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Rheological characterisation of sorbet using pipe rheometry during the freezing process

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ABSTRACT

Sorbet produced without aeration is a dispersion of ice crystals distributed randomly in a freeze-concentrated liquid phase. The rheological properties of this suspension will be affected by the viscosity of the continuous liquid phase and the volume fraction of ice crystals. The knowledge of the viscosity of sorbet is essential for the improvement of product quality, the selection of process equipment, and for the optimal design of piping systems. This work aimed firstly, at studying the influence of the ice volume fraction (determined by the product temperature) on the apparent viscosity of a commercial sorbet, and secondly, to propose a rheological model that describes the evolution of the viscosity of the product as a function of the ice volume fraction. The rheology of sorbet was measured in situ by means of a pipe rheometer connected at the outlet of a continuous scraped surface heat exchanger (SSHE). The pipe rheometer was composed of a series of pipes in PVC of different diameters, making it possible to apply a range of apparent shear rate from 4 to 430 s^{-1}. The flow behaviour index of sorbet decreased as the temperature of the product decreased, the effect of which indicates that the product becomes more shear thinning as the freezing of sorbet occurs. The consistency coefficient and therefore the magnitude of the apparent viscosity of sorbet increased with the decrease in product temperature and with the increase of the ice volume fraction. Results also showed that the rheological model described the experimental data within a 20% error.

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1. Introduction

The characterisation of the rheological properties of sorbet has significant applications throughout the manufacturing process of frozen desserts. The understanding of the influence of changes in product microstructure on its rheological properties is necessary for the improvement of the freezing process and the quality of the product. The knowledge of the viscosity of the product is also essential for the selection of process equipment, and for the optimal design of piping systems. The freezing of sorbet is carried out in a continuous scraped surface heat exchanger (SSHE) or freezer. Once the freezing of sorbet starts and ice crystals are being formed, the liquid sorbet mix starts to freeze concentrate and the viscosity of this continuous liquid phase increases (Burns and Russell, 1999; Goff et al., 1995). Simultaneously, the ice crystals are dispersed in the liquid sorbet mix by the rotation of the scraping blades, modifying the fluid flow field and increasing the viscosity of sorbet. Sorbet exiting from the freezer at a draw temperature between −4 and −6 °C, contains roughly 20–40% of the total amount of water in the form of ice crystals, which are suspended in a viscous liquid phase composed of water, sugar, stabilizers (polysaccharides) and salts. At this point, the product must have an adequate viscosity to be pumped for moulding and packaging. Further on, the product is hardened in a blast freezer to attain a core temperature of −18 °C (Cook and Hartel, 2010), where roughly 80% of the amount of water is frozen (Marshall et al., 2003).

The measurement of the viscosity of sorbet and ice cream is highly complex, because the product is temperature sensitive and it behaves as a non-Newtonian shear-thinning fluid (Burns and Russell, 1999; Haddad, 2009). A number of studies in the literature, based on oscillatory thermo-rheometry for the analysis of the rheology of ice cream, have reported viscoelastic behaviour which is strongly related to the ice crystal microstructure (Goff et al., 1995; Granger et al., 2004; Wildmoser et al., 2004). In order to improve the online control of product quality, it is necessary to

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Abbreviations: DRS, dasher rotational speed; MFR, mix flow rate; SSE, sum of squared errors; SSHE, scraped surface heat exchanger; TR22, evaporation temperature of r22.

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Nomenclature

$d_{c/e}$	internal diameter of contraction/enlargement pipe
d	internal diameter of pipe rheometer
k	consistency coefficient of sorbet, Pa s^n
k_{mix}	consistency coefficient for sorbet mix, Pa s^n
n	flow behaviour index index, –
nL	number of scraping blades, –
L	pipe length, m
R	pipe radius, m
N_R	rotational speed of scraping blades, rad s^{-1}
δP	pressure drop, Pa
$\dot{V}$	volumetric flow rate, m^3 s^{-1}
T	temperature of the product, °C
w_{ms}	initial mass fraction of solute (sweetener content), –
$w_{ms.i}$	initial mass fraction of solute (sweetener content), –
$w_{ms.f}$	final mass fraction of solute (sweetener content), –

Greek symbols

$\dot{\gamma}$	shear rate, s^{-1}
$\dot{\gamma}_w$	wall shear rate, s^{-1}
σ_w	wall shear stress, Pa
λ_w	thermal conductivity of the solute solution, W m^{-1} K^{-1}
λ_{ice}	thermal conductivity of ice, W m^{-1} K^{-1}
λ_{sorbet}	thermal conductivity of sorbet, W m^{-1} K^{-1}
η_{app}	apparent viscosity, Pa s
η	viscosity of a Newtonian suspension, Pa s
η_l	viscosity of the liquid phase of a suspension, Pa s
ρ_i	ice density, kg m^{-3}, –
ρ_s	sorbet density, kg m^{-3}, –
ϕ	particle concentration, –
$\phi_{m.ice}$	ice mass fraction, –
$\phi_{v.ice}$	ice volume fraction, –
ξ	thermal sensibility, K^{-1}

investigate further the rheology of frozen desserts flowing directly from the SSHE.

Pipe rheometers have been used to measure the apparent viscosity of ice cream and sorbet in situ and online during the freezing process (Cerecero, 2003; Martin et al., 2008; Elhweg et al., 2009). Pipe rheometers are generally composed of a set of pipes of different diameters, through which the product flows under pressure. The relationship between the shear rate and the shear stress is determined from volumetric flow rate and pressure drop measurements. The challenge of pipe rheometry measurements lies on the difficulties of controlling a steady temperature and flow conditions. Furthermore, the effects of wall slip behaviour and viscous dissipation must be evaluated so as to ensure accurate rheological measurements.

Apparent wall slip behaviour occurs in multi-phase systems due to the displacement of the disperse phase away from solid interfaces. This creates a layer of fluid near the wall region that has a lower viscosity and a higher velocity gradient as compared to the bulk of the product, forming a layer of high shear (Martin and Wilson, 2005). This apparent wall slip modifies the flow velocity profile and the shear rate gradient, the effect of which leads to inaccurate rheological measurements. Mooney (1931) proposed a method to identify the slip wall behaviour. This technique consists on tracing the flow behaviour curves (shear stress versus shear rate) for different pipe diameters and different flow rates. In the absence of wall slip, these curves overlap. However, a significant separation of these curves reveals the existence of wall slip. Apparent wall slip behaviour has been observed in multi-phase food products such as fruit purees (Balmforth et al., 2007), tomato ketchup (Adhikari and Jindal, 2001) and coarse food suspensions of CMC-green pea solutions. More recently Martin et al. (2008) and Elhweg et al. (2009) reported some evidence of apparent wall slip in ice cream, but wall slip effects were neglected due to insufficient data and control of pressure to discern clear trends.

The phenomenon of viscous dissipation refers to the mechanical energy dissipated during the flow of the fluid through the pipe which is converted into internal energy, increasing the temperature of the product along the pipe axis (Winter, 1977). Thus, due to the high shear rates obtained near the pipe wall, the temperature of sorbet will increase near the wall region, leading to the decrease in the viscosity of the product, increasing the fluid flow velocity and consequently leading to a higher wall shear rate. The impact of viscous dissipation can be assessed by evaluating the Nahme dimensionless number (Na), which indicates the degree at which the temperature rise will affect the viscosity of the product (Macosko, 1994). The effect of viscous dissipation becomes significant when $Na > 1$ (Macosko, 1994). Elhweg et al. (2009) reported that the phenomenon of viscous dissipation in ice cream was significant for a certain range of product temperatures (−6 to −12 °C) and shear rates (0.3–360 s^{-1}).

Sorbet produced without aeration is a dispersion of ice crystals distributed randomly in a freeze concentrated liquid phase. The flow of this suspension will be affected by the viscosity of the continuous liquid phase, the volume fraction (ϕ) of ice crystals, crystal–crystal interactions and ice crystal shape. A number of theoretical and empirical equations have been developed to describe the viscosity of Newtonian suspensions (Einstein, 1906; Mooney, 1951; Krieger and Dougherty, 1959; Thomas, 1965; Batchelor, 1977). A summary of the models available in the literature is shown in Table 1.

Most of these models are extended versions of the expression developed by Einstein (1906) to predict the evolution of the viscosity of a Newtonian suspension of rigid spheres ($\phi < 0.02$), as a function of the volume fraction ϕ of the suspended spheres and of the viscosity of the continuous phase η_l, written as:

$$\eta = \eta_l(1 + 2.5\phi) \tag{1}$$

This model takes only into account the Brownian movement of the spheres, neglects particle–particle interactions, and is only valid in the case of dilute solutions.

For higher particle concentrations ($\phi < 0.625$) and a range of particle size between 0.099 and 435 μm, Thomas (1965) proposed a semi-empirical expression which predicts the viscosity of Newtonian suspensions as a function of the viscosity of the continuous phase η_l and the volume fraction ϕ of the suspended rigid spheres, expressed as:

$$\eta = \eta_l(1 + 2.5\phi + 10.05\phi^2 + 0.00273\exp(16.6\phi)) \tag{2}$$

In this model, the first three terms inside the parentheses account for the effect of the hydrodynamic interactions of spheres and particle–particle interactions, whereas the exponential term considers the rearrangement of particles as the suspension is sheared (Thomas, 1965). This model has been widely used to predict the viscosity of ice slurries (Ayel et al., 2003; Hansen and Kauffeld, 2000), but has been reported to overestimate the viscosity of ice slurries when the ice concentration exceeds $\phi > 0.15$ (Hansen and Kauffeld, 2000). Haddad (2009) compared experimental viscosity data obtained in a scraped rheometer, during the batch freezing

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