Journal of Food Engineering 128 (2014) 46–52

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Experimental determination of thermal conductivity and thermal diffusivity of whole green (unripe) and yellow (ripe) *Cavendish* bananas under cooling conditions

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ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form 22 November 2013
Accepted 12 December 2013
Available online 22 December 2013

Keywords:
Thermal conductivity
Thermal diffusivity
Banana
Cooling

ABSTRACT

Bananas are cooled to 13 °C after their harvest to extend their shelf life and prevent post-harvest losses. Since they are subjected to chilling injuries at temperatures below 11 °C, thermal properties should be known to design a cooling process. For this purpose, thermal diffusivity and thermal conductivity of green and yellow *Cavendish* bananas were determined experimentally using analytical solution of heat transfer for an infinite cylinder. Experiments were carried out in cooling chambers, and temperature change of bananas were recorded using thermistors. Thermal conductivity–diffusivity values of the green and yellow bananas changed from 0.302 to 0.338 W/m-K and 1.442×10^{-7} to 1.500×10^{-7} m^2/s, respectively. These values were validated by literature data and additional experiments where simulated and experimental data were compared while the effect of banana peel on the cooling rates was also explained. These comparisons demonstrated the significance of knowing thermal conductivity–diffusivity values separately for designing and optimizing a cooling process.

1. Introduction

Bananas are members of the family *Musaceae*, genus musa and one of the important fruit crops grown around the world. They rank among citrus, pome fruit (apples and pears) and grapes as major international trading commodities (Kotecha and Desai, 1995; Turner, 1997; Paull and Duarte, 2011). They are typical climacteric fruits and characterized by ethylene production controlling ripening (including respiration, pulp softening, peel yellowing and aroma compounds production) (Clendennen and May, 1997). Green bananas (unripe) are typically cooled to 13 °C to extend their shelf life and prevent postharvest losses by slowing down their metabolism (Kotecha and Desai, 1995; Zhang et al., 2010). This process delays ripening and senescence. Cooling is generally carried out in cardboard cartons (Paull and Duarte, 2011). It should be a rather gentle process since bananas might be susceptible to chilling injury especially when subjected to temperatures below 11 °C (Kotecha and Desai, 1995; Turner, 1997). The chilling injury manifests itself as a smoky or dull yellow color after ripening. In addition to cooling upon harvest, transport of palletized bananas in containers has been a daily business, and adequate temperature measurement during transport is rather significant (Jedermann et al., 2013). Hence, knowing thermal properties (thermal diffusivity and thermal conductivity) of bananas is significant to predict cooling rate and for and optimal design of a cooling process.

Experimental determination of thermal diffusivity with a known heat transfer coefficient is a standard approach for further simulation of a process since it combines thermal conductivity, specific heat and density. Andrieu et al. (1986) reported the thermal diffusivity value of bananas as 1.37×10^{-7}–1.46×10^{-7} m^2/s for flesh at 20 °C while Gaffney et al. (1982) and Singh (1982) gave the values of 1.18×10^{-7} and 1.42×10^{-7} m^2/s at a moisture content of 76% and temperatures of 5 and 65 °C, respectively. In these studies, even though it was not reported, the values seemed to be reported for banana flesh. Mariani et al. (2008) determined the thermal diffusivity of whole bananas under various drying conditions. The whole ripe banana was assumed to hold infinite cylinder geometry, and thermal diffusivity values were determined as a function of temperature and moisture content. Ikegwu and Ekwu (2009) determined the thermal properties of peeled bananas using the formulas given by Sweat (1974) and reported thermal diffusivity and thermal conductivity of banana flesh as 1.50×10^{-7} m^2/s and 0.498 W/m-K, respectively while Bart-Plange et al. (2012) determined these values as 1.60×10^{-7} m^2/s and 0.458 W/m-K for peeled fresh ripe Gros Michel bananas. Sweat (1974) and Liang et al. (1999) also determined thermal conductivity value of

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http://dx.doi.org/10.1016/j.jfoodeng.2013.12.010

bananas in the range of 0.475 and 0.462 W/m-K, respectively. Similar to bananas, Njie et al. (1998) determined thermophysical properties of plantain. For moisture content of 57%, thermal conductivity and thermal diffusivity values of plantains were reported to be 0.45 W/m-K, and 1.51×10^{-7} m^2/s. Since either empirical formulas or probe method was used for determining the thermal conductivity, this might lead to the conclusion that the reported values are for banana flesh unless otherwise is noted. On the other hand, one can easily calculate a thermal diffusivity value of 1.33×10^{-7} m^2/s and thermal conductivity of 0.53 W/m-K with well-known equations of Choi and Okos (1986) assuming a moisture content of 80% and the rest for carbohydrates without the effect of peel at 20 °C.

For designing and optimizing a cooling process, knowing an apparent values of thermal diffusivity and thermal conductivity including both flesh and peel including the effect of respiration heat would be valuable. Ansari et al. (2007) demonstrates the slowing effect of skin on cooling rate of spherical fruits and vegetables, and with the cellulose and hemicelluloses content of banana shell (Ketiku, 1973) and its irregular and porous structure (Kamsonlian et al., 2011), a possible insulation effect should also be considered leading to a lower apparent thermal conductivity and thermal diffusivity values of whole bananas compared to flesh. Besides, effect of respiration rate on temperature increase is well-known, and ripening process is associated with respiration. Cuesta and Lamua (2009) expressed heat generation effect in chilling fruits and vegetables as a highly complex problem. In addition, Erdoğdu (2008) stated that the thermal conductivity and thermal diffusivity terms should be known separately with heat transfer coefficient for an effective simulation of a process. For the case of bananas, determining apparent values including the effects of peel and heat generation might be enough to design a cooling process. Palazoğlu (2006) demonstrated the significance of lower heat transfer coefficients as in the case of cooling. Huang and Lio (2009) also signified the effect of thermal conductivity and thermal diffusivity as essential parameters for designing a food processing operation. Based on these, the objectives of this study were to determine thermal diffusivity and thermal conductivity values of whole green (unripe) and yellow (ripe) bananas under cooling conditions where the temperature variation is not large (from 22 ± 1 °C to 8 ± 1 °C) to assume these thermophysical properties of the bananas to be constant.

2. Materials and methods

For the given objectives, mature green and yellow *Cavendish* variety of bananas were used in the experiments. The bananas were purchased from a wholesale centre, tested for external defects and graded based on their uniform outer appearance. The fruits were stored at 12 °C in plastic films in cardboard cartons to represent a commercial practice prior to the experiments. Moisture content of the bananas were determined applying the gravimetric method at 85 °C where a drying cabinet, UT20 (Heraeus Instruments, Hanau, Germany) was used. Thermal diffusivity and thermal conductivity values were determined using the analytical solution of an infinite cylinder while Archimedes principle was used for calculating the density. Specific heat value was calculated from ($\alpha = \frac{k}{\rho \cdot c_p}$). Since the variation in temperature during cooling conditions is not large, thermophysical properties and dimensions of the bananas were assumed to be constant, and the analytical solution of the diffusion equation describing the heat transfer in an infinite cylinder was applied. da Silva et al. (2012) also reported the use of diffusion equation to determine transport properties of food products with constant dimensions and thermophysical properties.

2.1. Mathematical background

The whole green (unripe) and yellow (ripe) bananas were assumed to hold the geometrical shape of an infinite cylinder where the heat transfer in the longitudinal direction might be neglected. Thus, the physical problem involved a one-dimensional medium initially at a uniform temperature and subjected to cooling conditions at constant temperature and heat transfer coefficient. Since the bananas were considered to be homogeneous (as a whole with pulp and peel including the effect of heat generation due to respiration), the resulting transport properties were apparent values of the thermal conductivity and thermal diffusivity. The heat loss as a result of moisture evaporation through the surface of the bananas were assumed to be negligible. The negligible (<0.5%) mass losses during the cooling stage verified this assumption.

Governing differential equation and solution for an infinite cylinder are given as follows with the initial uniform temperature distribution and symmetry at center with the boundary condition of surface convection, 3rd type boundary condition.

Governing differential equation:

$$\frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T}{\partial r}\right) = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} \tag{1}$$

subjected to

$$T(r, 0) = T_i \tag{2}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0$$

$$-k \cdot \left.\frac{\partial T}{\partial r}\right|_{r=R} = h \cdot [T(R, t) - T_\infty] \tag{3}$$

where T is temperature (°C); T_i is initial uniform temperature (°C), T_∞ is medium temperature (°C), r is location in geometry (m; from center, 0 to surface R); and α is thermal diffusivity (m^2/s), k is thermal conductivity (W/m-K) and h is convective heat transfer coefficient (W/m^2-K).

Solution for Eq. (1) subjected Eqs. (2) and (3) is:

$$\frac{T(r,t) - T_\infty}{T_i - T_\infty} = \sum_{n=1}^{\infty}\left[\frac{2}{\lambda_n} \cdot \frac{J_1(\lambda_n)}{J_0^2(\lambda_n) + J_1^2(\lambda_n)} \cdot J_0\left(\lambda_n \cdot \frac{r}{R}\right) \cdot \exp(-\lambda_n^2 \cdot Fo)\right] \tag{4}$$

where Fo $\left(Fo = \frac{\alpha \cdot t}{R^2}\right)$ is Fourier number and R is radius (m), and λ_n's are the roots of Eq. (5):

$$Bi = \lambda \cdot \frac{J_1(\lambda)}{J_0(\lambda)} = \frac{h \cdot R}{k} \tag{5}$$

where Bi is Biot number, and J_0 and J_1 are the first kind 0th and 1st order Bessel functions.

For Eq. (4), it is important to know how many terms of the infinite series solutions are required to obtain a correct solution to determine the temperature change, and It is a general knowledge that use of the first term would be enough when the Fourier number is greater than 0.2 since the temperature ratio variation following this point would be linear. As long as the thermal diffusivity is assumed to be constant, this first term approach may be easily used to determine these parameters with a known value of heat transfer coefficient (Erdoğdu, 2005, 2008).

Based on this temperature ratio $\left[\ln\left(\frac{T(r,t) - T_\infty}{T_i - T_\infty}\right)\right]$ becomes linear after a certain time (Fo > 0.2), the first term of Eq. (4) is then used to characterize this linear part. When the natural logarithm of both sides of Eq. (4) is taken using only the first term (n = 1), following equation is obtained: