

Thermal Diffusivity During Water Bath Cooking of Breadfruit (*Artocarpus communis*)

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Abstract-Breadfruit is a fruit originated from South Pacific, and afterwards, it was widespread in the rest of Oceania. In Colombia, it is known as “Fruta de pan” and in-home use, breadfruit has been consumed cooked, fried or roasted. The optimisation of water bath cooking could reduce the energy cost of these operations; therefore, this study aimed to determine the thermal diffusivity during the process of boiling baking cylinders of breadfruit. The process was carried out using a temperature controlled water bath designed for this purpose at 95 °C. The method used for the determination of diffusivity was based on the analytical solution of the heat transfer by conduction equation written in cylindrical coordinates. We found a thermal diffusivity value of $6.45 \cdot 10^{-7} \text{ m}^2/\text{s}$, which was within the range of values reported by other authors, although not in the product studied, since there were no previous studies on this matter for the breadfruit.

Keywords: Fruta de pan, Heat transfer, Conduction, Time-temperature profiles, Native products.

I. INTRODUCTION

Artocarpus communis, commonly known as breadfruit tree because of the "bread-like texture" of its edible fruits, is an equatorial lowland species of flowering tree in the mulberry family (*Moraceae*), which has about 50 genera and over 1000 species that grows best below elevations of 650 m [1]. *A. communis* is a fruit tree that is propagated by the root cuttings and the average age bearing the first crop is between 4 and 6 years. It produces its fruit up to 2-3 times in a year, and the number of fruits produced is very high. The fruit is aromatic, rich in latex and can weigh between 1 kg and 4 kg [2]. Breadfruit is a fruit originated from South Pacific, and afterwards, it was widespread in rest of Oceania. In Colombia, it is known as “Fruta de pan” and in-home use, breadfruit has been consumed cooked, fried or roasted [3], [4]. *A. communis* is edible and a valuable natural resource due to its high content of nutrients (84.2 % carbohydrates, 4.1 % proteins, 3.5 % fibre and 2.9 % minerals in dry weight) [5].

Water bath cooking is a wet cooking process, where the maximum water temperature is 100 °C at 1 bar, or under other pressure conditions [6]. The choice of cooking process parameters should represent an acceptable compromise between sensorial quality, microbiological quality and energy use [7]. Concerning the latter, optimising this type of process could reduce the energy cost of these operations, so it is of interest in engineering [8]. To control and optimise cooking operations, fundamental physical processes and physical properties must be analysed and estimated. Several studies have been devoted to studying the cooking process of some products, mostly meat and starchy products [6], [9]–[11].

There are no data related to the cooking of breadfruit; therefore, the objective of this work was to study the diffusivity during the cooking process of cylinders of *A. communis* from San Andrés Island (Colombia), looking for generating a calculation of thermal diffusivity.

II. MATERIALS AND METHODS

A. Raw material

The breadfruit (*A. communis*) was obtained from the Central Market of San Andrés Island (Colombia) in a commercially mature state, healthy and free of fungi and weevil. The peel was removed and cut in the shape of a cylinder 10 cm long and 3 cm in diameter.

B. Cooking procedure

Cooking processing operations were carried out using a temperature controlled water bath built and designed at our laboratory for this purpose following the same specifications used by Ayadi *et al.*, [6]. For this, J-type thermocouples were used to determine the time-temperature history of samples during cooking. One thermocouple was placed in the bath water to measure the process temperature. The second thermocouple was fixed at the geometric centre of the sample. The third one was placed just under the sample surface, at a maximum depth of 0.5 mm. At the beginning of the experiment, samples were placed in the water bath at $95 \pm 1^\circ\text{C}$. The water in the unit was not stirred during cooking. When the temperature at the centre of the sample had increased to the desired value (between 72°C and 76°C), the sample was removed from the hot water. Temperature changes in the water bath (T_w), sample centre (T_c) and on the sample surface (T_s) were monitored every 2 min. The water to sample ratio was 6 to 1.

C. Thermal diffusivity determination

To simplify the problem, the sample was modelled as a finite cylinder with radius R and length $2L$. The method used was based on the analytical solution of the conduction heat transfer equation written in cylindrical coordinates. This method was described and applied by Ayadi *et al.*, [6] to measure the thermal diffusivity of salami and ham products prepared from turkey meat. The method assumes a constant sample surface temperature (T_s) and constant thermal diffusivity. If the initial temperature distribution (T_0) is uniform, the exact solution of the conduction heat transfer equation written in cylindrical coordinates is described by Equation (1).

$$\frac{T_s - T}{T_s - T_0} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2(-1)^{m+1}}{\beta_m} \cos\left(\frac{\beta_m z}{L}\right) \frac{2J_0(\beta_n r/R)}{\beta_n J_1(\beta_n)} x \exp\left[-\left(\frac{\beta_n^2}{R^2} + \frac{\beta_m^2}{L^2}\right) \alpha t\right] \quad (1)$$

If the sample is exposed to the temperature difference for a long time, Equation (1) can be reduced to the first term of the series. For $m = n = 1$, $\beta_m = \pi/2$, $\beta_n = 2.405$, $J_1(2.405) = 0.519$, and at the centre of a cylindrical sample $z = 0$, $r = 0$ and $J_0(0) = 1.0$. The temperature change at the central point of the sample in the case of long exposure to external temperatures is then given by Equation (2).

$$\ln|T_s - T_c| = \ln(2.0396|T_s - T_0| - \left[\left(\frac{2.405}{R}\right)^2 + \left(\frac{2\pi}{L}\right)^2\right] \alpha t) \quad (2)$$

Then, thermal diffusivity can be calculated by using Equation (4). Equation (2) is linearly time-dependent and can be transformed to the equivalent linear form as Equation (3) shows with slope B and intercept A . The thermal diffusivity then can be calculated from Equation (4).

$$\ln|T_s - T_c| = A - Bt \quad (3)$$

$$\alpha = B \left[\left(\frac{2.405}{R}\right)^2 + \left(\frac{2\pi}{L}\right)^2 \right]^{-1} \quad (4)$$

B can be calculated from experimental data using linear regression. The temperature of the water bath during cooking was assumed to be constant.

III. RESULTS AND ANALYSIS

A. Time-temperature profiles and thermal diffusivity estimation

Fig. 1 shows the thermal history of breadfruit samples during the cooking process. The thermal centre of the product recorded with the thermocouples showed a linear temperature increase, reaching 75 °C in 1 h. This was most likely because the maximum internal energy within the sample was achieved [4]. Other authors obtained similar results for this temperature change in the centre of the sample of different foodstuffs [6], [9], [12], [13]. On the other hand, the surface temperature increased rapidly at the beginning of the process, stabilising at temperatures close to 90 °C. This means that the gelatinisation of starches started at nearby points from the surface of the sample shortly after the start of the cooking process and lasted almost to the end until the temperature of the points found near the axes reached the temperature of the cooking medium [6], [13].

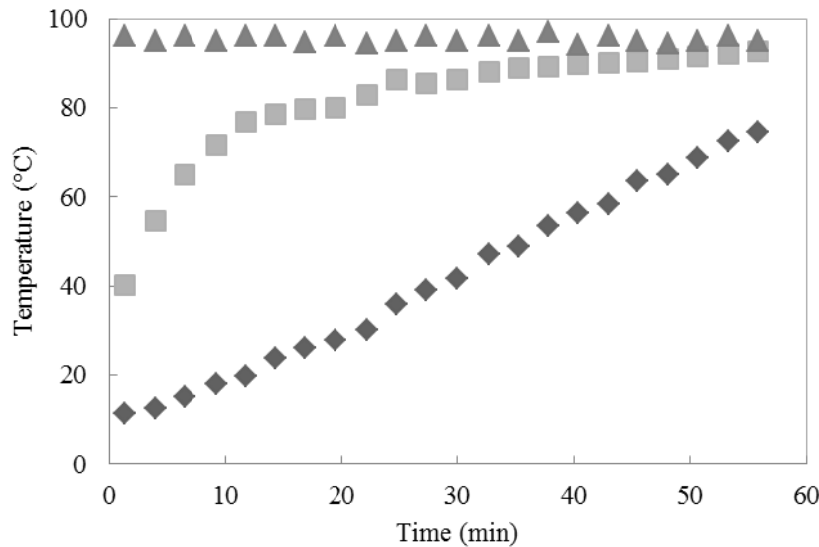


Fig. 1. Time-temperature profiles obtained during cooking of breadfruit in the water bath (▲), sample centre (◆) and on the sample surface (■)

Ayadi *et al.*, [6], in their work of determination of thermal diffusivity and salami and ham products prepared from turkey meat, recommended stopping cooking processing when a final internal temperature of 74 °C was reached. These authors found that between 35 min and 45 min the internal temperature of samples was close to 75 °C, just as it was evidenced in this work.

On the other hand, Fig. 2 shows a typical temperature profile over time (on a semi-log plot scale) obtained in this study. The adjustment of Equation (3) shows a curvilinear part at the beginning of the process, followed by a linear region, as reported by other authors [4], [6], [13]. On the other hand, Carciofi *et al.*, [9] in their baking study of mortadella observed two periods with different slopes, which was not found in the present study, possibly due to differences in the internal heat resistance of each type of material, as it has been reported by Tirado *et al.*, [4], [7].

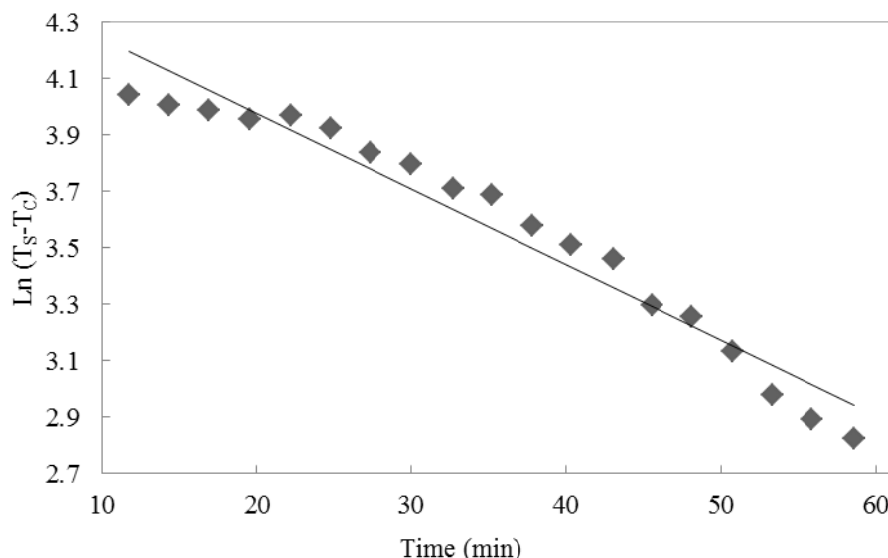


Fig. 2. The slope of the linear section of the dimensional relationship time-temperature.

The estimated thermal diffusivity of breadfruit is presented in Table 1. The value obtained in this work was comparable to those obtained by Ayadi *et al.*, [6] who found values of $5.11 \cdot 10^{-6} \text{ m}^2/\text{s}$, $7.02 \cdot 10^{-6} \text{ m}^2/\text{s}$, $6.02 \cdot 10^{-6} \text{ m}^2/\text{s}$ and $19.8 \cdot 10^{-6} \text{ m}^2/\text{s}$ during the cooking of standard salami, Tunisian salami, salami with olives and turkey ham respectively. Other studies have reported estimates of thermal diffusivity very close to those found in this work, however, none for breadfruit. Kong *et al.*, [14] said that the thermal diffusivity of lean beef ranged from $0.4 \cdot 10^{-7} \text{ m}^2/\text{s}$ at 30°C to $1.3 \cdot 10^{-7} \text{ m}^2/\text{s}$ at 66°C . Markowski *et al.*, [15] reported thermal diffusivity values obtained by analytical methods between approximately $3.5 \text{ m}^2/\text{s}$ and $4.5 \cdot 10^{-7} \text{ m}^2/\text{s}$. Sheridan and Shilton [16] studied the influence of cooking and fat content on thermal diffusivity of ground beef patties by using infrared radiation technology and reported that it varied with cooking progress and fat content, ranging from $1.22 \cdot 10^{-7} \text{ m}^2/\text{s}$ to $1.82 \cdot 10^{-7} \text{ m}^2/\text{s}$.

Table 1. Thermal diffusivity for baking breadfruit.

| Temperature ($^\circ\text{C}$) | B | R | L | Diffusivity ($D_a \cdot 10^7 \text{ m}^2/\text{s}$) |
|----------------------------------|---------|-------|------|-------------------------------------------------------|
| 95 | -0.0268 | 0.015 | 0.05 | 6.45 |

IV. CONCLUSIONS

In the present work, a diffusivity value of $6.45 \cdot 10^{-7} \text{ m}^2/\text{s}$ was found during the cooking of cylinders of breadfruit. This study reported for the first times this value for breadfruit samples. In the present study, the thermal diffusivity was assumed to be constant during heat treatment, and the value calculated was consistent with values provided by other authors who worked with different food matrices. There is a need for further investigation of time-dependent changes in thermal diffusivity of these kinds of native products in Colombia and Latin America.

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