Thermal properties of Conilon coffee fruits

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Abstract: - The specific heat, thermal conductivity and diffusivity of coffee fruits (Coffea Canephora) from the clone 32 of clonal variety EMCAPA 8131 were determined for moisture content ranging from 0.134 to 1.454 d.b. for unripe fruits and from 0.133 to 1.634 d.b. for ripe fruits (cherries). The specific heat was determined by the method of mixtures and the values from 1.442 to 3.298 kJ kg^{-1} K^{-1} and 1.431 to 3.615 kJ kg^{-1} K^{-1} were obtained for the unripe and cherry fruits, respectively and increased linearly with increasing moisture content. The thermal conductivity was measured by transient method with linear source of heat and its behaviour is similar to that of specific heat, ranging from 0.117 to 0.204 W m^{-1} K^{-1} and 0.108 to 0.216 W m^{-1} K^{-1} for unripe and cherry coffee, respectively. The thermal diffusivity values calculated by the indirect method from the results of specific heat and thermal conductivity ranged from 1.671×10^{-7} to 1.044×10^{-7} m^2 s^{-1} and 1.594×10^{-7} to 1.047×10^{-7} m^2 s^{-1} for unripe and cherry coffees, showing a decreasing linear ratio as moisture content increased.

Keywords: - Coffea Canephora; thermal conductivity; specific heat; thermal diffusivity.

I. INTRODUCTION

Knowledge on the physical and thermal properties of coffee is essential for research on phenomena of heat and mass transfers during drying process.

According to [1], [2] and [3] physical and thermal properties of grains are important in drying processes due to flow restrictions in heat and mass transfers. Each thermal property has a significant effect on the rate of drying of a single grain or of a grain layer [4].

Appropriate harvest, handling and processing operations are especially important to determine the final quality of a product, which affects the markets for the product. The knowledge of the thermal properties of agricultural products is necessary for the design of a new operation unit or for the analysis of processes such as drying and storage, as well as the prediction and control of many changes food undergoes during thermal and preservation processes. Similar studies show that moisture content has considerable effect on the thermal properties of agricultural materials and food [5–9].

The application of engineering principles to biological systems is often challenging due to inadequate databases of biological properties [10]. Data about these properties are useful for the management of agricultural materials, drying, processing, storage, equipment design and control [2]. Often, the physical properties of biological materials are dependent on the moisture content, which would affect the performance and the adjustment of the equipment. Therefore, the effect of moisture content on the physical properties of agricultural materials is an important consideration in post-harvest management and operations for the processing of food and agricultural products. Knowledge of the thermal properties of agricultural materials is essential for modeling, optimization and design of practices and processing equipment for operations based on heat treatment, including dehydration, bleaching, cooking, heating, cooling, vaporizing and freezing [11].

Thermal conductivity is defined as the ratio between the density of heat flux and temperature gradient in the material. Determining the ability to which an agricultural product conducts heat is necessary to predict or control the flow of heat in this product during processing operations, such as steady and transient. Thermal conductivity can be expressed based on Fourier's law of heat conduction, as presented below:

$$k = \frac{q}{A}\frac{dx}{dt} \qquad (1)$$

Methods for determining thermal conductivity can be classified into two categories: steady and transient state methods of heat transfer [1]. The steady state method requires a long time to be completed and there may be moisture content migration, which may introduce significant errors of measurement [1], [12], [13].

Both difficulties can be avoided by using the transient method of heat flow to determine the thermal conductivity of different grains.

The methods of linear heat source and temperature sensor have been used to determine the thermal conductivity of agricultural materials.

The thermal conductivity determination through the method of temperature sensor in thermal transient state was used in avocado pulp [14], fresh seafood, powdered squid, octopus and squid king [15], palm fruits [16], banana, apple and papaya [17] and potato cubes [18].

The method of linear heat source in transient state has been used by many researchers to determine the thermal conductivity of grains and seeds, such as barley, lentils and peas [11], cassava, sweet potato and plantain chips [19], parchment coffee [20] and borage seed [21]. There is consensus among researchers that conductivity increases as moisture content increases.

Knowledge on specific heat is essential to determine the amount of energy required in the process of heating or cooling in agricultural products. It is defined as the amount of heat required to raise the temperature of a body by 1°C per unit mass without changing its state.

The mixing method is a versatile method used by various researchers to determine the specific heat of granular materials. The specific heat of agricultural products rises with increasing moisture content [6]. Singh (2001) [22] studied the specific heat of cumin seeds and found values for specific heat ranging from 1.330 to 3090 kJ kg^{-1} K^{-1} due to temperature increase, from -70 to 50°C, and the moisture content values ranging from 1.8 to 20.5 d.b. Aviara (2001) [8] determined the specific heat of shea fruit depending on moisture content and temperature (3.32 to 20.70 d.b. and 30 to 90°C). They concluded that both have significant influence on agricultural materials. Subramanian (2003) [23] determined the specific heat of millet grain and flour, from 1.33 to 2.40 kJ kg^{-1} K^{-1}, for moisture contents ranging from 0.11 to 0.43 d.b. The mixing method was used by [24] to estimate the specific heat of maize; [20] used it for coffee in parchment. The specific heat rates of grass [12], fungi [25] and pistachio [26] were also determined by this method. Jaramillo (1989) [27] and Montoya (1989) [28] determined the specific heat of parchment coffee. Their results showed that it is not simple to relate the specific heat with grain moisture content. Jaramillo (1989) [27] found a nonlinear relationship between specific heat and grain moisture content, while [28] found linear correlation.

To complete the study on the thermal properties of agricultural materials, it is convenient to use the ratio between the ability of a material to transport energy and to store energy. It is the thermal diffusivity, defined as:

$$\alpha = \frac{k}{\rho \cdot C_p} \qquad (2)$$

Equation (2) helps estimating the time required to transport energy in the processes of heating, cooling, freezing and cooking. On the fact that the lack of information in the literature for Conilon coffee, this study aimed to determine the main thermal properties: specific heat, thermal diffusivity and conductivity, depending on the moisture content of the product.

II. NOMENCLATURE

Cp$_{H2O}$	Specific heat of water (kJ kg^{-1} K^{-1})
C	Constant of the calorimeter (kJ K^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
mac	Hot water mass (kg)
mp	Product mass (kg)
q	Heat (W m^{-1})
Teq	Temperature of balance (°C)
Tac	Temperature of hot water (°C)
Tp	Temperature of the product (°C)
t	Time (s)
Mc	Moisture content (d.b.)
α	Diffusivity (m^2 s^{-1})
ρ	Bulk density (kg m^{-3})
δ	Measurement uncertainty

III. MATERIAL AND METHODS

This work was developed in the Laboratory of Physical Properties and Quality Evaluation, in the Centro Nacional de Treinamento em Armazenagem – CENTREINAR (National Center for Storage Training), of the Universidade Federal de Viçosa, Minas Gerais, Brazil. Coffee fruits from the Coffea Canephora species,

clone 32 of clonal variety EMCAPA 8131 have been used. They were collected from an experimental farm of EPAMIG, in the municipality of Leopoldina. Unripe and ripe fruits have been used in the experiment.

The drying process was carried out in a forced ventilation oven at temperature of $60 \pm 3°C$, from where samples were obtained. They presented moisture contents ranging from 0.134 to 1.454 d.b. for the unripe beans and 0.133 to 1.634 d.b. for the ripe fruits. The moisture content of the product has been determined by the oven method, at the temperature of $105 \pm 3°C$, with three replicates [29].

All tests were performed for five moisture contents, considering two groups of coffee fruits tested in three replicates for each point in the study.

Thus, tools were used to provide the values of thermal properties for agricultural materials, specific heat, thermal conductivity and bulk density.

A mixing calorimeter was used to determine the specific heat of the mass of coffee fruits [5], [6] . The specific heat of the product is determined by the following equation [30]:

$$C_p = \frac{Cp_{H2O} \cdot m_{ac}\left(T_{ac} - T_{eq}\right) + C\left(T_{ac} - T_{eq}\right)}{m_p\left(T_{eq} - T_p\right)} \quad (3)$$

The method of theoretically infinite cylinder was used to determine thermal conductivity like [5], [6]. The thermal conductivity was determined through (4), [30]:

$$k = \frac{q}{4\pi L(T_1 - T_2)}\ln\left(\frac{t_2}{t_1}\right) \quad (4)$$

The bulk density was determined by filling a cylindrical container with 500 ml of coffee fruits from a height of 15 cm at a constant rate and then weighting the contents. The ratio between the mass and volume of the coffee container was defined as bulk density.

With the values of thermal properties, (2) was used to characterize the thermal diffusivity of the product.

Uncertainty is a fact in engineering. Therefore, it is necessary to know the uncertainty of the data, usually defined as the range within which the researcher is 95 confident that the true value lies.

The method described by [31] was used for the analysis of the uncertainty in the experimental results. This method is based on careful specification of the various uncertainties of the experimental primary measurements. Assuming that a measured variable "R" is a function of several independent primary variables x_1, x_2,...., x_n, then, we have:

R = R (x_1, x_2, ..., x_n) (5)

Assuming that w_1, w_2, ..., w_n, are the individual uncertainties of the respective independent primary variables x_1, x_2, ..., x_n, this method proposes that the uncertainty resulting from the final dimension "w_R " should be calculated by the following equation:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} \cdot w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} \cdot w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} \cdot w_n\right)^2\right]^{1/2} \quad (6)$$

The "ESS - Engineering Equation Solver" software system for engineering, "Uncertain Propagation" tool, which is based on the method described by [31], was used to minimize the mathematical effort to analyse the various uncertainties of experimental results.

The adjusted equations were compared through the model identity test to verify the null hypothesis that the equations are statistically equal. The identity test of the model is based on the difference between the sum of the parameter squares for the complete model and the sum of parameter squares for the reduced model [32]. Initially, the test was conducted for all equations adjusted for each relationship. Then, the identity test of the model was used to compare each equation. In other words, the test was applied for every treatment, both unripe and cherry.

IV. RESULTS AND DISCUSSION

The methodology reported by [32] to identify the regression models demonstrated that the models found for specific heat, thermal conductivity and thermal diffusivity of unripe and cherry coffee fruits are identical. Therefore, it is possible to obtain a common or reduced model with all data (Table 1).

The specific heat of coffee fruits was determined between 1.431 and 3.615 kJ kg^{-1} K^{-1} for a range of moisture content from 0.133 to 1.634 d.b., (Tables 2 and 3). The regression analysis revealed a linear relationship between the moisture content and specific heat (Table 1). It demonstrates that specific heat increases as moisture content of coffee fruits increases (Figure 1). This behaviour is very similar to that found by other researchers. Chandrasekar (1999) [33] determined the specific heat of Robusta parchment coffee for moisture content ranging from 0.1 to 0.35 d.b. and obtained values between 1.04 and 2.36 kJ kg^{-1} K^{-1}. In regard to Arabica coffee in parchment with moisture content in the range of 0.12 and 0.44 d.b., the specific heat values were between 0.78 and 2.18 kJ kg^{-1} K^{-1}. Afonso Júnior (2002) [5] assigned values between 1.2146 and 2.5251 kJ kg^{-1} K^{-1} for Arabica coffee variety Catuaí, for dry cherry; between 1.2254 and 2.4653 kJ kg^{-1} K^{-1} for husked cherry; and between 1.1290 and 2.3848 kJ kg^{-1} K^{-1} for parchment coffee. Borém et al (2002) [7] studied five varieties of Arabica coffee in parchment and found variation in specific heat from 1.0 to 3.0 kJ kg^{-1} K^{-1}, for moisture contents ranging between 0.1 and 0.95 d.b. Other authors found similar data while determining the specific heat of different products [8], [20–22], [34].

Table 1. Regression equations of specific heat, thermal conductivity and thermal diffusivity for unripe and cherry Conilon coffee and common model.

Treatment	Thermal property	Model Y = aX + b	R^2
Cherry	Specific heat C_p	1.4392 Mc +1.2643	0.993
	Thermal conductivity, k	0.0705 Mc +0.1083	0.953
	Thermal diffusivity, α	-3,4246E-008Mc+1,5921E-007	0.958
Unripe	Specific heat C_p	1.4225 Mc +1.2017	0.994
	Thermal conductivity, k	0.0602Mc +0.1203	0.911
	Thermal diffusivity, α	-4,9614E-008Mc+1,7180E-007	0.957
Common	Specific heat, C_p	1.4386 Mc +1.2307	0.991
	Thermal conductivity, k	0.0659Mc +0.1142	0.922
	Thermal diffusivity, α	-4,1108E-008Mc+1,6508E-007	0.924

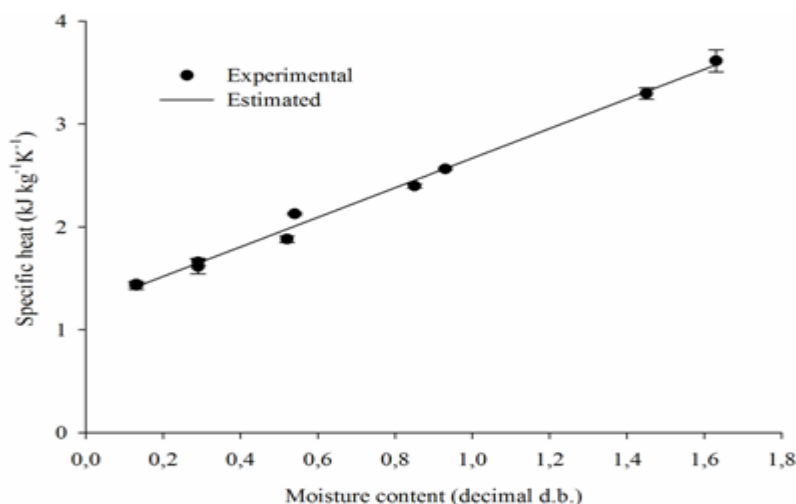R^2: coefficient of determination; Mc: Moisture content.

Figure 1. Experimental and estimated values of specific heat, according to the moisture content of Conilon coffee fruits.

Table 2. Statistical analysis and uncertainties of the thermal properties of cherry fruits of Conilon coffee.

Mc (d.b.)	k, (W m^{-1} K^{-1})			□ k	Cp, (kJ kg^{-1} K^{-1})			□ Cp	□ (m[2] s^{-1})	□ □
	Mean	Std.Dv.	Std.Err.		Mean	Std.Dv.	Std.Err.			
1,634	0,216	0,0099	0,0057	0,006056	3,615	0,1073	0,0620	0,03782	1,047E-07	3,12E-09
0,930	0,184	0,0029	0,0017	0,003088	2,564	0,0109	0,0063	0,03044	1,281E-07	2,63E-09
0,535	0,155	0,0015	0,0009	0,002603	2,128	0,0108	0,0062	0,02962	1,339E-07	2,26E-09
0,293	0,127	0,0026	0,0015	0,001821	1,658	0,0345	0,0199	0,02715	1,492E-07	3,24E-09
0,133	0,108	0,0014	0,0008	0,001597	1,431	0,0389	0,0224	0,02469	1,594E-07	3,63E-09

Table 3. Statistical analysis and uncertainties of the thermal properties of unripe fruits of Conilon coffee.

Mc (d.b.)	k, (W m^{-1} K^{-1})			δk	Cp, (kJ kg^{-1} K^{-1})			δCp	α (m^2 s^{-1})	δα
	Mean	Std.Dv.	Std.Err.		Mean	Std.Dv.	Std.Err.			
1,454	0,204	0,0080	0,0046	0,003852	3,298	0,0547	0,0316	0,03612	1,044E-07	2,28E-09
0,855	0,172	0,0067	0,0039	0,002502	2,399	0,0186	0,0107	0,03006	1,2E-07	2,30E-09
0,524	0,163	0,0068	0,0039	0,002409	1,883	0,0317	0,0183	0,02921	1,461E-07	3,13E-09
0,287	0,141	0,0053	0,0031	0,00209	1,614	0,0713	0,0412	0,0262	1,6E-07	3,51E-09
0,134	0,117	0,0023	0,0013	0,001979	1,442	0,0139	0,0080	0,02391	1,671E-07	3,95E-09

The thermal conductivity of coffee fruit was 0.108 - 0.216 W m^{-1} K^{-1} for moisture content ranging from 0.133 to 1.634 d.b., (Table 2 and 3). Variation of thermal conductivity according to moisture content rate is shown in figure 2. It shows that thermal conductivity increases linearly with increasing moisture content. Similar behaviour was observed by [5] for Arabica coffee variety Catuaí, when values between 0.0843 and 0.1415 W m^{-1} K^{-1} were assigned for dry cherry; between 0.0934 and 0.1735 W m^{-1} K^{-1} for husked cherry; and between 0.1033 and 0.1762 W m^{-1} K^{-1} for coffee in parchment. Borém et al (2002) [7] assigns values of thermal conductivity between 0.10 and 0.20 W m^{-1} K^{-1}, while [33] obtained values between 0.10 and 0.20 W m^{-1} K^{-1} for Robusta coffee in parchment, with moisture content ranging from 0.11 to 0.35 d.b.; and obtained specific heat values between 0.07 and 0.16 W m^{-1} K^{-1} for Arabica coffee in parchment, with moisture content between 0.12 and 0.44 d.b.
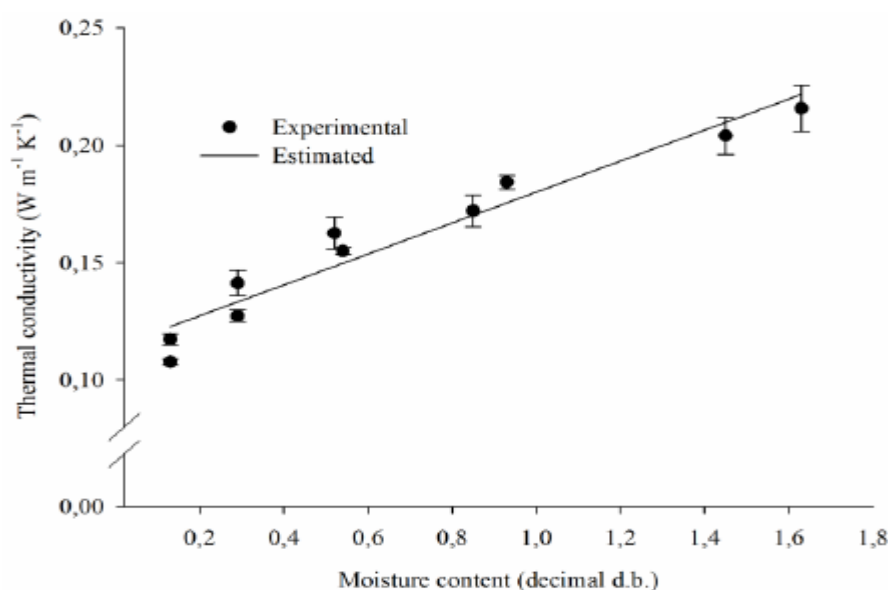

Figure 2. Experimental and estimated values of thermal conductivity according to the moisture content of Conilon coffee fruits.

Similar variations have been recorded for the thermal conductivity of maize, sunflower, wheat and barley [35], pumpkin seeds [34], rice flour [36], shea fruits [8], borage seed [21], cumin seeds [22] and parchment coffee [20], among others.

The thermal diffusivity values were determined by applying equation 2 for each level of moisture content studied (Table 2 and 3). The thermal diffusivity for coffee fruits was determined between 1.671 × 10^{-7} and 1.044 × 10^{-7} m^2 s^{-1} for moisture content ranging from 0.133 to 1.634 d.b. A decreasing ratio of the thermal diffusivity with the growth of moisture content was determined by regression analysis (Figure 3). Similar behaviour was recorded in other studies, which determined the thermal properties of different species and varieties of coffee. Chandrasekar (1999) [33] stands out among them for Robusta coffee in parchment. With moisture content ranging from 0.11 to 0.35 d.b., it obtained values between 2.36 × 10^{-7} and 1.69 × 10^{-7} m^2 s^{-1}; and for Arabica coffee in parchment, with moisture content ranging between 0.12 and 0.44 d.b., specific heat values between 2.08 × 10^{-7} and 1.44 × 10^{-7} m^2 s1 were found. For the five types of coffee studied, [7] found thermal diffusivity decrease with increasing moisture for a range of values between 1.0 × 10^{-7} m^2 s^{-1} and 3.0 × 10^{-7} m^2 s^{-1}. Pabis (1988) [5] records for Arabica coffee, variety Catuaí, ranged between 1.069 × 10^{-7} and 1.544 × 10^{-7} m^2 s^{-1} for dry cherry; between 1.357 × 10^{-7} and 1.699 × 10^{-7} m^2 s^{-1} for husked cherry; and between 1.344 × 10^{-7} and 2.078 × 10^{-7} m^2 s^{-1} for coffee in parchment.
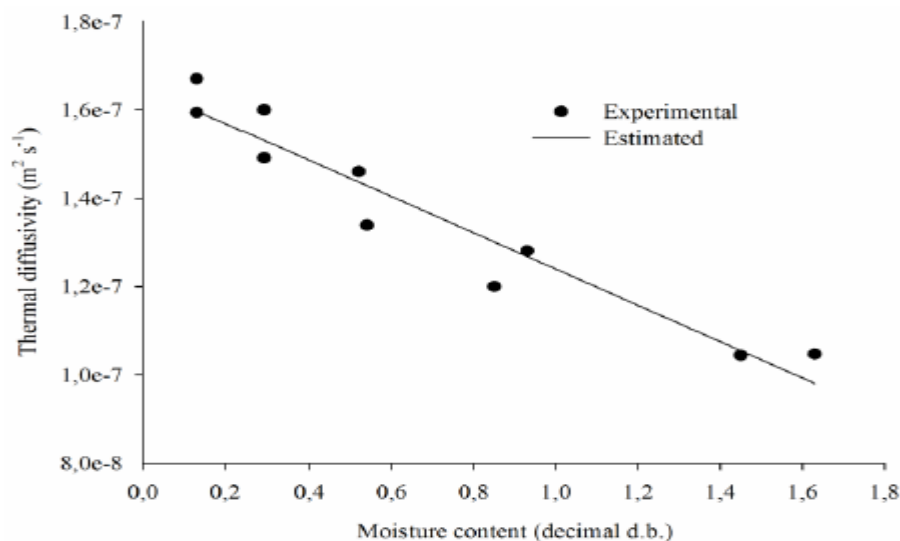
Figure 3. Experimental and estimated values of thermal diffusivity, according to the moisture content of Conilon coffee fruits.

Similar behaviour was recorded in the determination of thermal diffusivity of rice flours [36], pumpkin seeds [34], borage seed [21] and peanuts [6].

V.   CONCLUSIONS

Thermal properties of coffee fruits from Coffea canephora, clone 32 of clonal variety EMCAPA 8131, such as thermal conductivity, thermal diffusivity and specific heat were determined for five levels of moisture content and two ripening stages (unripe and cherry).

The specific heat, thermal conductivity and thermal diffusivity for moisture content ranging from 0.133 to 1.634 d.b. were determined between 1.431 and 3.615 kJ kg^{-1} K^{-1}; 0.108 and 0.216 W m^{-1} K^{-1}; and 1.044×10^{-7} to 1.671×10^{-7} m^2 s^{-1}, respectively, for the Conilon coffee fruits getting a common regression model for each of them.

It was determined that the thermal properties of Conilon coffee depend on the moisture content. The specific heat and thermal conductivity of fruits of Conilon coffee increases with increasing moisture content, whereas thermal diffusivity decreases with increasing moisture content.

VI.   ACKNOWLEDGEMENTS

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