STUDY OF SENSITIVITY OF PARAMETERS THAT AFFECT OPERATION OF BANANA'S DRYING (MUSA SPP): BY SOLAR ENERGY

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Abstract: *The drying is a process widely used as a way to add value to the fruits, as well as, to preserve the physical and chemical qualities for the storage and posterior distribution. This study deals the solar drying of bananas. The dry banana presents high sugar content. It can be classified like a product of high energetic value, easily assimilate. A mathematical model that considers the term of absorption solar radiation and emission of infra-red radiation, that by natural convection and evaporation is well established where the development of the model of the process and the tests significantly contribute for the understanding of the mechanisms and involved processes in the drying. The evolution from temperature with the time as well as the moisture content of the product during the process of solar drying is determined. There is a good correspondence between the rate of drying and the rates of heating of the banana during the drying, mainly at the beginning of the process where the reduction of the moisture is easier. Finally, the simulation is used to investigate certain physical processes that limit the solar drying. The objective of this paper was to describe the behavior of the temperature and moisture of the banana during the drying by means of graphics in which it showed of integrated form the evolution in the time.*

Keywords: *Dry, solar radiation, temperature, moisture.*

1. INTRODUCTION

The drying process is used since the antiquity for being of easy application, however of complex understanding due to several mechanisms that the process involves, such as: process of mass and heat transfer, and mechanics of fluids. This process besides extending the shelf-life reduces the weight of the product for the transport and the necessary space for the storage (Fioreze, 2004).

The drying is the remove, volunteer or not, total or partial, of a gaseous or liquid phase of any material (Fioreze, 2004). It can be natural, by means of solar energy or artificial, made by means of mechanical dryers. It is called mixed, when the drying is processed in the terraces and dryers. The solar drying is recommended in regions of dry climate, with good solar irradiation and scarce pluvial precipitations, preferably windy at the epoch where the drying is done (Miranda de Souza, 1991). In the drying of fruits a substantial loss of vitamins can occur, mainly due to thermal treatments. On the rich fruits in carbohydrates, during the dehydration, it occur a natural browning in the surface, due to enzymatic action. This browning can be controlled, putting the fruits in a sulphur solution (metabisulphite of sodium), in the ambient temperature, before the drying (Fioreze, 2004).

The banana (*Musa spp*) of the family Musácea is rich in sugars, minerals, mainly in phosphorus and potassium, besides contain mean levels of calcium, iron, copper, zinc, iodine, manganese, cobalt and vitamin A, thiamin, riboflavin, Niacin and vitamin C (Simão, 1971). The drying of fruits is a widely beneficial alternative for conservation and commercialization. According to FAO, 1991 Brazil is the world second largest producer and consumer of banana (Borges, 2008). The Brazilian production is distributed throughout the national territory, being the largest producer in the Northeast region (34%), followed by the North (26%), Southeast (24%), South (10%) and Centre-West (6%) Regions (Borges, 2008). This fruit *in nature* presents 70% moisture content (Borges, 2008). The dry banana presents high of sugars content. It can be classified between the products of high nourishing value, easily assimilate. Its energy value is of the order of 318cal/100g (Simão, 1971).

The mathematical simulation is a tool that is becoming more common due its practice and economy. By means of this methodology it's possible completely analyze the costs of a process. To simulate a drying process the several variables involved need to be represented by a mathematical model appropriate. The development of the model of the process and the tests significantly contribute for the understanding of the mechanisms and involved processes in the drying. The models have become increasingly complex, and new techniques for computer simulation have been developed for the solutions (Fioreze, 2004). The mathematical model of solar drying of bananas was developed using a numerical solution to generate a computational simulation. The objective of this work is to determine the temperature in function of time and also the moisture of the product during the process of solar drying. A study of the sensitivity of the parameters it is carried through to determine which parameters influence the evolution of the temperature and the text of humidity of the banana. Finally, the simulation also is used to investigate definitive physical processes that limit the solar drying.

2. MATHEMATICS SIMULATION

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.

2.1. 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

$$m_b . c_{pb} . \frac{dT_b}{dt} = \dot{Q}_{abs} - \left(\dot{Q}_{rad} + \dot{Q}_{conv} + \dot{Q}_{evap} \right) \tag{1}$$

Where:

$m_b =$ mass total of banana (kg)

$dT_b =$ variation in banana temperature (^{o}C)

$dt =$ variation in time (h)

$\dot{Q}_{abs} =$ absorbed radiant energy (w)

$\dot{Q}_{evap} =$ evaporative heat loss (w)

$\dot{Q}_{rad} =$ Radiant heat loss (w)

$\dot{Q}_{conv} =$ surface convection heat loss (w)

$c_{pb} =$ specific heat capacity the banana (kj / kgk)

and 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

$$c_{pb} = 1{,}34 + 2{,}62 X_{wb} \tag{2}$$

Where:

$X_{wb} =$ moisture contente in wet basis $(\%)$

2.1.1. SOLAR ABSORPTION

The solar energy absorbed for unshaded bananas can be written

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

where:

$\dot{Q}_{abs} =$ absorbed radiant energy (w)

$\alpha =$ absorptivity of solar radiation

$l_b =$ length of banana (m)

$d_b =$ dia banana (m)

$\dot{q}_i =$ Incident radiant energy $\left(w/m^2\right)$

And: $\dot{q}_i = \dot{q}_h / \cos\theta$ (4)

where:

$\dot{q}_i =$ Incident radiant energy $\left(w/m^2\right)$

$\dot{q}_h =$ radiation on the horizontal surface $\left(w/m^2\right)$

where l_b .d_b 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 a 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

$$\dot{Q}_{abs} = \alpha\left(l_b . d_b\right)\dot{q}_h \quad (5)$$

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).

2.1.2. 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.

$$\dot{Q}_{conv} = hc.\left(\pi . d_b . l_b\right).\left(T_{kb} - T_{ka}\right) \quad (6)$$

where:

$\dot{Q}_{conv} =$ surface convection heat loss (w)
$l_b =$ legenth of banana (m)
$d_b =$ dia banana (m)
$T_{kb} =$ absolute temperature in banana (k)
$T_{ka} =$ absolute temperature in ambient (k)
$h_c =$ convective heat transfer coefficient $\left(w/m^2 k\right)$

and: $h_c = Nu . \frac{k_A}{d}$ (7)

where:

$Nu =$ nusselt number
$k_A =$ thermal condutictivity of air (w/mk)
$d =$ characteristic length in banana (m)

The correlation for natural convection is given

$$Nu = \frac{h_c.d}{k_A} = a(Gr\ .\Pr)^n \tag{8}$$

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

Where: k_A = thermal conductivity of air (w/mk)

$$Nu = b.\mathrm{Re}^m \tag{9}$$

In the range, 35 < Re < 5 X 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.

2.1.3. 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

$$\dot{Q}_{rad} = \varepsilon.\sigma.(\pi.d_b.l_b).(T_{kb}^4 - T_{ka}^4) \tag{10}$$

where:

$\dot{Q}_{rad}$ = Radiant heat loss (w)
ε = long-wave emissivity
σ = Stefan-Boltzmann constant (w/m^2k^4)
l_b = legenth of banana (m)
d_b = dia banana (m)
T_{kb} = absolute temperature in banana (k)
T_{ka} = absolute temperature in ambient (k)

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 Brazil, Eq. 10 is a reasonable approximation. Equation 8 can be linearized, as in Duffie and Beckman (1991), as follows:

$$\dot{Q}_{rad} = h_r(\pi dl)(T_b - T_a) \tag{11}$$

where the radiative heat transfer coefficient, h_r can be written

$$h_r = \xi\sigma(T_{kb} + T_{ka})(T_{kb}^2 + T_{ka}^2) \tag{12}$$

2.1.4. EVAPORATIVE ENERGY

The rate of energy loss by evaporation is given by

$$\dot{Q}_{eva} = (L - f.T_b)\dot{m}_{H_2O} \tag{13}$$

where L = 2448 kJ/kg (latent heat of vaporization) and f = 0.2386 kJ/kg K (constant), (Anon. 1987). Evaluating the evaporative heat loss in Eq. 13 requires the determination of the drying rate. And $\dot{m}_{H_2O}$ = rate of moisture evaporation (kg/s).

2.1.5. RATE OF MOISTURE LOSS

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

$$\frac{dX}{dt} = -k\left(X - X_e\right) \tag{14}$$

where:
$X =$ moisture content (%) in dry basis.
$X_e =$ moisture content equilibrium

and

$$\dot{m}_{H_2O} = M_{bd}\,\frac{d\left(X/100\right)}{dt} \tag{15}$$

where M_{bd} is the mass of dry banana. The value for K (drying constant s^{-1}) was given by the Arrhenius equation (Phoungchandang and Woods 2000) as

$$k = 0{,}6854\exp\left(\frac{-3316{,}1}{T_b + 273{,}15}\right) \tag{16}$$

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

$$X_e = \left(\frac{C_1 + C_2 T_b}{\left(\frac{1}{RH_b} - 1\right)^{1/C_3}}\right) \tag{17}$$

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.

2.1.6. 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

$$RH_b = \frac{1}{x}.\left(\frac{H}{0.6220 + H}\right) \tag{18}$$

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 ºC.

$$\ln\left(p_{ws}\right) = \frac{C_8}{T_{kb}} + C_9 + C_{10}T_{kb} + C_{11}T_{kb}^2 + C_{12}T_{kb}^3 + C_{13}\ln\left(T_{kb}\right) \tag{19}$$

Equation (19) and the values of the constants are presented in Anon. (1989b).

3. SOLUTION PROCEDURE

The change in moisture content defined in Eq. 14 is written in finite difference form as

$$\Delta X = \Delta t * \left(-K\left(X - X_e\right)\right) \tag{20}$$

where K and X_e are given by Eq. 16 and 17. The change in temperature defined in Eq. 1 can be written in finite difference form as:

$$\Delta T_b = \frac{\Delta t}{m_b.c_{pb}}\left[\alpha.(dl).q_i - \pi.(dl).(h_e + h_c)\right] - \left[\left(L - f.T_b\right).\frac{M_{bd}\left(\Delta X/100\right)}{m_b.c_{pb}}\right] \tag{21}$$

4. RESULTS AND DISCUSSION

The kinetic of drying of a product is the most important information necessary to perform satisfactory resulted of the operation of banana's drying by solar energy. However, due to uncertainty of the process, particularly when it is related to biological materials, all the necessary data for the studied conditions are not usually available. In the drying by natural convection, the temperature of air and humidity of the product have significant effect in its kinetic.

The characteristics of each product, associates to the properties of the solar radiation to the mean of adopted heat transfer, determine diverse conditions of drying. Initially, the banana has a high moisture content around 70% w.b. Therefore, it is useful to analyze the data on the radioactive properties for other vegetal materials and based in this analyzis, the absortivity of solar radiation of the banana was taken as 0,8 and the emissivity as 0,9 for the mathematical simulation. The temperatures used ranged from (20, 24, 28 and 32 °C) for the air-drying and 20º C for the banana, while the relative humidity was set at 50% thereby humidity in their absolute values: (0.00726, 0.009297 0.01183, 0.01495) kg water / kg dry air. The radiation on the horizontal surface was of 671W/m^2 and is the angle of incidence was of 40º. It was made for an average size of the product where considered the diameter of 0.031m and the length of 0.093m.

The drying done at relatively low temperatures gives the best features of the product that when used excessively high temperatures can cause cooking of the product. And not yet offers conditions for certain volatile substantiates to be gotten loose of the food, contributing for the permanence of the original qualities of the product.

According to the mathematical simulation it is observed that of all the variables set as shown in figures 1 and 2, the variation in temperature and the incidence of solar radiation increases the temperature of the banana (Fig. 1) and also the rate of drying (Fig. 2). So every day the temperature of the banana tends to increasingly larger values are set at 45 C for any ambient temperature and the increase in temperature over time for the banana is due to the loss of heat through evaporation is reduced for each day the process of drying and consequently the higher temperatures are reached at the end of the process of drying the banana, as shown in (Fig. 1).

As time goes on during the drying the product (banana) will lose moisture content and moisture content of this concept stems from the fact of food are made of a solid substance, known as dry matter and a certain amount of water, ranging in certain limits.

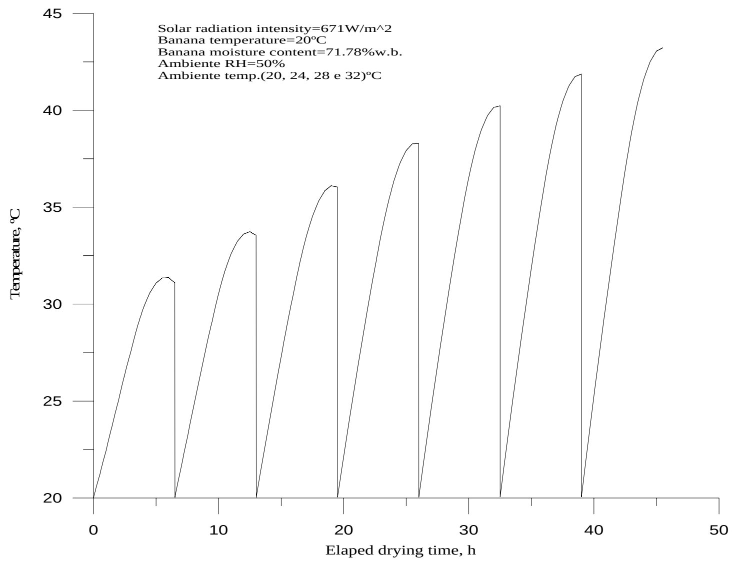

Figure 1. Variation in banana temperature due to the sensitivity of the solar-drying model to variation in the ambient temperature

Increasing the temperature of the banana increases the rate of drying (Fig. 2) in two ways: The first involves the internal rate of spread increases as that described by the Arrhenius equation (eq. 16). The second involves the moisture content the equilibrium to balance the banana dry that is approximate to the RH on the surface of the product (banana), which decreases with increasing temperature the banana.

As the product is dry, its surface will appear in regions not covered by the film of water. The average humidity of the product at this point is known as "critical moisture." From that point, the limiting factor is the handling of the drying of moisture within the product, and it enters the period of decreasing rate of drying. The physical meaning of critical moisture content, is that until this point the product is great danger that, once its surface has a high humidity, won this stage in a process of drying, the risk decreases.

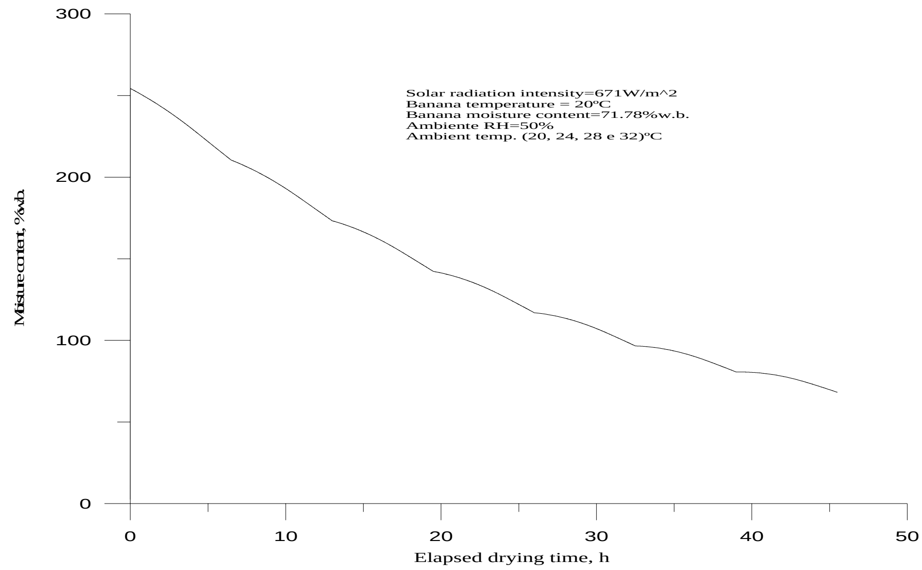

Figure 2. Variation in banana moisture content due to the sensitivity of the solar-drying model to variation in the ambient temperature

With these observations the drying get a better view provided by the use of the mathematical model used. Increasing the temperature of the banana drying is faster to a lower moisture content (Fig. 2), which is particularly important during the final stages of drying, where there is a problem in obtaining the safe level of water activity (Phoungchandang and Woods 2000).

5. CONCLUSION

The mathematical model of drying of bananas was developed to determine the temperature in function of time and also the moisture content of the product during the process of solar drying.

This model is generally applicable to solar drying in a single layer and the climate variables such as temperature and relative humidity. It is enough flexible to examine the effect on the geometry of the considered product as a finite cylinder.

The analysis of temperature environment and the index of solar radiation was essential in this mathematical model for the drying of banana, as identified through this analysis is that even with the increase in temperature which ranged from (20, 24, 28 and 32 ºC) of the product (banana) also had an increase in its temperature until it reaches 45ºC in the loss of heat through evaporation is reduced, and thereupon to higher temperatures were reached at the end of drying. Another analysis of this model is important as an increase in the rate of drying the banana by the Arrhenius equation (eq. 16) and an approximation of the moisture balance with the RH on the surface of the banana which decreases with increasing temperature of the product (banana).

Therefore no matter the temperature for this model, because it shows that for any ambient temperature reaches the banana the temperature of drying without major changes in the process thus ensuring the provision of the mathematical model, because the values of temperature and moisture content of bananas on calculated by the mathematical model are very close to the values found in literature. However, it is necessary to make the one study of the sensitivity of the parameters that influence the operation of drying of the banana (Musa spp) by energy solar gone deep and to test the estimates experimentally.

6. ACKNOWLEDGEMENTS

Coordination of Improvement of Higher Education Personnel - (CAPES).

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8. RESPONSIBILITY NOTICE

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