Solar Drying of Bananas: Mathematical Model, Laboratory Simulation, and Field Data Compared

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ABSTRACT: A mathematical model for the solar drying of bananas was developed using a numerical solution procedure to generate a computer simulation. The solution incorporated terms for solar absorption, long-wave emission, natural or forced convection, and evaporation. The model was in good agreement with laboratory results obtained under artificial lights and also field data from researchers in Thailand. The model showed drying to be insensitive to ambient relative humidity but sensitive to factors affecting banana temperature. Reducing exposure to wind was shown to increase banana temperature and so reduce drying time by typically 15%, while also lowering the final moisture content achievable. The results are potentially useful to producers.

Key Words: banana, solar, drying, simulation, model

Introduction

In their paper on the drying and storage properties of banana, Phoungchandang and Woods (2000) described the importance of sun-dried banana to the Thai producers. Dried and packaged, it adds value to their product as a convenience food and enables its storage and distribution. The bananas are sun-dried on an open woven bamboo mesh, with some spacing for ventilation. It takes 6 to 7 d, and bananas are covered in a polythene sheet, top and bottom, overnight. Phoungchandang and Woods (2000) observed that the drying time was long and that the final water activity in commercial packs (about 0.7) might be reduced to extend shelf life.

The simulation of indirect solar driers with separate collector and drying chamber is well established (Bala and Woods 1993, 1994a, 1994b, 1995). In this paper, a computer simulation of the open solar-drying process is developed. Previous models of open solar drying have been presented by Elepano and Oosthuizen (1991) and Sodha and others (1985). However, there are significant differences in the physical assumptions and modeling techniques used here:

(1) Previous work considered drying on a solid floor with the resulting conduction losses. In this work, the bed is raised, and conduction losses are replaced by free or forced convection heat loss.

(2) Moisture loss is now considered limited by internal diffusion, described using the Newton model of Phoungchandang and Woods (2000).

(3) Long-wave radiation heat loss from the crop to the sky and surroundings is included.

Experimental data for direct solar drying is presented by Njie and Rumsey (1997). However, they considered a stacked shallow bed of cassava chips, which is not readily compared with the single layer of individual bananas investigated in this work.

The computer model is verified against laboratory data obtained under lights. These were compact source iodide lamps, as described by Gillett (1977) and Beeson (1978), having a spectral distribution close to that of the sun. The experimental results of Rakwichian (1992) for open sun drying in Thailand were also compared with the model. The simulation is used to investigate some of the physical processes limiting solar drying.

Theory

The temperature rise and moisture loss during solar drying are described by means of the transient energy conservation equation, combined with an equation for rate of moisture loss.

Energy balance

This can be stated as follows: The rate of sensible energy gain is equal to the solar radiation absorbed less the energy losses due to convection, long-wave radiation, and evaporation. Algebraically this can be written

$$M_b C_{pb} \frac{dT_b}{dt} = \dot{Q}_{abs} - (\dot{Q}_c + \dot{Q}_r + \dot{Q}_e) \tag{1}$$

where the banana temperature, T_b, is taken to be uniform (Woods 1991). The specific heat of banana is taken from Dickerson (1969), as cited in Anon. (1989a) as

$$C_{pb} = 1.675 + 0.025 X_{wb} \tag{2}$$

Solar absorption. The solar energy absorbed for unshaded bananas can be written

$$\dot{Q}_{abs} = \alpha(ld)\dot{q}_i \tag{3}$$

and

$$\dot{q}_i = \dot{q}_h / \cos\theta \tag{4}$$

where ld is the projected area of the banana, $\dot{q}_i$ is the radiation intensity on the plane normal to the light source, $\dot{q}_h$ is the radiation intensity measured on a horizontal surface, θ is the angle of incidence of light to the vertical, and α is the absorptivity of solar radiation. The value of α for banana during drying is discussed below.

Equation 3 is valid in the laboratory experiment, where the bananas are arranged with their axis normal to the light beam and so that they do not shade each other. During commercial drying, bananas are randomly oriented and normally close together (Phoungchandang 1999). For this situation, we write

$$\dot{Q}_{abs} = \alpha(ld)\dot{q}_h \tag{5}$$

where $\dot{q}_h$ is the radiation incident on the horizontal surface. Equation 5 is used in the prediction of the field trial of Rakwichian (1992), with $\dot{q}_h$ calculated for a particular latitude and time of year using the method of Duffie and Beckman (1991).

Convection. The convective heat loss is predicted using dimensionless correlations from the literature. These are for natural or forced convection processes, and conduction effects are assumed negligible for the open woven mesh supporting the banana. The correlation for natural convection is given by

$$Nu = \frac{h_c d}{k_A} = a(Gr\,Pr)^n \tag{6}$$

For GrPr < 10^9, the flow is laminar, and a = 0.53, and n = 0.25 (Simonson 1988). In this application, the value of GrPr is always well into the laminar range, and turbulent flow need not be considered.

For forced convection, describing the effect of wind, the following correlation was used

$$Nu = b\,Re^m \tag{7}$$

In the range, 35 < Re < 5 × 10^3, which encompasses this work, the appropriate values are b = 0.583 and m = 0.471 (Wong 1977).

These correlations are strictly for single long cylinders. However, they form a starting point in the development of the model to be verified against laboratory and fieldwork.

Emission (long wave). For a surface with a long-wave emissivity, ε at a temperature, T_b in a black body enclosure at a temperature, T_a, we can write

$$\dot{Q}_r = \varepsilon\sigma(\pi dl)(T_{Kb}^4 - T_{Ka}^4) \tag{8}$$

This is valid for a laboratory at an ambient temperature, T_a. In the field, it is sometimes necessary to consider the sky temperature as different from ambient. However, at high humidities, as encountered in Thailand, Eq. 8 is a reasonable approximation.

Equation 8 can be linearized, as in Duffie and Beckman (1991), as follows:

$$\dot{Q}_r = h_r(\pi dl)(T_b - T_a) \tag{9}$$

where the radiative heat transfer coefficient, h_r, can be written

$$h_r = \varepsilon\sigma(T_{Kb} + T_{Ka})(T_{Kb}^2 + T_{Ka}^2) \tag{10}$$

Evaporative energy. The rate of energy loss by evaporation is given by

$$\dot{Q}_e = (L - fT_b)\dot{m}_{H_2O} \tag{11}$$

where L = 2448 kJ/kg and f = 0.2386 kJ/kg K (Anon. 1987). Evaluating the evaporative heat loss in Eq. 11 requires the determination of the drying rate.

Rate of moisture loss

Phoungchandang and Woods (2000) have shown that, for air-dried bananas, the moisture loss can be written

$$\frac{dX}{dt} = -K(X - X_e) \tag{12}$$

and

$$\dot{m}_{H_2O} = M_{bd}\frac{d(X/100)}{dt} \tag{13}$$

where M_{bd} is the mass of dry banana. The value for K was given by the Arrhenius equation (Phoungchandang and Woods 2000) as

$$K = 0.6854\exp\left(\frac{-3316.1}{T_b + 273.15}\right) \tag{14}$$

and the equilibrium moisture content, X_e, was given in the form of the Modified-Oswin Equation (Phoungchandang and Woods 2000) as

$$X_e = \frac{(C_1 + C_2T_b)}{(\frac{1}{RH_b} - 1)^{1/C_3}} \tag{15}$$

where C_1 = 16.68, C_2 = −0.1212, and C_3 = 0.9020. The RH used must be the value at the banana surface, which is determined by the following method.

RH at the banana surface

This is calculated assuming that there is no moisture transfer resistance across the air boundary layers, as demonstrated by Phoungchandang and Woods (2000). The humidity ratio, H, at the banana surface can therefore be considered equal to ambient. Based on Anon. (1989b), the RH at the banana surface is then given by

$$RH_b = \frac{1}{x}\frac{H}{(0.6220 + H)} \tag{16}$$

where $x = P_{ws}/P_a$, P_a is the atmospheric pressure and P_{ws} is the saturation pressure at the banana surface given by the following equation in the range, 0 to 200 °C.

$$\ln(P_{ws}) = \frac{C_8}{T_{Kb}} + C_9 + C_{10}T_{Kb} + C_{11}T_{Kb}^2 + C_{12}T_{Kb}^3 + C_{13}\ln(T_{Kb}) \tag{17}$$

Equation (17) and the values of the constants are presented in Anon. (1989b).

Radiation properties

The authors are not aware of any specific data on the radiative properties of peeled, drying banana. Initially the banana is at a high-moisture content, but for most of the drying process, the surface is at a moisture content around 30% to 40% w.b. It is therefore useful to look at data for other high- and low-moisture plant material.

Looking first at data for dry grain crops (about 10% w.b.), Arinze and others (1987) reported an average value of 0.80 for the absorptivity of solar radiation and 0.79 for long-wave emissivity for a range of grains. This field data was obtained by comparing the performance of solar collectors with grain covered absorbers and plain black absorbers. The laboratory results for the spectral distribution of reflectance for a number of grains (Massie and Norris 1965) supports the results of Arinze and others (1987). Although reflectance is high between 0.7 to 1.4 μm, above and below this we can expect high absorptivity.

For higher moisture contents, the most documented material is the leaf. For the spectral region (0.4 to 2.5 μm), Monteith and Unsworth (1990) note that above 0.7 μm the reflectance is high. Hallstrom and others (1988) also note a high reflectance for living plant material in the 0.7 to 1.4 μm range. Monteith and Unsworth (1990) quote a 25% reflectance of solar incidence overall, based on a 0.1 reflectance below 0.7 μm and 0.4 above. If the transmittance of banana can be taken as 0, this gives an absorptance of 0.75, which is close to the value of 0.80 for dry grain. However, the authors are not aware of any data on the transmittance of banana. Hallstrom and others (1988) reports results for potato. For wavelengths above 1.25 μm, 63% of radiation is absorbed in the 1st 4.8 mm, and below 1.25 μm, 63% is absorbed within 0.5 mm depth. For bananas (dia 31 mm), it therefore seems reasonable to assume a negligible transmittance.

For a banana temperature of 40 °C, the peak infrared emittance, from Wien's law (Duffie and Beckman 1991), takes place at 9 μm. Data on leaves is available up to 2.5 μm for 20 crops (Gausman and others 1973), and at 2.5 μm the reflectance is below 10% on average. Above 1.4 μm the absorptance of water at a depth of 3 mm is close to 100% (Hallstrom and others 1988). It therefore seems reasonable to assume that banana at a moisture content above dry grain will have an infrared emittance above 0.80.

Based on these observations, the absorptivity of solar radiation, of banana has been taken as 0.8 and the long-wave emissivity, ϵ as 0.9. These values will be indirectly tested when the model is compared with experiment.

Solution procedure

The change in moisture content defined in Eq. 12 is written in finite difference form as

$$\Delta X = \Delta t \times K(X - X_e) \tag{18}$$

where K and X_e are given by Eq. 14 and 15. The change in temperature defined in Eq. 1 can be written in finite difference form as

$$\Delta T_b = \frac{\Delta t}{M_b C_{pb}}\left[\alpha l d q_i - \pi d l(h_c + h_r)(T_b - T_a)\right] - (L - fT_b)\frac{M_{bd}(\Delta X / 100)}{M_b C_{pb}} \tag{19}$$

where h_c and h_r are given by Eq. 6 or 7 and Eq. 10.

At a given time, the moisture reduction over the interval, t, is calculated from Eq. 18 and then the temperature rise from Eq. 19 at the current values of T and X. The procedure is subsequently repeated for the updated temperature and moisture content, marching forward in time. The numerical solution was programmed in the BASIC language. The time step used in the model throughout this work was Δt = 36s, as the numerical solution was found to be insensitive to Δt for values of 900, 360, 180, and 36s (Phoungchandang 1999).

Results and Discussion

Sensitivity of the model to ambient conditions

Before the model is validated against laboratory and field data, it is useful to examine the predicted effect of the ambient temperature and humidity on drying. This is important, as the laboratory conditions in the U.K. were not controlled at tropical levels, although the heating of the building gave reasonably high temperatures.

The effect of ambient temperature, while holding all other variables constant at specified values, is shown in Fig. 1 and 2. Increasing the ambient temperature, under the same irradiance, increases the banana temperature (Fig. 1) and also the drying rate (Fig. 2). The increase in banana temperature increases drying rate in 2 ways. First, the rate of internal diffusion increases as described by the Arrhenius equation (Eq. 14). Second, the equilibrium moisture content that the drying banana approaches is related to the RH at the banana surface and decreases with increasing banana temperature as analyzed in the Theory section. These observations give an important insight into the process provided by the use of the model. Increasing banana temperature gives faster drying to a lower moisture content and could be particularly important during the final stages of drying where there is a problem in achieving a safe level of water activity (Phoungchandang and Woods 2000).

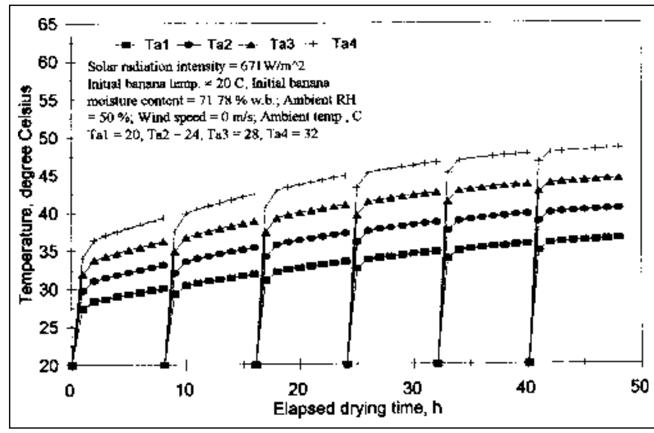

Fig. 1—Variation in banana temperature due to the sensitivity of the solar-drying model to variation in the ambient temperature

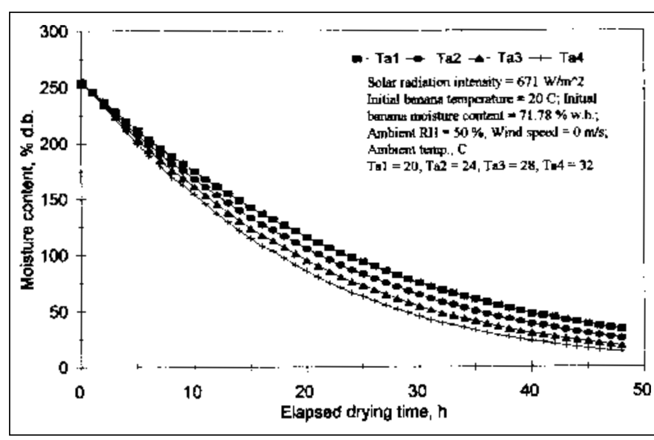

Fig. 2—Variation in banana moisture content due to the sensitivity of the solar-drying model to variation in the ambient temperature

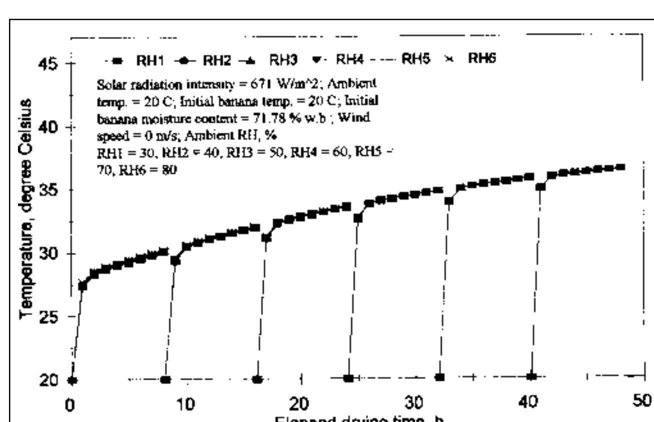

Fig. 3—Variation in banana temperature due to the sensitivity of the solar-drying model to variation in the ambient relative humidity

The sensitivity to ambient RH was also examined under the same conditions as the sensitivity to ambient temperature above, except that ambient was fixed at 20 °C. As shown in Figs. 3 and 4, for RH values of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8, the banana temperature and moisture curves are virtually coincident. This is an important result. First, the model demonstrates that bananas can be dried to low-moisture contents in the humid tropics because the RH at the heated banana surface is substantially below ambient. Second, the laboratory experiments in the U.K. were performed in a heated building giving a relatively low RH. The model indicates that this will not produce results significantly different from those under tropical RH values.

Laboratory results and model compared

The mean laboratory temperature and RH (decimal) during drying are: 19.0 °C (s.d. = 1.44 °C) and 0.318 (s.d. = 0.0476) at 671 W/m^2 and 20.1 °C (s.d. = 1.55 °C) and 0.335 (s.d. = 0.0581) at 846 W/m^2.

The experimental results for temperature are shown in Fig. 5. Each d there is a rapid transient heating of the banana, which flattens off when the heat losses equal the energy absorbed by the radiant heat source. As the drying rate declines with time (Fig. 6 and 7), the evaporative heat loss is reduced, and in general, higher temperatures are achieved towards the end of the drying process, as Fig. 5 illustrates. There are some fluctuations due to the variation in ambient temperature. Apart from the initial few d, the banana temperature approached a value of 35 to 40 °C at the end of each d.

The moisture reduction with time is shown in Fig. 6 and 7 for 671 W/m^2 and 846 W/m^2 intensities, respectively. At the higher intensity, the banana dries slightly more rapidly and to a lower moisture content, but they do not differ dramatically. This is due to the spacing of the bananas so that they do not shadow each other, which in part reduces the effect of light angle. In Figs. 6 and 7, the experimental results are also compared with the computer model. As might be expected, the natural convection model (Eq. 6) for 0 wind velocity) gave better agreement with the laboratory data than the forced convection model. However, these simulated results for forced convection are informative as they give us some indication as to what may happen under field conditions. It is perhaps surprising that the simulation predicts increasing air velocity reduces drying rate. The explanation for this lies in the cooling effect on the bananas. As shown in Fig. 8 and 9, even at low velocities (0.1 m/s), the predicted banana temperature is significantly reduced. As explained above, when considering the effect of ambient temperature, reducing banana temperature reduces diffusion rate within the banana, and the RH at the surface also increases. These effects combine to reduce drying rate. In Figs. 8 and 9, we can also see that, at high-moisture contents, the experimental temperature rise each d is slower than that predicted by the computer simulation. During bagged

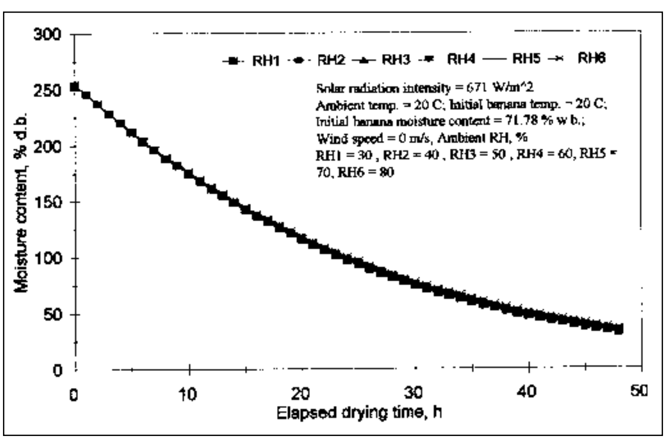

Fig. 4—Variation in banana moisture content due to the sensitivity of the solar-drying model to variation in the ambient relative humidity

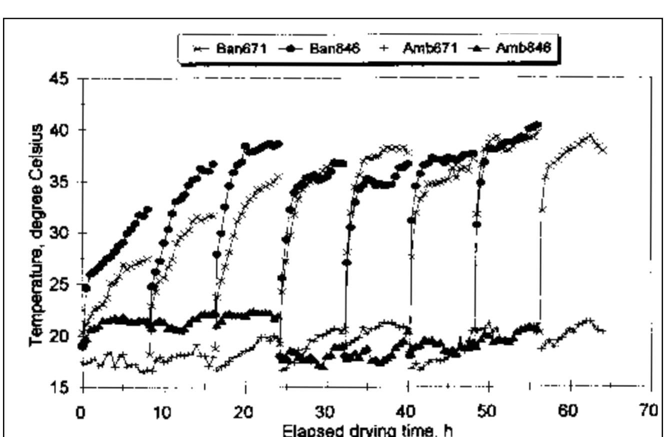

Fig. 5—Ambient and banana temperatures during drying under laboratory lights at an irradiance of 671 W/m^2 (Ave. Ta = 19.0 °C, Ave. Tb = 32.9 °C) and 846 W/m^2 (Ave. Ta = 20.1 °C, Ave. Tb = 34.3 °C)

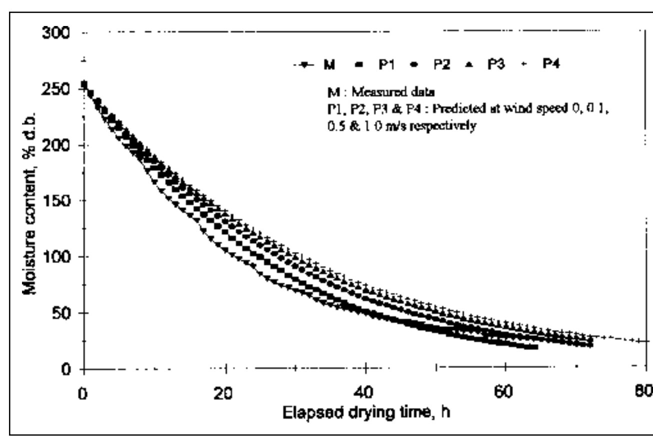

Fig. 6—Effect of wind speed on banana moisture content as predicted using the solar-drying model compared with the observed experimental data during drying under laboratory lights at an irradiance of 671 W/m^2

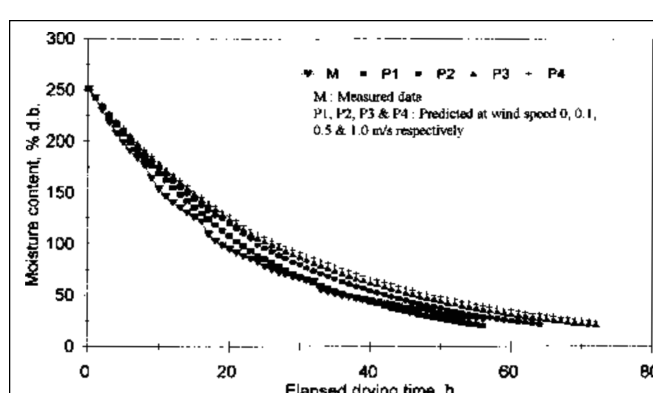

Fig. 7—Effect of wind speed on banana moisture content as predicted using the solar-drying model compared with the observed experimental data during drying under laboratory lights at an irradiance of 846 W/m^2

overnight storage, moisture returns to the surface, and therefore evaporation is greater than predicted by the lump model used. This would also explain the experimental drying rate being greater than the prediction in the earlier stages (Fig. 6 and 7).

Field results and model compared

The computer simulation was also compared with the field drying data of Rakwichian (1992). In this work, as part of an experiment to compare banana drying methods, bananas were directly sun dried for 6 h per d on a raised open mesh for six d and covered at night, top and bottom, by a plastic sheet. This is typical of commercial practice in Thailand (Phoungchandang and Woods 2000). Rakwichian (1992) recorded ambient temperatures and relative humidities, and these are presented in Table 1. However, the author did not measure solar intensity during the drying experiment. The solar intensity data was therefore generated using the method of Duffie and Beckman (1991) for Bangkok during the month of March. Details of the calculation procedure are presented in Phoungchandang (1999), and some specific values are presented in Table 1. Using the prediction for solar intensity and interpolating between the hourly values for temperature and RH, the field data of Rakwichian (1992) is modeled. The predicted banana temperatures are presented in Fig. 10. The peak temperatures are higher than in the laboratory and are again significantly reduced by the wind effect.

The experimental drying curve of Rakwichian (1992) is compared with the computer simulation in Fig. 11. The computer simulation for 0.1m/s air velocity gives the best agreement with the field data, so it is useful to note that Rakwichian (1992) recorded wind velocity as less than 1m/s. Drying time is substantially reduced (75%) compared with the laboratory situation. In this fieldwork, the higher peak banana temperatures and hence drying rate, compared with the laboratory, can be attributed to the significantly higher ambient temperatures. These averaged

Table 1—The calculated daily radiation intensity variation on a horizontal surface for March in Bangkok (Duffie and Beckman 1991) and the hourly ambient conditions from Rakwichian (1992)

Time (h)	Radiation Intensity q_h (W/m^2)	Temperature (C)	Relative Humidity (decimal)
9.00	484	32	0.57
9.30	565	—	—
10.00	637	32	0.62
10.30	696	—	—
11.00	741	33	0.63
11.30	768	—	—
12.00	777	35	0.59
12.30	768	—	—
13.00	741	35	0.59
13.30	696	—	—
14.00	637	35	0.59
14.30	565	—	—
15.00	484	35	0.54

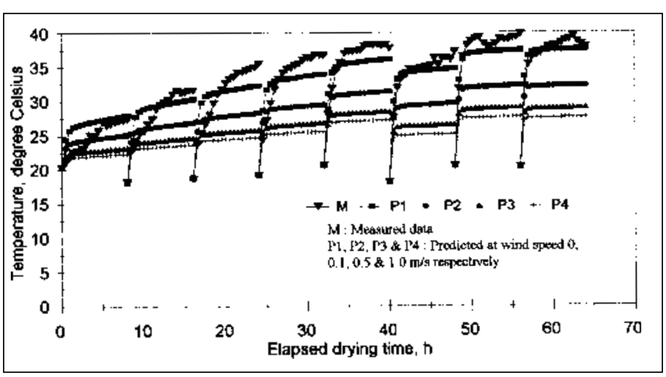

Fig. 8—Effect of wind speed on banana temperature as predicted using the solar-drying model compared with the observed experimental data during drying under laboratory lights at an irradiance of 671 W/m²

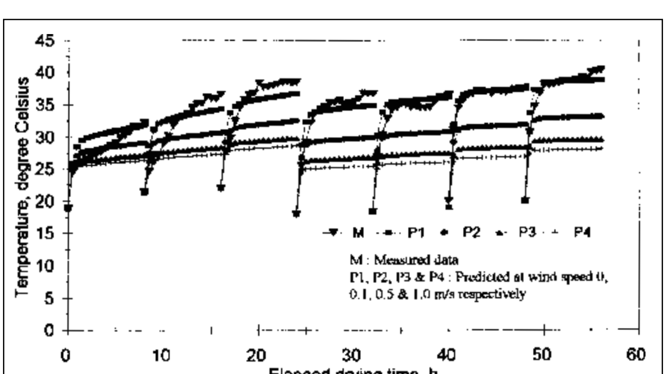

Fig. 9—Effect of wind speed on banana temperature as predicted using the solar-drying model compared with the observed experimental data during drying under laboratory lights at an irradiance of 846 W/m²

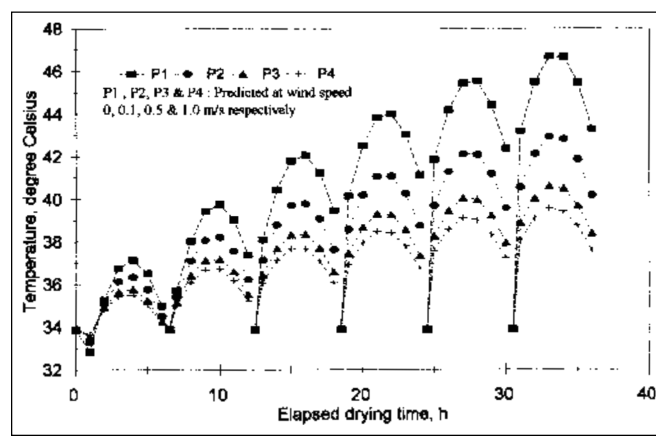

Fig. 10—Banana temperature variation with wind speed as predicted using the solar-drying model for the field conditions of Rakwichian 1992 (March, Bangkok)

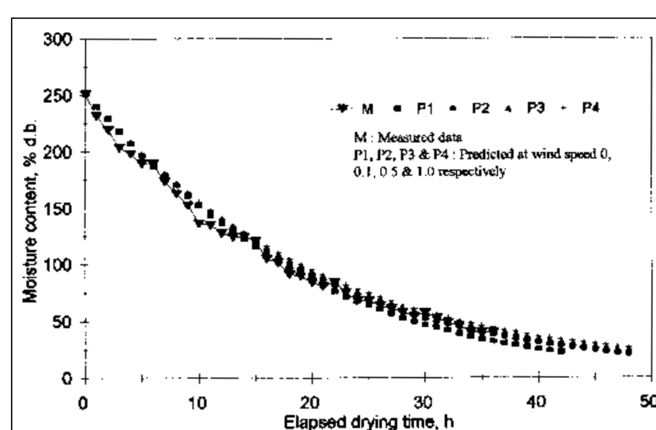

Fig. 11—Banana moisture content variation with wind speed as predicted using the solar-drying model compared with observed experimental data (Rakwichian 1992) during solar drying in the field (March, Bangkok)

33.9 °C (s.d. + 1.46 °C) in the field compared with 19.0 °C (s.d. = 1.44 °C) and 20.1 °C (s.d. = 1.55 °C) in the laboratory. The average ambient RH for the field results was 0.590 (s.d. = 0.030).

Drying time and wind velocity

In order to assess the possible benefit of sheltering bananas from the wind during drying, wind data for the main banana-growing Thai province of Pisanulok has been obtained (Anon. 2000a). For the year 1999, the mean monthly wind velocity ranges from 0.51 to 0.98m/s with an average of 0.63m/s. There is little difference between the wet and dry seasons, and so 0.63m/s is taken as typical. We now consider the mathematical model of field drying for Rakwichian's conditions as shown in Fig. 11. The drying curves for 0m/s (natural convection) and 0.5m/s (simulated velocity closest to Pinsanulok mean of 0.63m/s) are now compared. The banana moisture content required to produce a water activity of 0.65 in the pack is 25.9% d.b. (Phoungchandang and Woods 2000). Examining the results from the model, the drying time down to 25.9% d.b. is reduced from 49 to 42 h when the air velocity drops from 0.5 to 0m/s. This is a 14% reduction. A similar analysis of the laboratory data in Fig. 6 and 7 give reductions of 24% and 21%, respectively. This suggests that there is the potential for a 15% reduction in drying time by locating the drying tray in a sheltered position or designing the tray to reduce wind exposure. In applying these observations, the effect of higher banana temperatures on sensory properties will need to be considered, and Phoungchandang (1999) has conducted an initial study in this area.

Conclusions

A MATHEMATICAL MODEL OF THE DIRECT SUN DRYING OF BANANA has been developed and shown to be in good agreement with experimental results under lights and a set of field data from Thailand. The model is generally applicable to the sun drying of crops in a single layer and is sufficiently adaptable to examine the effects of different support materials, geometries, wind velocities, and climates.

The model predicts the drying process to be sensitive to factors that increase banana temperature but not to ambient humidity. The model demonstrates that 1 method of increasing banana temperature is through reducing wind exposure, which is calculated from the model to reduce drying time by typically 15%. Such exposure could be reduced by locating the drying tray to take advantage of the shelter of structures, vegetation, and ground contours. Alternatively, the trays could be modified to reduce air movement around the bananas. The need for a lower storage moisture content than currently observed in commercial packs was identified by Phoungchandang and Woods (2000). These results suggest that reduced exposure to wind would also reduce the final moisture content achievable. Locating the drying tray in a sheltered location could also influence the microclimate, giving a higher local air temperature around the trays, due to the solar radiation intercepted at the surrounding ground level not being dissipated as rapidly by the wind. This would also assist drying. These predictions need to be tested experimentally.

Materials and Methods

Apparatus

The laboratory light source consisted of an array of metal halide lamps often referred to as Compact Source Iodide (CSI). The spectral distribution of the CSI lamps gives a good approximation to the solar spectrum at sea level. The array comprised 4 × 4 lamps at a nominal spacing of 0.6 × 0.6m and at a height of 3.4 m above the floor. The spacing of the lights was adjustable, and each light was pivoted so that the angle of incidence could be set.

The supporting tray for the bananas was constructed from plastic tubing and plastic mesh. Plastic, being a polymer, has a similar thermal conductivity to the natural fiber mesh used in Thailand. The rectangular frame was constructed from 20-mm tubing with dimensions of 500 × 500 mm in the horizontal plane and a height of 700 mm. The mesh supporting the bananas had 15 × 15 mm apertures. The lightweight construction of the frame enabled the whole assembly, with bananas, to be placed on a balance increasing the height by 100 mm.

The tray was located so that the intensity of radiation, $\dot{q}_h$, as measured by a horizontally placed solarimeter, was either 671 W/m^2 or 846 W/m^2. This was achieved using light angles to the vertical of 40° and 30°, respectively, giving respective distances from light array center to tray center of 3.35 and 2.95 m. The uniformity of irradiance was assessed by taking 3 × 4 solarimeter readings over a 375 × 500 mm area of the mesh drying surface. For the 671 W/m^2 intensity, the standard deviation was 8.2%, and for 846 W/m^2, the standard deviation was 11.7%. Gillett (1977) considered that a 10% variation was reasonable for thermal performance experiments given the heat transfer normal to the light direction.

Instrumentation

Temperature was measured using T-type thermocouples of small dia, 0.2 mm giving low conduction errors. Four thermocouples were inserted into the banana center. The mean peeled banana dia was 31 mm and length, 94 mm (Phoungchandang and Woods 2000). Ambient temperature was sensed by 2 thermocouples located just outside the tray area and shaded by aluminum foil. Temperatures above and below the tray were monitored by 4 thermocouples at opposite corners, above and below the tray, again shielded by foil. The weight measurement was performed to a resolution of 0.01g. Since the essential measurement is the change of weight, this is a good indicator of accuracy. The data logging system recorded all these measurements at intervals of 30 min.

The radiation intensity was measured by a solarimeter (Casella W6500—http://www.casella.co.uk) placed horizontally.

Moisture content was determined based on Pearson (1976), as detailed in Phoungchandang and Woods (2000), at the start and on completion of drying.

The relative humidity in the laboratory was measured manually using aspirated wet- and dry-bulb thermometers. As was shown above in the Results and Discussion, the drying process is insensitive to ambient RH. The RH was therefore taken as a series of spot readings. Subsequently, we obtained hourly readings of outside temperature and humidity from the Meteorological Office (Anon. 2000b) for a station within 1 mile of the laboratory. These were processed using psychrometric theory (Anon. 1989b), assuming the humidity ratio (fraction of moisture in air), H, in the laboratory to be equal to the outside value. This is well justified, as the moisture sources in the laboratory were negligible, given that the ventilation gave an estimated 3 air changes per h (Anon. 1989c). The ambient conditions, which provide input data to the computer simulation of the laboratory results, were based on the RH values derived from the Meteorological Office data and the measured laboratory temperatures.

Experimental drying method

The variety of banana used in this experiment was *Musa* cv Klue namwa ABB. The samples were imported from Thailand as hand luggage and stored at Newcastle at 13 °C, as described in more detail by Phoungchandang and Woods (2000). The ripeness index of the bananas was typically 5 (Stover and Simmonds 1987) with a few fruits at 4 or 6, but none at 7 with brown spotting. No pretreatments were used. Given the limited number of bananas available, it was decided to perform 2 experiments, each with a large number of bananas, to obtain a more commercially realistic drying situation than multiple experiments with small numbers. Two experiments were performed at 671 and 846 W/m^2, each employing 27 bananas (about 2000g). The large numbers used should also give good average values. At the start of the experiment, the balance was tared to 0, and the empty tray was placed on it. When the balance reading of the tray was stable, the true weight of the tray was recorded. The sample (27 bananas) was spread on the tray to form a single layer. The bananas were orientated perpendicular to the light path, at a spacing of approximately 25 mm, which was far enough to avoid shadowing. Then, the overall weight of the tray and sample was recorded.

Drying took 7 to 8 d with an exposure under lights of 8 h per d. Following exposure, the bananas were kept in polythene bags to simulate overnight packed storage as performed commercially in Thailand. After each d's drying, the equilibrium relative humidity was checked using the method described in Phoungchandang and Woods (2000). When the water activity of the dried banana fell to 0.65, the experiment was terminated. Samples were double wrapped in polythene bags and stored at 13 °C.

Nomenclature

a	constant
b	constant
C_1-C_3,	constant
C_8-C_{13}	constant
C_p	specific heat capacity (kJ/kg K)
d	dia of banana (m)
f	constant (kJ/kg K)
Gr	Grashof number
h_c	convective heat transfer coefficient (W/m^2K)
h_r	radiative heat transfer coefficient (W/m^2K)
H	absolute humidity (kg H_2O/kg dry air)
k_A	thermal conductivity of air (W/mK)
K	drying constant (s^{-1})
l	length of banana (m)
L	latent heat of vaporization (kJ/kg)
$\dot{m}_{H_2O}$	rate of moisture evaporation (kg/s)
M	constant
M_{bd}	mass of banana dry matter (kg)
n	constant
Nu	Nusselt number
P_a	atmospheric pressure (kPa)
Pr	Prandtl number
P_{ws}	saturation vapor pressure of water (kPa)
$\dot{q}_h$	radiation on the horizontal surface (W/m^2)
$\dot{q}_i$	incident radiant energy (W/m^2)
$\dot{Q}_{abs}$	absorbed radiant energy (W)
$\dot{Q}_c$	surface convection heat loss (W)
$\dot{Q}_e$	evaporative heat loss (W)
$\dot{Q}_r$	radiation heat loss (W)
Re	Reynolds number
RH	relative humidity (decimal)
t	time (s)
T	temperature (°C)
T_K	absolute temperature (K)
x	pressure ratio (P_{ws}/P_a)
X	moisture content (% d.b.)
X_{wb}	moisture content (% w.b.)

Greek letters

α	absorptivity of solar radiation
ϵ	long-wave emissivity
σ	Stefan-Boltzmann constant (W/m^2K^4)
θ	angle of incidence of solar radiation to the vertical (degrees)

Subscripts

a	ambient
b	banana
d.b.	dry basis
e	equilibrium
w.b.	wet basis

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