541×10^{-6} m $\times$ 275×10^{-6} m in the case of apples according to Reeve, 1953), interconnected and filled with air, thus providing a uniform macroporous structure. Water is contained mainly in the vacuole as a sugar solution in the case of apples. The osmotic properties given to the cell by the semipermeable cellular membrane insure that all water in the voids will be present as water vapor. When the system is removed from equilibrium at the start of a sorptional equilibration experiment, it is assumed that the controlling internal water migration step is the flow of water vapor through the intercellular spaces. The validity of the assumption has been discussed by Rotstein and Cornish (1978a).

Three assumptions needed for solving the mathematical problem. First, there is local equilibrium at each internal point. Second, the system can be treated as a quasi-one-phase system so that it is possible to define effective values for water-air mass diffusivity and for the thermal conductivity of the foodstuff. Third, the water vapor flows through a stagnant air phase.

The equilibration here described is that corresponding to a desorption process the food material will lose water until it reaches equilibrium with the prevailing external water activity. There is a significant decrease in sample volume as moisture decreases. This is a fact largely ignored in the previous literature, as shown by the few citations in Bruin and Luyben's (1980) comprehensive review. This shrinkage is a function of moisture content which can be represented by Eq. 1 (Lozano et al., 1980):

$$\frac{V_b}{V_{b,o}} = 0.17 + 0.11X \qquad (1)$$

Shrinkage can be incorporated into the analysis by using the approach suggested by Crank (1975), relacing the usual volume-fixed section by an alternative frame of reference to carry out the material and energy balances. The convention used here is to define a section fixed with respect to the mass of dry matter. To do this, consider a slab of material being equilibrated such that the length in two directions is large enough to make the process unidimensional along, say, the x axis.

Solid density ρ_s refers to the volume occupied by 1 kg of dry matter when no pores remain. Bulk density ρ_b is the density measured to include the volume of solid and liquid material plus all pores. Bulk density of dry matter, ρ_{db}, refers to the mass of dry matter per unit volume of moist sample, i.e., the same volume as in ρ_b. It is easy to see:

$$\rho_{db} = \frac{\rho_b}{1 + X} \qquad (2)$$

$$\rho = \left(\frac{\rho_{db}}{1 - \epsilon}\right)_{X=0} \qquad (3)$$

A fictitious z length for the volume containing 1 kg of dry matter can be related to the actual sample volume containing the same amount of dry matter by Eq. 4:

$$\frac{\Delta x}{\Delta z} = \frac{\rho_s}{\rho_{db}} \qquad (4)$$

leading to:

$$\Delta z = \frac{\rho_b}{(1 + X)\rho_s} \Delta x \qquad (5)$$

Transport Equations

Because z refers to the volume of compacted dry matter, it will not be affected by shrinkage, thus providing a suitable basis to develop the continuity and energy equations by writing the appropriate balances for a volume of dry solid which contains the unit weight of dry matter.

Thus, the continuity equation can be written:

$$-\frac{\partial n}{\partial z} = \frac{\partial \rho_s X}{\partial t} \qquad (6)$$

The flux, using the stagnant air assumption as indicated above:

$$n = -\rho_g \frac{\epsilon \rho_s}{\rho_{db}} D' \frac{\partial \omega}{\partial z} + \omega n \qquad (7)$$

It is convenient to use vapor mol fractions:

$$n = -\rho_g \frac{\epsilon \rho_s}{\rho_{db}} D' \frac{M_w}{M_g} \frac{\partial y}{\partial z} + ny \qquad (8)$$

Since $X = X(y,T)$, invoking the local equilibrium assumption the chain rule can be used on the righthand side of Eq. 6 to make the dependence explicit. This result and Eq. 8 allow to write Eq. 6 as:

$$Q_l \frac{\partial y}{\partial t} + \frac{\partial ny}{\partial z} = \frac{\partial}{\partial z}\left\{\rho_g e D' \frac{M_w}{M_g} \frac{\partial y}{\partial z}\right\} + P_l \frac{\partial T}{\partial t} \qquad (9)$$

where

$$Q_l = \rho_s \left(\frac{\partial X}{\partial y}\right)_T \qquad (10)$$

$$P_l = -\rho_s \left(\frac{\partial X}{\partial T}\right)_y \qquad (11)$$

$$e = \frac{\rho_s}{\rho_{db}} \qquad (12)$$

Equation 9 can be further developed to obtain Eq. 13:

$$\beta\left(\frac{\partial \delta}{\partial z} + \frac{\delta}{(1 - y)}\right)\frac{\partial y}{\partial z} + \beta\delta \frac{\partial^2 y}{\partial z^2} = Q_l \frac{\partial y}{\partial t} - P_l \frac{\partial T}{\partial t} \qquad (13)$$

where:

$$\beta = \frac{p \rho_s M_w}{R(1 - y)} \qquad (14)$$

$$\delta = \frac{\epsilon D'}{\rho_{db} T} \qquad (15)$$

This is a nonlineal second-order partial differential equation, where β, δ, $(\partial X/\partial y)_T$ and $(\partial X/\partial T)_y$ are functions of T and y.

The general multicomponent energy transfer equation (Bird et al., 1960), for the case of constant total pressure, negligible viscous dissipation and body forces and ideal gas behavior, simplifies to:

$$\sum_i \left(\gamma_i \frac{\partial \hat{H}_i}{\partial t} + \hat{H}_i \frac{\partial \gamma_i}{\partial t} + \hat{H}_i \underline{\nabla} \cdot n_i + n_i \cdot \underline{\nabla} \hat{H}_i\right) = \underline{\nabla} \cdot (k \underline{\nabla} T) \tag{16}$$

This balance equation refers again to a solid volume containing the unit weight of dry matter. Thus:

$$\gamma_v = \rho_v \frac{\epsilon \rho_s}{\rho_{db}} \tag{17}$$

$$\gamma_a = \rho_a \frac{\epsilon \rho_s}{\rho_{db}} \tag{18}$$

$$\gamma_\ell = X \rho_s - \gamma_v \tag{19}$$

$$\gamma_s = \rho_s \tag{20}$$

These definitions are replaced in Eq. 16, enthalpies are replaced as a function of temperature, and the following expression for the one-dimensional case is obtained:

$$(\rho_e \hat{c}_e + \xi \Delta \hat{H}_{sp}) \frac{\partial T}{\partial t} + n \hat{c}_{pv} \frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \Psi \Delta \hat{H}_{sp} \frac{\partial y}{\partial t} \tag{21}$$

where:

$$\rho_e \hat{c}_e = (\rho_v \hat{c}_{pv} + \rho_a \hat{c}_{pa}) + (X \rho_s - e \rho_v) \hat{c}_{p\ell} + \rho_s \hat{c}_{ps} \tag{22}$$

$$\xi = e \rho_v \left\{-\frac{1}{T} + f\left(\frac{\partial X}{\partial T}\right)_y\right\} - \rho_s \left(\frac{\partial X}{\partial T}\right)_y \tag{23}$$

$$\Psi = -e \rho_v \left(\frac{1}{y} + f\left(\frac{\partial X}{\partial y}\right)_T\right) + \rho_s \left(\frac{\partial X}{\partial y}\right)_T \tag{24}$$

$$f = \frac{1}{\epsilon} \frac{\partial \epsilon}{\partial X} - \frac{1}{\rho_{db}} \frac{\partial \rho_{db}}{\partial X} \tag{25}$$

Equation 21 is again a second-order nonlineal partial differential equation in T and y. It will have to be solved simultaneously with Eq. 13.

The initial conditions are uniform temperature and moisture content throughout the sample, thus resulting in uniform values for the water vapor mole fraction. The heat and mass transfer boundary conditions are continuity in the fluxes at the interface. Thus:

$$T(z,o) = T_o \qquad 0 < z < L \tag{26}$$

$$X(z,o) = X_o \qquad 0 < z < L \tag{27}$$

$$y(z,o) = y_o \qquad 0 < z < L \tag{28}$$

$$n|_{z=Z} = k_y \{y(z,t) - y(\infty,t)\} \tag{29}$$

$$q|_{z=Z} = -h\{T(Z,t) - T(\infty,t)\} \tag{30}$$

Where Z is an invariant value resulting from:

$$Z = \left[\frac{\rho_b}{(1 + X)\rho_s}\right]_{X=0} \cdot L \tag{31}$$

If shrinkage is neglected the above equations remain formally similar but they change in substance. The actual length x replaces z in all equations. Identifying with primes the corresponding new variables, Eq. 10 is replaced by:

$$Q_l' = \left(\rho_{db} + X \frac{\partial \rho_{db}}{\partial X}\right)\left(\frac{\partial X}{\partial y}\right)_T \tag{32}$$

Equation 11 by:

$$P_l' = -\left(\rho_{db} + X \frac{\partial \rho_{db}}{\partial X}\right)\left(\frac{\partial X}{\partial T}\right)_y \tag{33}$$

Equation 12 by:

$$e' = \epsilon \tag{34}$$

In the energy equation, Eq. 21, $\ell_e \hat{c}_e$ remains except that e' replaces e. Equation 23 is replaced by:

$$\xi' = \epsilon \rho_v \left\{-\frac{1}{T} + f'\left(\frac{\partial X}{\partial T}\right)_y\right\} - \rho_{db} \left(\frac{\partial X}{\partial T}\right)_y \tag{35}$$

Equation 24 by:

$$\Psi' = -\epsilon \rho_v \left\{\frac{1}{y} + f'\left(\frac{\partial X}{\partial y}\right)_T\right\} + \rho_{db} \left(\frac{\partial X}{\partial y}\right)_T \tag{36}$$

and Eq. 25 by:

$$f' = \frac{1}{\epsilon} \frac{\partial \epsilon}{\partial X} - \frac{X}{\epsilon \rho_v} \frac{\partial \rho_{db}}{\partial X} \tag{37}$$

The initial and boundary conditions are modified in a similar way.

Transport Properties

Bulk density and porosity of apples as a function of moisture content have been reported by Lozano et al. (1980). From them:

$$\rho_b = 0.852 - 0.462 \exp(-0.66X) \tag{38}$$

$$\epsilon = 1 - 0.553 \exp(0.051X) + 0.3 \exp(-0.609X) \tag{39}$$

The dry matter bulk density and solid density, Eqs. 2 and 3 can be calculated using Eqs. 38 and 39.

Effective diffusivity for fresh apples has been reported by Forbito et al. (1981). Harper (1962) measured the effective diffusivity for the system toluene-air in freeze-dried apple tissue. Reworking his data on the assumption that Kundsen flow and surface diffusion can be disregarded, it indicates a tortuosity value $\tau = 6.3$, similar to that for fresh apple. Thus it can be assumed that the change in effective diffusivity as moisture decreases parallels the change in porosity, which is available as indicated above. It was assumed an initial value of $D' = 0.5 \times 10^{-7}$ m^2/s. Thermal conductivity of fresh apples was reported by Sweat (1974); data on thermal conductivity of apples as a function of moisture content were published by Lozano et al. (1979). From the latter:

$$k = 0.489 - 0.443 \exp(-0.206X) \tag{40}$$

Equilibrium data, both as $X = X(y,T)$ and the partial derivatives $(\partial X/\partial T)_y$ and $(\partial X/\partial y)_T$ are needed. These have been provided experimentally by Rotstein and Cornish (1978b) and as a correlation established on the grounds of equal chemical potential for the intervening air and cell phases. The external heat and mass transfer coefficients were obtained from correlations (Treybal, 1968). The heat of sorption was approximated by water heat of vaporization at the same temperature and pressure.

EXPERIMENTAL

A 2-L glass vessel was used to measure the kinetics of desorption. The vessel contained 200 cm^3 of saturated LiCl solution to provide a relative humidity $\phi = 0.111$. An internal magnetically-driven fan was used to obtain different degrees of turbulence by using a variable transformer. Air velocities were measured by a hot wire anemometer. The sample was suspended from a thin stainless-steel wire which was hooked to a suitable scale. The whole was housed in a constant temperature room at 33° ± 0.5°C.

The samples were Granny Smith apple pieces cut into paralellepipeds of 3×10^{-2}m by 3×10^{-2}m and thickness of 3×10^{-3}m. Temperature readings at the center of each sample were obtained from a thin thermocouple suitably inserted. The air velocity was 1 m/s. Initial conditions of the apple slices, corresponding to Eqs. 26 and 27, were $T_o = 20°$C and $X_o = 4.3$ kg/kg.

Numerical Solution and Results

Equations 13 and 21 provide a system of two nonlinear partial differential equations in two dependent variables, y and T, which are functions of position and time. They have to be solved using the initial boundary conditions outlined in Eqs. 26 through 30. To solve the equations a numerical

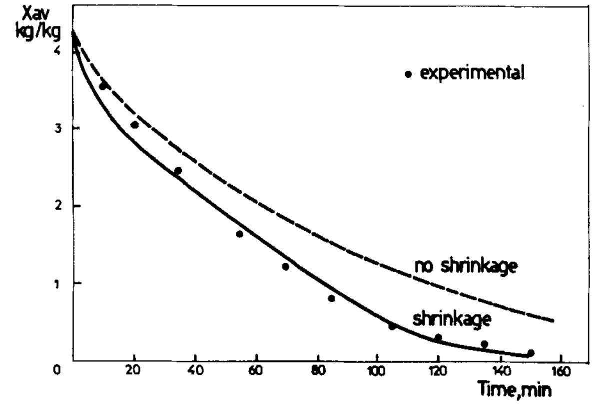

Figure 1. Average moisture content of apple sample starting from fresh fruit. Experimental results and model prediction with and without allowance for shrinkage.

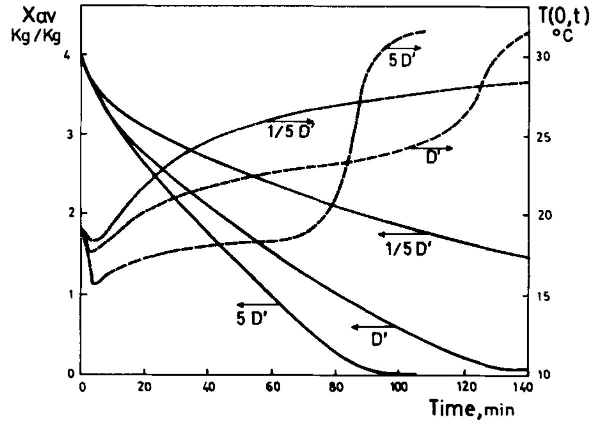

Figure 3. Change in prediction of kinetics of average moisture decrease and center temperature of sample, with different effective diffusivities.

procedure was developed. Its main features were: a) Initial guesses of the convective term and nonlinear coefficients were updated each time a new solution was available; b) Integration was carried out over a control volume; c) The time profile corresponded to a fully implicit scheme, the concentration profile to a central differences scheme; and d) Relaxation was used to avoid infeasible results due to the initial shape of the equilibrium expression.

The results are point values of vapor concentration and temperature at each time, which were in turn converted in moisture contents X by the equilibrium expression (Rotstein and Cornish, 1978b). Averaging the point moisture contents over the sample volume results in X_{av}, the value to be compared with the experimental moisture content data obtained experimentally as a function of time.

The same numerical procedure was applied to the equations corresponding to the nonshrinkage case, the counterparts to Eqs. 13, 21 and 26 to 30, modified as indicated in Eqs. 32 through 37 and in the text. This provided a solution to be compared with both the experimental data and the simulated moisture content and temperature profiles obtained with due allowance for shrinkage.

Figure 1 shows the predicted moisture content of the sample, X_{av}, as a function of time. This prediction is compared with experimental results and with the numerical solution for the case with no shrinkage. Figure 2 indicates the temperature at the sample center, experimental and predicted with and without allowance for shrinkage.

Sensitivity

It is interesting to see how sensitive are the predictions from the mathematical simulation to changes in the intervening parameters. To do this the effective diffusivity was changed fivefold and the other transport properties were successively duplicated or halved, one by one, with the exception of porosity and heat of sorption that were multiplied by 1.2 and 0.8, on physical grounds.

Changes in the effective diffusivity coefficient result in a different prediction for the average moisture content (Figure 3) and the center temperature (Figure 3) as a function of time. Figure 4 shows the sensitivity of moisture content and center temperature predictions to changes in the effective thermal conductivity. Figure 5 indicates the effect of changing the external heat transfer coefficient. Figure 6 shows the result of modifying the external mass transfer coefficient; Figure 7, the effect of modifying the heat of sorption value; and Figure 8, the effect of changing the value of porosity on the predicted average moisture content and center temperature.

DISCUSSION

The starting full turgor structure described above has been substantiated by many authors including Smith (1938), Hardy (1949), Skene (1966), and Slatyer (1967). The pore size represented by the size of intercellular spaces makes it reasonable to consider for the mass diffusional flux a molecular regime, rather than Knudsen or transition regime.

Figure 1 indicates that the solution allowing for shrinkage provides a reasonable simulation of the loss of average moisture content, i.e., loss of moisture from the entire sample as a function of time. If shrinkage is disregarded the moisture loss predicted is much less and quite far from the experimental values as time goes on. Since the solution to the problem involves obtaining point values of moisture contents which are then averaged over the sample volume to build Figure 1, there is a potential masking effect, and closeness to experimental values is not necessarily a final test for the model. Therefore, the center temperature, a point value, was also monitored, and its change as a function of time is, Figure 2, compared with the model predictions with and without allowing for shrinkage. The shape of the temperature profile departs significantly from that of a purely conductive phenomenon, showing

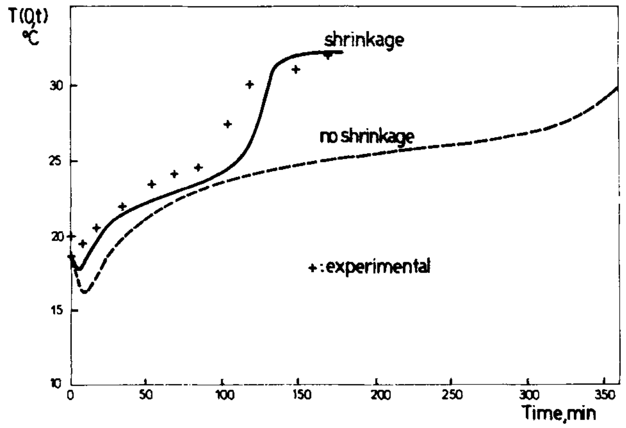

Figure 2. Temperature at the center of apple sample as a function of time. Experimental results and model prediction with and without allowance for shrinkage.

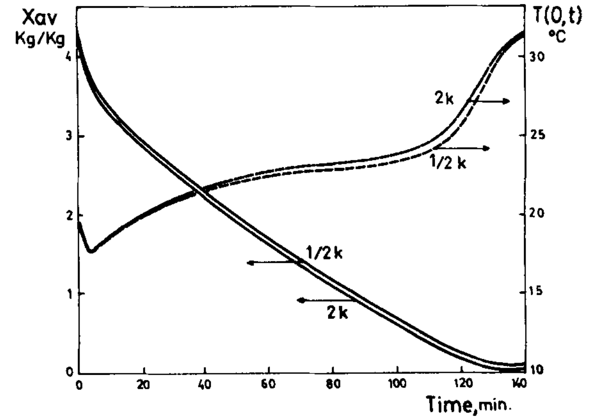

Figure 4. Change in prediction of kinetics of average moisture decrease and center temperature with different effective thermal conductivities.

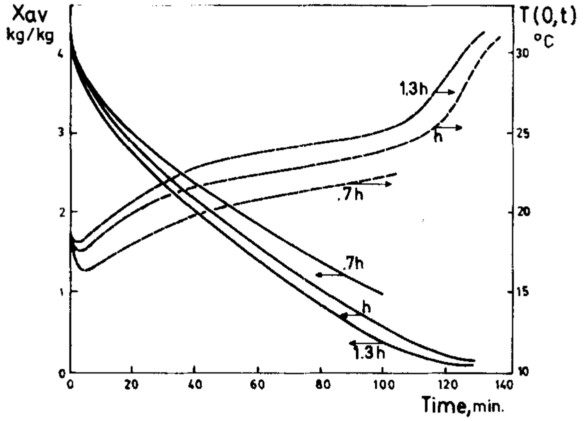

Figure 5. Predicted kinetics of average moisture decrease and center temperature for different heat transfer coefficients.

the influence of the energy requirements and convective transport which were included in the model.

It can be seen that the solution with shrinkage succeeds in representing the experimental behavior. Differences in actual values can be explained on the basis of minor errors in the estimation of parameters, as will be seen below. The prediction when shrinkage is not taken into account is far removed from the actual data, although it does show the unusual shape of the temperature evolution. The initial cooling effect is probably shorter in time and intensity than shown, the prediction being influenced by conditions of the numerical solution as it starts. The experimental data (Figure 2) corroborates this statement.

The sensitivity of the solution to the value of different transport properties appears to be of interest, once it is established that the model is a reasonable simulation of reality. Some of the parameters used above have a limited certainty, especially so in the case of effective diffusivity and heat of sorption. In the case of apples there is a fair amount of data on the value of transport properties as a function of moisture content. This is not the case for most of the foodstuffs. Although the present and other authors are carrying out efforts to systematically provide more data, the goal of an extent of knowledge as there is for other chemical engineering materials is still far away. Thus, assuming that many fruits and vegetables will show a behavior similar to apples, the sensitivity study should be useful in indicating what range of accuracy is needed for each property. Since all fruits and vegetables are made up of cellular tissue with intercellular spaces, the assumption appears to be valid. In addition it should help to understand the impact of changes in processing conditions that would affect the value of the properties under consideration. The parallel between equilibration rate and drying rate gives additional interest to the conclusions to be reached.

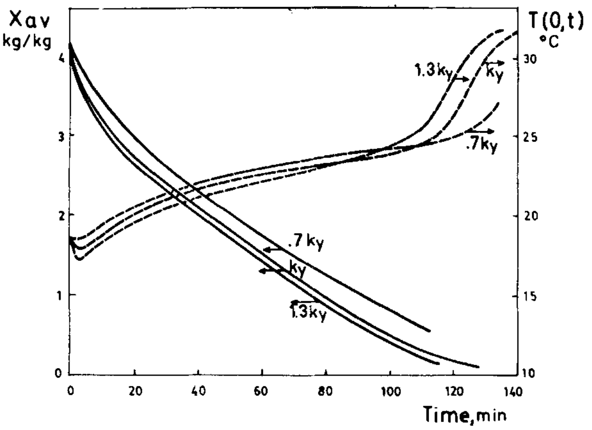

Figure 6. Change in prediction of kinetics of average moisture decrease and center temperature when changing mass transfer coefficients.

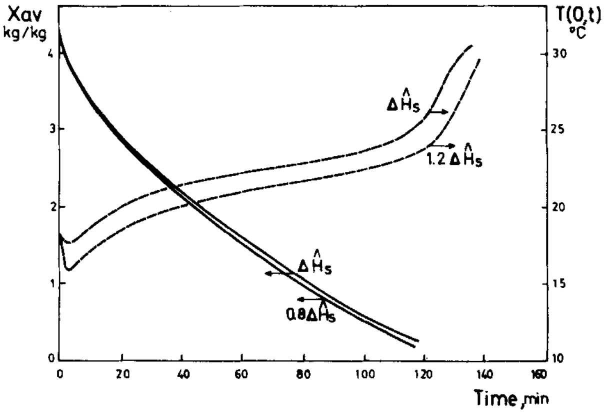

Figure 7. Predicted kinetics of average moisture decrease and center temperature for different heat of desorption values.

Figure 3 shows that a fivefold increase or decrease of the effective diffusivity results in a major change in moisture loss with time. The purpose was to span one order of magnitude, because literature estimates differ in that much (Forbito et al., 1981). It indicates that D' must be estimated with great accuracy and changes in the product that would result in increasing its value would increase the equilibration rate. Since the ratio between effective and molecular diffusivity in this case is porosity over tortuosity, changes which would increase that ratio would result in an increased rate. This beings to mind the case of explosion—puffing and its dramatic results in improving drying rates, and suggests the interest of following this line of thought. In Figure 3 the above contentions are also corroborated in terms of center temperature prediction. As expected, the temperature profile departs further away from a conductive profile; the larger is the effective diffusivity.

Figure 4 shows that a fourfold change in effective thermal conductivity has little effect on the predicted moisture decrease and center temperature decrease with time. This indicates that for similar foods when the process is unbalanced towards external control, as sorptional equilibration usually is, there is no need for a great accuracy in estimating thermal conductivity. On the other hand, Figure 5 indicates that a change in the heat transfer coefficient results in a significant change in rate of equilibration. Since the heat transfer coefficient is a design parameter, the result suggests that higher turbulence is needed if a faster equilibration rate is desired. It also shows that it is misleading to consider internal control only in modeling this process. Temperature predictions substantiate the conclusion, showing a high sensitivity of the center

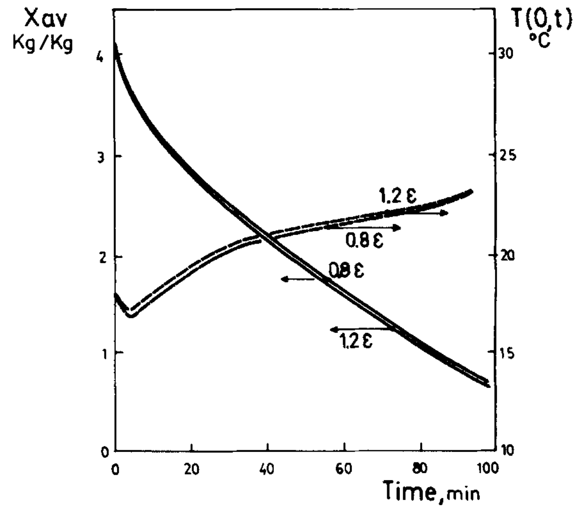

Figure 8. Change in prediction of kinetics of average moisture decrease and center temperature when modifying the porosity value.

temperature prediction to the value of h. The way the sigmoid curve tends to flatten indicates that this peculiar shape is much influenced for the insufficient supply of heat to this coupled heat and mass transfer phenomenon. Figure 6 indicates, as expected, a strong parallel between sensitivity to the mass transfer coefficient and that to the heat transfer coefficient.

When the heat of sorption needs to be estimated, it should be considered whether the heat of vaporization is a good enough estimate or a larger energy requirement on account of the sorptional force field. Figure 7 shows a not too large sensitivity to the value used. In the case of porosity, Figure 8 indicates that a ±20% change in the value of porosity, as it appears explicitly in Eqs. 13 and 21, has negligible effect on the predicted average moisture content and center temperature evolution with time.

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NOTATION

$\hat{c}_p$ = specific heat at constant pressure
e = defined in Eq. 12
e' = defined in Eq. 34
f = defined in Eq. 25
f' = defined in Eq. 37
h = heat transfer coefficient, $J/K \cdot m^2 \cdot s$
k = effective thermal conductivity $J/m \cdot s \cdot K$
k_y = mass transfer coefficient, $kg/m^2 \cdot s$
n = mass flux, $kg/m^2 \cdot s$
q = heat flux, $J/m^2 \cdot s$
t = time, s
x = length, m
y = mole fraction, mol/mol
z = fictitious length, m
D' = effective diffusivity, m^2/s
$\hat{H}$ = specific enthalpy, J/kg
L = sample width, m
P_l = defined in Eq. 11
P_l' = defined in Eq. 33
Q_l = defined in Eq. 10
Q_l' = defined in Eq. 32
T = absolute temperature, K
V = volume, m^3
X = moisture content, kg H_2O/kg dry matter
Z = defined in Eq. 31

Greek Letters

β = defined in Eq. 14
γ = concentration, kg/cm^3
δ = defined in Eq. 15
ϵ = porosity, m^3/m^3
ξ = defined in Eq. 23
ξ' = defined in Eq. 35
ρ = density, kg/m^3
ϕ = rrelative humidity
ψ = defined in Eq. 24
ω = mass fraction, kg/kg

Subscripts

a = air
b = bulk
db = bulk property of dry matter
g = gas phase
i = index representing the intervening phases
l = liquid phase
o = initial
s = solid
sp = sorption
v = vapor

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