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Relationship between the thermal conductivity and rheological behavior of acerola pulp: Effect of concentration and temperature

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A B S T R A C T

This study aimed to evaluate the thermal conductivity and rheological behavior of acerola pulp at concentrations of 5.5, 7.5, 9.5, 11.5 and 13.5 °Brix and temperatures of 20, 30, 40, 50 and 60 °C. Among the models used to determine conductivity, Maxwell-Eucken was used for data acquisition. Linear equations were fitted to evaluate the influences of concentration and temperature on the thermal conductivity of the pulp. The pulp structure, particle sizes and relation between insoluble and soluble solids were also discussed. The rheological behavior, specifically apparent viscosity *versus* shear rate, was influenced by both the soluble solids content and the temperature. Among the mathematical models used to test the fit of the experimental data, the Herschel–Bulkley model provided the best statistical adjustments and was then used to determine the rheological parameters. Apparent viscosity was correlated with temperature by the Arrhenius equation. Acerola pulps were shear thinning and thermal conductivity increases with viscosity decreasing with increasing temperature. The structures and concentrations had an impact upon the effective thermal conductivity. The temperature and concentration values have been fixed and equation expressing conductivity as a function of apparent viscosity was proposed, which enable the evaluation of an existing relationship between the two properties.

1. Introduction

Acerola (*Malpighia* spp.), also called cherry Antilles, is a tropical tree that produces fruit very rich in vitamin C (Manica et al., 2003). In Brazil, this tree is planted in all regions, and Pernambuco, Ceará, São Paulo and Bahia are the main producers (Ritzinger, Kobayashi, & Oliveira, 2003). Acerola is a climacteric fruit and is highly perishable, so this fruit requires an agile commercialization process (Ritzinger et al., 2003, 198 pp.). For the processing of acerola, thermal processes involving heat transfer, including heating, cooling and freezing, are needed.

The correct sizing of a food production system often relies on accurate data regarding the thermophysical (Mercali, Sarkis, Jaeschke, Tessaro, & Marczak, 2011) and rheological properties of the fruit and the transportation requirements of the product (Ikhu-Omoregbe, 2009). Among the thermophysical properties, the thermal conductivity is considered the most influential during thermal processing, and this property is highly dependent on the composition and temperature of the food (Carson, 2006). This knowledge allows the processing time and the amount of energy needed in the thermal process to be estimated.

The rheological behavior of the food should also be considered because these properties provide a better understanding of the structural organization of food and are important for process engineering calculations, including equipment such as agitators, pumps, heat exchangers, piping and homogenizers (Conceição, Fernandes, Prado, & Resende, 2012).

Considering the consumer demand for processed foods with high quality, there is a need to define changes in rheological properties of foods in processing operations that may affect their overall acceptability. So it is important the determining of rheological behavior of pulps and developing of models that describe the rheological behavior in terms of product concentration and processing temperature (Nindo, Tang, Powers, & Takhar, 2007). The knowledge of the rheological behavior is also important to determine the functionality of ingredients in new products, quality control of the final or intermediate product texture and evaluation by correlation with sensory data (Steffe, 1996).

To evaluate the thermal conductivity and rheological properties of fruit pulp, several important parameters such as temperature, concentration of soluble solids, moisture and chemical composition are needed (Rahman, 2009). Large amounts of data on the effect of

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Nomenclature

B	Parameter adjustment –
C	Coefficients from adjusted equations –
E_a	Activation energy J/g mol
K_H	Consistency index (Herschel–Bulkley) Pa s^n
R	Gas constant J/g mol K
T	Temperature °C or K
X	Volumetric fraction –
c	Concentration °Brix
k	Thermal conductivity W/m K or W/m °C
x	Mass fraction –
z	temperature or concentration °C or °Brix
$\dot{\gamma}$	Shear rate s^{-1}
η	Viscosity Pa s
ρ	Density kg/m^3
σ	Shear stress Pa

Subscripts

a	Apparent
c	Continuous
d	Disperse
e	Effective
i	Pure component
me	Maxwell-Eucken
n	Number of components
n_H	Flow behavior index (Herschel–Bulkley)
pa	Parallel
se	Series

these factors on the thermal conductivity and rheology have been published in national and international literature (Azoubel, Cipriani, El-Aouar, Antonio, & Murr, 2005).

Studies published on the influence of shear rate upon the thermal conductivity of non-Newtonian fluids were performed for mango juice by Ikhu-Omoregbe (2009) and for the orange juice concentrate and the mango juice concentrate at three different mean temperatures by Qi Lin, Chen, Chen, and Bandoadhayay (2003). In Ikhu-Omoregbe (2009), the juice concentrate was found to be shear thinning and the thermal conductivity values increased with increasing rate of shear. The thermal conductivities were also found to increase with the presence of solids in the juice. Furthermore, the thermal conductivity values were found to be significantly higher with the coarser particles for a given temperature and shear rate. The thermal conductivity was also observed to increase asymptotically to a constant value with time of shear. The models were based on the assumption that the relationship between thermal conductivity and shear rate is linear. In the work of Qi Lin et al. (2003), the values of the thermal conductivity *versus* shear rate for the orange juice concentrate and the mango juice concentrate at three different mean temperatures were compared. It can be seen that the thermal conductivity for both fluids increases significantly, with increasing shear rate. The effect of temperature on the thermal conductivity at the same shear rate was visible and was more significant at higher temperature, especially for the mango juice. Lee and Irvine (1997) observed for non-Newtonian fluids such as aqueous carboxymethylcellulose (CMC) and Separan solutions, that the increase in thermal conductivity with shear rate was greater for lower-concentration solutions than for high-concentration solutions. The thermal conductivity of both CMC and Separan solutions increased with increasing temperature and shear rate. Their results showed a linear relationship between shear rate and thermal conductivity.

The previous studies showed that Non-Newtonian liquid and semi-solid food substances have varying thermal conductivity under a shearing environment. If a shear rate effect exists on the thermal conductivity and apparent viscosity is also related to shear rate is therefore reasonable to suggest that there will be changes in the thermal conductivities when the apparent viscosity of these substances are modified. The aim of this study was to evaluate the rheological behavior of acerola pulp, determine its thermal conductivity and develop equations for the simultaneous evaluation of the influences of temperature and concentration on the conductivity and rheology of the pulp. Subsequently, the thermal conductivity can be related to the apparent viscosity as a function of concentration and temperature.

2. Material and methods

2.1. Sample preparation

Acerola was purchased at the local market of Lavras-MG. The separation of the pulp was performed with an electric depulper (Macanuda, Joinville, Santa Catarina), yielding a pulp with 7.5 °Brix. A portion of the sample was removed and diluted to 5.5 °Brix, and the other portion was concentrated in a freeze-dryer (Edwards High Vacuum - Model - L4KR). The pulp was removed after 34 h, before it was fully freeze-dried. After freeze-drying, a product was obtained with an approximate concentration between 14.0 and 15.0 °Brix. These concentrations were adjusted to 9.5, 11.5 and 13.5 °Brix by adding distilled water. The soluble solids were determined by direct reading from a hand-held refractometer (Atago - N1, Tokyo, Japan).

2.2. Chemical analyses

Subsequently, the approximate chemical composition of the pulp was characterized at different concentrations. The amount of moisture, protein, fiber and ash were determined according to the methodology of the AOAC (1996), and the fat content was determined according to the methodology of the Instituto Adolfo Lutz (2008, 1020 pp.). Carbohydrates were determined by the difference between the total (100%) and the percentages of moisture, protein, fat, fiber and ash.

2.3. Insoluble solids and particle sizes

The insoluble solids images were acquired using a light microscope (Meiji ML 5000, Meiji Techno America, Santa Clara, CA, USA) with an attached video camera (Cole-Palmer 49901-35, Cole-Palmer, Vernon Hills, IL, USA) and polarized light filter.

To determine the insoluble solids in fruit pulps at different concentrations, the samples were then centrifuged (SPLABOR, model SP-701, Presidente Prudente, Brazil) at 3248× *g* for 20 min, and the mass of precipitate and final volume were measured. The precipitate was separated, dried in vacuum oven at 65 °C for 48 h and insoluble solids (g/100 g of pulp) were determined.

2.4. Determination of rheological properties

In this work, rheological measurements were performed using a DVIII Ultra Brookfield rotational viscometer with concentric cylinders (Brookfield Engineering Laboratories, Stoughton, USA). A