BATCH DRYING OF BANANA: MODELLING AND EXPERIMENTS

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Abstract In the present study, a mathematical model for drying of food products undergoing shrinkage has been developed. The model, which includes the influence of both material and equipment, is capable of predicting dynamic behaviour of the dryer. Heat and mass transfer equations are solved simultaneously using a numerical technique. The material model is capable of predicting the instantaneous temperature and moisture distribution inside the material. The equipment model, on the other hand, describes the transfer process in the tunnel dryer and predicts the instantaneous temperature and humidity ratio of air at any location of the tunnel. For evaluation purposes, the model was applied to drying experiments in the range of air temperatures between 40^0 and 60^0C and air velocity between 0.3m/s and 0.7 m/s. A solar dryer was used to conduct experiments. Banana slices were dried over a wide range of operating conditions. Initial moisture content of the sample was about 4.0 g/g dry and final moisture content was in the range of 0.22 to 0.25 g/g dry. The initial thickness and diameter of banana slices were approximately 4-mm and 30 mm, respectively. The prediction of the average moisture content and material temperature compared favourably with the experimental results. The predicted air temperature and humidity ratio of a batch type tunnel dryer also agreed fairly well with the experimental results. The model is capable of predicting dynamic behaviour of drying of fruits undergoing shrinkage and, as such, it can be used as a design tool.

Keywords: Drying, Mathematical model, Shrinkage, Experiments

INTRODUCTION

Drying of fruits and vegetables demands special attention, as these are considered important sources of vitamins and minerals essential for mankind. Dried fruits and vegetables have gained commercial importance and their growth on a commercial scale has become an important sector of agricultural industry. Losses of fruits and vegetables in developing countries are estimated to be about 30-40% of production [1]. The need to reduce post-harvest losses is of paramount importance for these countries.

Drying is a complicated process involving simultaneous heat and mass transfer. Fruits and vegetables have certain morphological features quite distinct from other natural materials that greatly influence their behaviour during drying and preservation. Fruits are generally characterized by high initial moisture content, high temperature sensitivity (i.e. colour, flavour, texture and nutritional value subject to thermal deterioration), and shrinkage of materials during drying. The required amount of thermal energy to dry a particular product depends on many factors, such as, initial moisture

content, desired final moisture content, temperature and relative humidity of drying air, and air flow rate.

Many mathematical models have been proposed to describe the drying processes [2-5]. Reviews of the different mathematical models have been presented by Luikov [6], Rossen and Hayakawa [7] and Fortes and Okos [8]. Shrinkage of material during drying has been considered by Gekas et al. [9], Jomma and Puiggali [10] and Clara et al. [11] in their drying models. The existing mathematical models are either too simplistic and, hence, deviate significantly from real processes or too complex to have any practical application. It is thus essential to develop a model which should not only be meaningful and relatively simple to use, but also significantly accurate to predict temperature and moisture distribution during drying.

The majority of the models, described earlier, have not considered the equipment model which expresses the effect of heat and mass transfer in the material on the drying medium, which is vital in designing a dryer

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for a particular task. At present, there are very few models that represent the batch drying of tropical fruits specially banana. As shrinkage in fruits is an observable phenomenon, it must be taken into account in order to obtain reliable predictions of performance.

In this study, a simulation model has been developed to describe heat and mass transfer processes taking place inside the dryer. Shrinkage of material is taken into account in the model developed. Experiments were performed under different operating condition to validate the model.

MATHEMATICAL MODEL

1. Material model

Shrinkage of agricultural products during drying may have significant effect on mass diffusivity and the moisture removal rate, and it is necessary to take into account the effect of shrinkage [12]. To simplify the model, it is assumed that moisture movement and heat transfer are unidirectional, no chemical reaction takes place during drying, and the material shrinks as drying progresses. If it is considered that material surface shrinks at a velocity 'u' towards the centre of the material sample, the shrinkage effect can be considered as analogous to convective flow.

Let us consider a sample of material and control volume as shown in Figure 1.

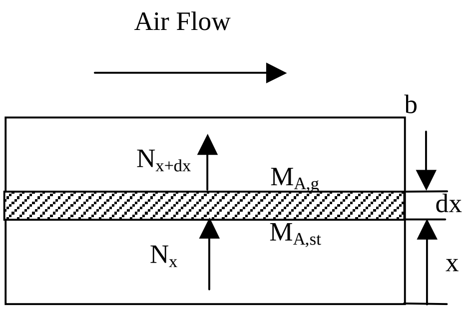

Fig. 1: Elemental control volume in the material sample

The mass and heat conservation equations can be written as [14]

$$\frac{\partial M}{\partial t} + u\frac{\partial M}{\partial x} = D\frac{\partial^2 M}{\partial x^2} \quad (1)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \frac{\partial^2 T}{\partial x^2} \quad (2)$$

For the materials undergoing shrinkage, diffusion coefficient D in equation (1) is not constant [13] but varies with moisture content. So, to consider the real condition, effective diffusion coefficient is introduced. Thus the actual equation that describes the diffusion of moisture in the material is given by,

$$\frac{\partial M}{\partial t} + u\frac{\partial M}{\partial x} = D_{eff}\frac{\partial^2 M}{\partial x^2} \quad (3)$$

D_{eff} can be calculated from the following equation [13]

$$\frac{D_{eff}}{D_o} = \left(\frac{b}{b_0}\right)^2 \quad (4)$$

where the thickness ratio is obtained from the following equation [15]

$$b = b_0\left[\frac{\rho_e + M_{ave}\rho_s}{\rho_e + M\rho_s}\right] \quad (5)$$

This study assumes a linear distribution of shrinkage velocity. Thus at any point in the sample, shrinkage velocity

$$u(x) = u(b)\frac{x}{b} \quad (6)$$

and velocity at the exposed surface is

$$u(b) = \frac{b - b(old)}{\Delta t} \quad (7)$$

The moisture content throughout the specimen is assumed to be uniform at the beginning of drying. In the middle of the specimen, x=0, (Figure 1 shows half thickness of the specimen) the moisture gradiant is considered zero. The initial and boundary conditions of equations (2) and (3) are given below.

The initial conditions are: $M|_{t=0} = M_0$, $T|_{t=0} = T_0$

Boundary conditions:

at x=0, $\frac{\partial M}{\partial x}\Big|_{x=0} = 0$ and $\frac{\partial T}{\partial x}\Big|_{x=0} = 0$

and at x = b, moisture balance can be written as;

$$-D_{eff}\frac{\partial M}{\partial x}\Big|_{x=b} + uM\Big|_{x=b} = h_m(M - M_e)\Big|_{x=b} \quad (8)$$

Energy balance at the boundary, x=b can be expressed as

$$\left(k\frac{\partial T}{\partial x} - \rho C_p uT\right)\Big|_{x=b} = h(T_a - T)\Big|_{x=b} - h_m\rho(M - M_e)h_{fg}\Big|_{x=b} \quad (9)$$

Mass transfer coefficient, h_m can be determined from the following relationships [16] for laminar flow and turbulent flow, respectively

$$Sh = \frac{h_m L}{D} = 0.332\,\mathrm{Re}^{0.5}\,Sc^{0.33} \text{ and}$$

$$Sh = \frac{h_m L}{D} = 0.0296\,\mathrm{Re}^{4/5}\,Sc^{1/3}$$

Similarly, heat transfer coefficient can be calculated from the following relationships for laminar and turbulent flow, respectively

$$NU = \frac{hL}{k} = 0.332\,\mathrm{Re}^{0.5}\,P_r^{0.33}$$

$$NU = \frac{hL}{k} = 0.0296\,\mathrm{Re}^{0.5}\,P_r^{0.33}$$

2. Equipment Model

In obtaining a set of differential equations, which constitutes equipment model, the following assumptions were made.

1. Thermal properties of moisture and air are constant.

2. The problem is one dimensional and conduction heat transfer within the bed is negligible.
3. Uniform product size and uniform distribution of drying product in the drying chamber.

If we consider an element dz at a distance Z from the inlet of the dryer, as shown in the Figure 2, energy and moisture balance equations can be written as [14]

$$-G_o C_{pa} \frac{\partial T_a}{\partial z} dzdt = \in \rho_a dz C_p \frac{\partial T_a}{\partial t} dt +$$
$$(1-\in)\rho_s \frac{\partial T_s}{\partial t}(c_s + c_m M)dzdt + h_{fg} \frac{\partial M}{\partial t} \rho_s (1-\in) dzdt \quad (10)$$

and $$\Rightarrow G_o \frac{\partial Y}{\partial z} + \in \rho_a \frac{\partial Y}{\partial t} = \rho_s (1-\in) \frac{\partial M}{\partial t} \quad (11)$$

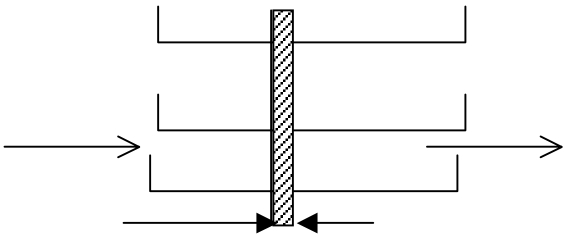

Fig. 2: Control volume in the dryer section

In the above equations time derivatives $\frac{\partial T_a}{\partial t}$ and $\frac{\partial Y}{\partial t}$ are negligible in comparison to their space derivatives [17] Hence equations (10) and (11) can be written as

$$-\frac{G_o c_{pa}}{\rho_s (1-\in)} \frac{\partial T_a}{\partial z} = \frac{\partial T_s}{\partial t}(c_s + c_m M) + \frac{\partial M}{\partial t} h_{fg} \quad (12)$$

$$G_o \frac{\partial Y}{\partial z} = \rho_s (1-\in) \frac{\partial M}{\partial t} \quad (13)$$

Initial and boundary conditions are:
at x=0 and t = 0; $T_a = T_0$ $dT_a/dt = 0$ and $Y = Y_0$
dY/dt = 0.
At x> 0, t= 0 ; $Ta = T_0$, $Y = Y_0$
The above equipment model together with the material model developed earlier constitutes a complete modelling tool for a batch type tunnel dryer.

Governing differential equations describing drying characteristic and dryer behaviour were solved numerically. Some physical properties of banana were taken from reference [18]. Diffusion coefficient, initial moisture content, equivalent moisture content and final thichness of the sample were determined experimentally. A computer program in FORTRAN was developed to solve the set of finite difference equations.

EXPERIMENTS

To perform drying tests, a tunnel type solar dryer with v-corrugated collector was designed and constructed, as shown in Figure 3. With the control of auxiliary heater and fan, the dryer was capable of maintaining a constant temperature and air velocity during the tests.

Instrumentation

Instrumentation for the drying tests included the measurement of following parameters

- Temperature changes of air along the dryer.
- Temperature changes of material with time.
- Relative humidity of air at inlet and outlet of the dryer.
- Air velocity.
- Change of weight of material with time.
- Change of the thickness of the sample with time.

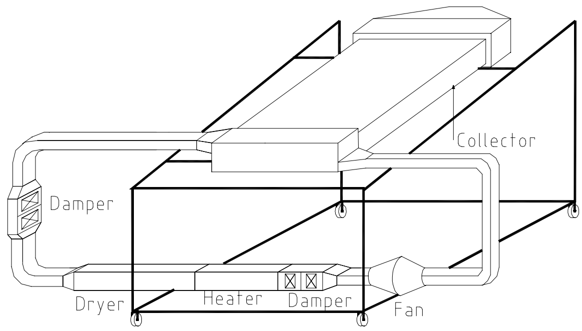

Fig. 3: Solar drying test facility

The temperatures were measured using T-type thermocouples. All thermocouples were calibrated using standard thermometers and connected to a data logger. Relative humidity at inlet and outlet were measured by a humidity transmitter, which gave voltage reading proportional to the relative humidity. A reading of 1-5 volts represented 0-100% relative humidity.

Moisture content of the material was measured using a load cell, which was calibrated using standard weights. Air flow rate was calculated by measuring the air velocity at the entrance of the dying section. A calibrated hot wire anemometer measured the air velocity. The surface temperature of the material was measured by installing a 'wall-mount' type thermocouple on material surface.

Drying test procedure

Drying tests were performed according to the ASAE standard. Banana has been selected as drying specimen because a large quantity of banana is produced in ASEAN countries and not enough information on banana drying is available in the literature.

During the course of the experiment, material and air temperature, relative humidity, air velocity and material weight were monitored at one-minute intervals during the first hour and at 5 to 15 minutes intervals from the 2nd hour of drying onwards. Initial moisture content was about 4.0 g/g dry and final moisture content was 0.22 to

0.25 g/g dry. The initial thickness and diameter of banana slices were approximately, 4-mm and 30 mm, respectively. Thickness of material was measured at one-hour interval to monitor the shrinkage of the material.

RESULTS AND DISCUSSION

Experiments were conducted at different air flow rates and temperatures to determine drying characteristics of banana. Air velocity was varied from 0.3m/s to 0.7 m/s and temperature was varied from 40^0 to 60^0C. Variables considered for this experiment are shown Table 1.

Table 1: Variables considered in the drying experiments

Temperature ^{0}C	Air Velocity m/s
60	0.7
	0.5
	0.3
50	0.7
	0.5
	0.3
40	0.7
	0.5
	0.3

1. Drying characteristic

Diffusion coefficient for each drying condition is determined from experimental data using the following equation as suggested by Hawlader et al. [19].

$$\ln\frac{M}{M_o} = \ln(8/\pi^2) - \pi^2 Dt/L^2 \quad (14)$$

The predicted as well as experimental results for each drying experiment are presented in the following sections.

Figures 4 shows the experimental and predicted

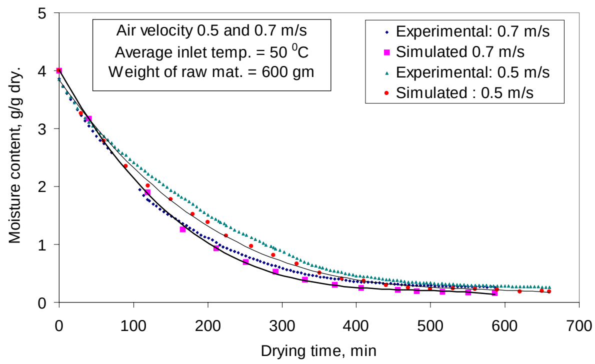

Fig. 4: Experimental and predicted variation of moisture content with time at temperature 50^0C and air velocity 0.5 and 0.7 m/s.

variation of average moisture content of material with time at different drying conditions. In the simulation, constant inlet air and humidity ratio was considered. Moisture content of the material at any time step was determined by averaging the calculated moisture distribution in the sample. The initial moisture content was 4.0 g/g dry and final moisture content is about 0.25 g/g dry. From the drying curves, it can be seen that no constant drying rate period is evident. The predicted and experimental results show very close agreement, which validates the model developed to express drying characteristics. Other tests considered in this study also show similar results.

2 Temperature and moisture distribution in material during drying

In drying operation, it is important to know the temperature and moisture distribution in the material and its change during drying. The present mathematical model developed for drying can predict the moisture and temperature distribution inside the material during drying. The moisture distribution within the sample as a function of thickness is shown in Figures 5 at 50^0C temperature and 0.75 m/s air velocity.

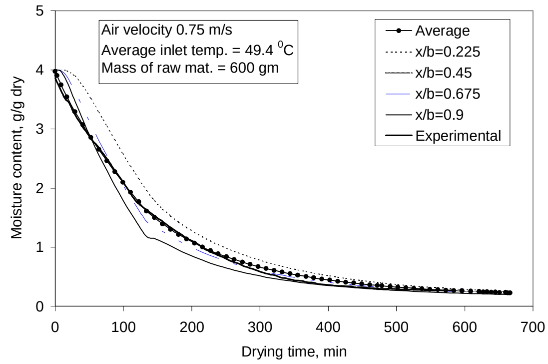

Fig. 5: Moisture profile of material during drying (T=50^0C; V = 0.75 m/s).

From the figure, it can be seen that the surface directly exposed to the drying air approached the equilibrium moisture content faster and the changes in the deeper layers of materials are slow. In the present study, moisture distribution inside the material was not measured experimentally. Only overall (average) moisture content was determined experimentally. To compare with the experimental results, predicted average moisture content of the entire sample was calculated. Experimental and predicted moisture profile shows reasonably close agreement.

3. Material Temperature distribution

The surface temperature of the materials was recorded continuously during drying. Using the computer programme, temperature was predicted at different locations from the centre of the material. Figure 6 shows the predicted temperature distribution inside the material with time at air velocity of 0.5 m/s and temperature 60^0C. The respective experimental surface temperature was also plotted on the same graph. The predicted surface temperatures agreed reasonably well with those obtained from experiment.

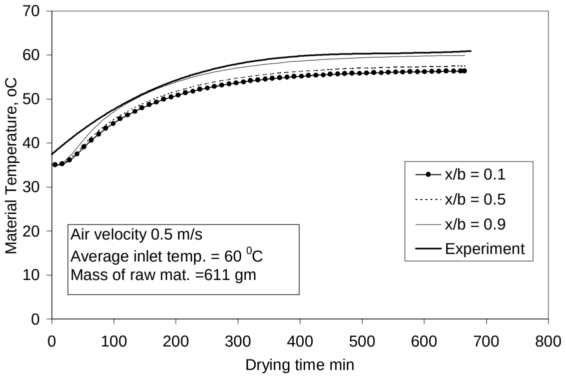

Figure 6: Temperature distributions in material during drying with time; T= 50 ^{0}C and V=0.75 m/s

4. Dryer characteristics

Figures 7 shows the temperature distribution of drying air along the dryer.

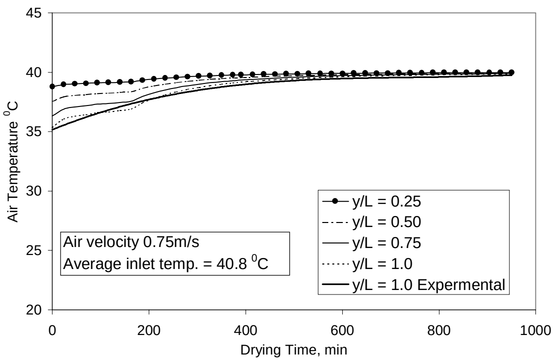

Fig. 7: Predicted and experimental temperature distribution along the dryer with time, T= 40^{0}C and V= 0.75 m/s

In the experiment, dryer temperatures at inlet and outlet were recorded throughout the drying period. However, from the simulation program, the temperature variation at different locations of the dryer with time was computed. In this way, dryer outlet temperature was predicted. The predicted outlet temperatures are compared with measured temperatures for different drying conditions.

In a batch type tunnel dryer, air humidity increases as it passes through the dryer. The humidity ratio of the drying air at different locations of the dryer with time was determined with the computer program. Outlet air temperature and relative humidity was measured in the experiments. In Figure 8, the predicted air moisture content distribution along the dryer with time is presented. The measured outlet humidity ratio is also plotted for comparison. The reasonable agreement in both temperature and humidity distribution validates the material model and related assumptions. Some fluctuations can be observed. This is mainly because of the difficulty to maintain the dryer inlet temperature constant in the experiments.

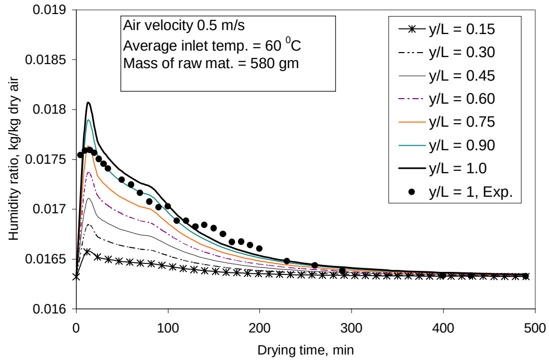

Fig. 8: Experimental and predicted dryer outlet air HR with time, T= 60^{0}C and V = 0.5 m/s

In the case of drying banana, drying potential is found to be a strong function of temperature and weak function of air velocity which can be seen in Figures 9 and 10. Drying time is almost directly proportional to the air temperature. This information is very useful in the design of a dryer.

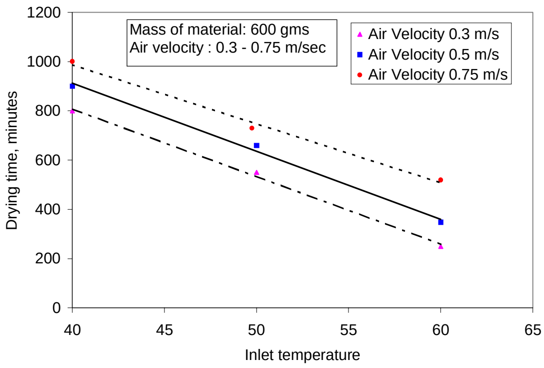

Fig. 9: Relationship between drying time and drying temperature

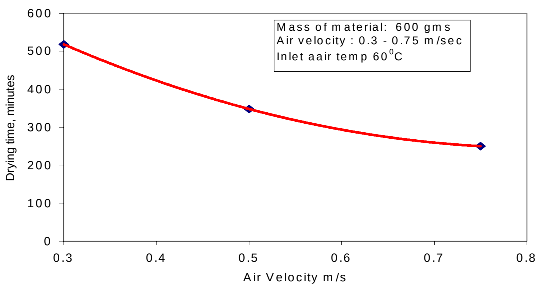

Figure 10 Relationship between air velocity and drying time

CONCLUSIONS

A mathematical model describing simultaneous heat and mass transfer processes is proposed to describe the characteristics of the product being dried. An equipment model describing the effect of heat and mass transfer in the material on the drying medium has also been developed. The mathematical model provides a good prediction of the drying rate, temperature and moisture distribution of material, and temperature and moisture distribution of the drying air along the dryer as well as with time. As both the material and equipment models agree closely with experimental values, mathematical formulation and the related assumptions are considered reasonable to predict the performance of dryers.

NOMENCLATURE

b	half thickness of drying specimen (m)
b_0	initial half thickness of specimen (m)
C_m	specific heat of moisture (J/kg ^{0}K)
C_{pa}	specific heat of air (J/kg ^{0}K)
C_s	specific heat of solid material (J/kg ^{0}K)
D	diffusion coefficient (m^2/s)
D_{eff}	effective diffusion coefficient (m^2/s)
D_0	reference diffusion coefficient (m^2/s)
G_o	air flow rate kg/m^2s
h	convective heat transfer coefficient [W/m^2K]
h_{fg}	enthalpy of evaporation (J/kg ^{0}K)
h_m	mass transfer coefficient (m/s)
k	thermal conductivity [W/m K]
M	moisture content of specimen (g/g dry)
M_0	initial moisture content of specimen (g/g dry)
M_{ave}	av. moisture content across the thickness (g/g dry)
M_e	equilibrium moisture content of specimen (g/g dry)
N_U	Nusselt number
P_r	Prandlt number
Re	Reynolds number
Sc	Smith number
Sh	Sherwood number
t	time (sec)
T	temperature, temperature of drying material (^{0}C)
T_0	initial material temperature (^{0}C)
T_a	temperature of drying air (dry bulb) (^{0}C)
T_s	material surface temperature (^{0}C)
u	shrinkage velocity (m/s)
Y	air humidity ratio (kg/kg dry air)
ρ_a	density of air (kg/ m^3)
ρ_e	density of water (kg/ m^3)
ρ_s	density of dry solid (kg/ m^3)
$\in$	bed void fraction

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