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Thermal conductivity as influenced by the temperature and apparent viscosity of dairy products

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ABSTRACT

This study aimed to evaluate the rheological behavior and thermal conductivity of dairy products, composed of the same chemical components but with different formulations, as a function of temperature. Subsequently, thermal conductivity was related to the apparent viscosity of yogurt, fermented dairy beverage, and fermented milk. Thermal conductivity measures and rheological tests were performed at 5, 10, 15, 20, and 25°C using linear probe heating and an oscillatory rheometer with concentric cylinder geometry, respectively. The results were compared with those calculated using the parallel, series, and Maxwell-Eucken models as a function of temperature, and the discrepancies in the results are discussed. Linear equations were fitted to evaluate the influence of temperature on the thermal conductivity of the dairy products. The rheological behavior, specifically apparent viscosity versus shear rate, was influenced by temperature. Herschel-Bulkley, power law, and Newton's law models were used to fit the experimental data. The Herschel-Bulkley model best described the adjustments for yogurt, the power law model did so for fermented dairy beverages, and Newton's law model did so for fermented milk and was then used to determine the rheological parameters. Fermented milk showed a Newtonian trend, whereas yogurt and fermented dairy beverage were shear thinning. Apparent viscosity was correlated with temperature by the Arrhenius equation. The formulation influenced the effective thermal conductivity. The relationship between the 2 properties was established by fixing the temperature and expressing conductivity as a function of apparent viscosity. Thermal conductivity increased with viscosity and decreased with increasing temperature.

Key words: yogurt, fermented milk, thermal conductivity, rheology

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INTRODUCTION

Technological advances have supported the development of new dairy products while the dairy market has registered sustained and continuous growth (Nagpal et al., 2012; Masson et al., 2016). Food engineering within the dairy sector is an expanding field of study, which results in significant improvements in product quality and greater knowledge of ingredients and their influence on chemical composition, structure, and rheological and sensory properties (Chandrapala and Zisu, 2016). Although technological processes such as fermentation are traditionally used, the dairy sector has developed techniques to produce a diverse range of milk-based products and dairy ingredients (Nagpal et al., 2012).

Yogurt, fermented dairy beverages, and fermented milk all have the same components (water, protein, fats, carbohydrate, and ash) but in different contents in their intrinsic composition (Reddy and Datta, 1994; Minim et al., 2002; Munir et al., 2016). Yogurt is formed during the slow lactic fermentation of milk lactose by thermophilic lactic acid bacteria (Park and Haenlein, 2013; Shori and Baba, 2014). The resulting lactic acid reacts with milk protein, promoting the characteristic texture of this product (Serafeimidou et al., 2013). Fermented dairy beverages are dairy products resulting from the mixing of milk and whey, vegetable fat, fermented milk, lactic acid starter culture, and other dairy products. The milk base represents at least 51% (vol/vol) of the total ingredients of the product, fermented by a specific microorganism culture (Brazil, 2005). From the technological viewpoint, the main difference between yogurt and fermented dairy beverages is the addition of whey to the latter, which results in lower viscosity (Castro et al., 2013). Fermented milk means a lactic product where fermentation involves the action of lactic acid bacteria and results in coagulation and a reduction in pH. According to legislation, the cultures or microorganisms used in the fermentation define the name of the product to be yogurt or fermented milk (Brazil, 2007; Park and Haenlein, 2013). It is evident that the technology for the manufacture of fermented

Table 1. Chemical composition of the dairy products

Product	Composition (%)					
	Moisture	Protein	Fat	Carbohydrate	Fiber	Ash
Yogurt	60.48	5.10	4.23	30.00	0.00	0.18
Fermented dairy beverage	68.17	3.53	3.36	24.66	0.00	0.25
Fermented milk	86.82	1.51	0.00	11.48	0.00	0.08

milk is very similar to the production of yogurt; however, low viscosity is a desirable and notable feature of fermented milk (Tamime, 2006).

In food processing, correct dimensioning of the equipment used, better understanding of food structural organization, and process optimization all depend on accurate data of the thermal properties and rheological behaviors of the products as well as their behaviors during the process as a function of temperature to ensure the high quality of the final product (Ahmed et al., 2005; Moura et al., 2005; Mercali et al., 2011; Augusto et al., 2012). Another important application of thermal properties is accurate modeling and simulation of industrial processes, which are useful for the prediction of process behavior and critical for decision making and optimization without putting the real process at risk. However, these thermal properties are worked separately using empirical models derived from experimental results and require more computational effort (Munir et al., 2016). Thermal conductivity is considered the most important property in thermal processing at high and low temperatures (Muramatsu et al., 2005; Carson, 2006), and there is a correlation between the apparent viscosity and thermal conductivity (Pereira et al., 2014) because shear rate is related to thermal conductivity, and these 2 variables vary with intrinsic composition and temperature. For this reason, it is important to characterize the rheological properties and study models that describe the rheological behavior as a function of the temperature used during processing (Nindo et al., 2007). The viscosity of dairy products is important in regard to sensory perceptions of food products (Sodini et al., 2004; Walstra et al., 2006).

The thermal conductivity of fluid dairy products increases linearly with increasing temperature and decreases with increasing total solid contents (Reddy and Datta, 1994; Minim et al., 2002; Munir et al., 2016). The flow behavior and apparent viscosity also vary with temperature (Penna et al., 2001; Munir et al., 2016); an increase in temperature causes a decrease in the viscosity of the liquid phase, increasing the movement of particles in suspension (Pelegrine et al., 2000). There is a great need for thermal conductivity values and apparent viscosity results of these dairy products for processing, preservation, and production. Given the above, the aims of this study were to evaluate the influence of temperature on thermal conductivity and apparent viscosity of yogurt, fermented dairy beverages, and fermented milk and to develop mathematical models from experimental measures that correlate their thermal conductivity and apparent viscosity.

MATERIALS AND METHODS

Sample Acquisition and Chemical Composition

Yogurt, fermented dairy beverages, and fermented milk were purchased in the local market in the municipality of Lavras, Brazil. The composition of yogurts, fermented dairy beverages, and fermented milks in ranged from 2.00 to 3.11% protein, 0 to 2.94% fat, 11.11 to 15.90% carbohydrate, 0% fiber, 0.10 to 0.13% ash, and 77.92 to 85.29% water, as shown in Table 1. According to the information from the yogurt manufacturers, the samples tested had modified starch plus gelatin added. The fermented dairy beverages had modified starch plus pectin added. The chemical composition of the 3 commercial products were obtained from their labels.

Experimental Measurements of Thermal Conductivity

Thermal conductivity measurements were performed using a hot wire probe, also known as a transient-state method. In this technique, the heat is transferred to the material through the probe. The probe is resistively heated at a constant rate using a source that provides a continuous electrical current, and then it is possible to determine the thermal conductivity of a food experimentally (Dawson et al., 2006). The probe was constructed from a hypodermic needle with an external diameter of 0.6 mm and a length of 70 mm, into which was placed a resistance heating wire (nickel-chromium; Omega Engineering Inc., Stamford, CT) with a length of 0.36 m and diameter of 0.08 mm, together with a small type-T thermocouple AWG 30 (Omega Engineering Inc.) located at the exact center of the probe. All components were insulated with epoxy resin. By apply-