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Correlation between in-line measurements of tomato ketchup shear viscosity and extensional viscosity

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ABSTRACT

The viscosity and shear thinning behavior are essential characteristics of tomato ketchup. A real-time monitoring of those characteristics during processing is important to obtain a good quality of the final product and to reduce production waste. This work investigates the measurement of rheological in-line flow properties of tomato ketchup, using a real-time technique that combines ultrasound velocity profiling (UVP) and pressure difference (PD) assessment. In-line data were compared to those obtained off-line using a rotational viscometer. There was a poor correlation with the Bostwick measurement, whereas the flow curves calculated from flow velocimetry data were very similar to those measured off-line. The extensional viscosity of ketchup was determined through the measurement of Hyperbolic Contraction Flow; the curve followed a trend similar to that for the shear viscosity over the deformation rate investigated.

1. Introduction

The viscosity of tomato ketchup is a major quality component for consumer acceptance. A rigorous selection of ingredients and a continuous control and adjustment of the variables for processing are necessary to achieve a constant and desirable quality in the final product (Barringer et al., 1998; Bottiglieri et al., 1991; Jin Choi et al., 2006). Since small variations of processing conditions and raw materials affects the tomato ketchup flow behavior and its final viscosity, several methods have been developed to monitor its flow and consistency during processing. The standard method for determining the tomato ketchup consistency is using a Bostwick consistometer (ASTM 2002). This is a quick and inexpensive measurement that is regularly carried out for samples taken during processing and for the final product. The relationship between the viscosity measurement by shear rheology and the Bostwick measurement has been studied by several authors (Barringer et al., 1998; Bottiglieri et al., 1991; Haley and Smith, 2003; McCarthy et al., 2008), but while rotational viscometry is more expensive and difficult to use for continuous quality monitoring, the Bostwick measurement presents other significant limitations. Bostwick measurement data are influenced by the operator skills, leveling, dryness/cleanness of the instrument, temperature of the sample, shape of the leading edge of the flow, and serum separation at the edge of the flow. In-line viscometry of tomato ketchup was developed to overcome these limitations, though at higher price. In-line ketchup viscosity measurements were performed by means of magnetic resonance (McCarthy and McCarthy, 2009), pressure differential (Barringer et al., 1998), in-line absorption photometry (Haley and Smith, 2003), and ultrasonic Doppler velocimetry (Jin Choi et al., 2006). Shear flow was characterized with these methods and it was assumed that this type of deformation was representative to the flow in the pipes during processing. An essential condition for this assumption is that the liquid sticks to the pipe wall and shearing is the main flow type, but it would not hold true if an abrupt restriction in pipe cross section occurs. In the latter case, as the fluid accelerates due to the rapid cross section change, extensional flow would become dominant and the deformation imposed by elongation would add to that imposed by shear (Cruz and Pinho, 2003; Debbaut and Crochet, 1988). Extensional deformation with the restriction of pipe section occurs often during tomato ketchup processing and when the final product is squirted out of a bottle. To have a complete description of its flow behavior is then important to characterize the ketchup extensional viscosity together with the shear viscosity. Off-line extensional viscosity has

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been investigated generally for emulsions (Rao, 2014; Różańska, 2012; Różańska et al., 2013), but specific results for the tomato ketchup are lacking, mainly due to the experimental constraints and difficulties to obtain reliable data. In this study, off-line extensional viscosity measurements of commercial ketchup were carried out by hyperbolic contraction flow (Wikström and Bohlin, 1999; Stading and Bohlin, 2001). These results and off-line measurements of the shear viscosity were correlated to those obtained in-line with a rheometer that combines of Ultrasound Doppler Velocity Profiling (UVP) and the pressure difference (PD) technique (Claesson et al., 2013; Wiklund et al., 2013). This comparison aims to further the understanding of the tomato ketchup flow in pipes and to provide a base to evaluate its extensional viscosity from real time in-line measurements.

2. Materials and methods

2.1. Materials

Commercial specimens of Heinz tomato ketchup were used for this study. All experiments were carried out at room temperature (≈23 °C).

2.2. Rheological measurements

2.2.1. Continuous shear rheology

The off-line apparent viscosity of the tomato ketchup was measured over a shear rate range of 0.1–100 s^{-1} using an Ares-G2 (TA instruments, Waters LLC, USA) strain controlled rotational rheometer equipped with a cone-plate geometry having a 40 mm diameter; 0.02 rad cone angle, and 0.027 mm gap truncation. The yield stress was measured using a Reologica Stresstech stress controlled rotational rheometer equipped with a cone-plate geometry having a 30 mm diameter; 0.07 rad cone angle, and 0.150 mm gap truncation.

2.2.2. Hyperbolic contraction flow

The tomato ketchup apparent extensional viscosity was measured using a Hyperbolic Contraction Flow rig (Wikström and Bohlin, 1999) mounted in an Instron 5542 Universal Testing Instrument (Instron Corporation, Canton, USA). Measurements were performed at room temperature using a die with inlet radius of 10 mm and outlet radius of 2 mm imposing a Hencky constant strain of 4.5. The extensional strain rates used were in the range 0.1 s^{-1}, to 10 s^{-1}, the data was evaluated as described previously (Binding, 1988; Stading and Bohlin, 2001). Experimental limitations such as the instrument maximum speed and the formation of turbulent flow at high piston speed prevented the extensional viscosity measurement at higher rates. The transient extensional stress was monitored until a stable plateau value was reached from which the steady-state, transient extensional viscosity was calculated. The Power-law parameters acquired with the continuous shear measurements were used to calculate the extension rates, the Hencky strain and to compensate for the shear stress contribution to the total stress (Wikström and Bohlin, 1999). The calculated shear contribution was generally small (<1%) and practically negligible.

2.2.3. Pulsed ultrasound Doppler velocimetry and the enhanced tube viscometry method

Ultrasound Doppler techniques were first introduced by Shigeo Satomura, a Japanese physicist, for practical medical diagnostics in the 1950s (Sigel, 1998). Pulsed ultrasound Doppler velocimetry and imaging techniques has since then been developed are now widely used for many academic and industrial applications (Takeda, 1995). Based on this technology, a novel in-line fluid characterization system and method for complex industrial fluids and suspensions, Flow-Viz, has been developed over 15 years by SP and CPUT (Wiklund et al., 2014). Using the Flow-Viz method, the shear stress at the wall and the shear stress distribution inside the pipe is calculated from a pressure drop measurement over a fixed distance of pipe (Fig. 1). The shear rate is estimated using a pulsed ultrasound sensor that allows true multi-point measurements of the liquid velocity distribution across the pipe diameter (Fig. 1). The velocity gradient is measured from the pipe wall up to the position where it attains a constant velocity. This flat region of the velocity profile with constant velocity is commonly known as "plug flow region" (Chen et al., 1970; Dash et al., 1996; Slatter, 1997). The Flow-Viz can be regarded as a UVP + PD method since it combines Pulsed Ultrasound Velocimetry (UVP/PUV) with Pressure Difference measurements (PD) (Kotze et al., 2012; Wiklund et al., 2002, 2014, 2007). This method is non-invasive since it does not affect the current flow and does not give any additional pressure drop (Kotze et al., 2014). Since the measurements take only few seconds, the instrument software provides in real time, complete viscosity vs. shear rate distributions, i.e. flow curves and associated rheological model parameters such as the flow index, n, and consistency index, K. The fluid yield stress can also be estimated from the UVP data. It can be obtained either directly from the measured plug radius R^* in the velocity profile data or from a model fitting procedure (Eqs. (1)–(3)). Fig. 1 shows a schematic illustration of direct yield stress estimation from the plug velocity profile and the corresponding rheogram.

The equation for the Herschel-Bulkley model is as follows:

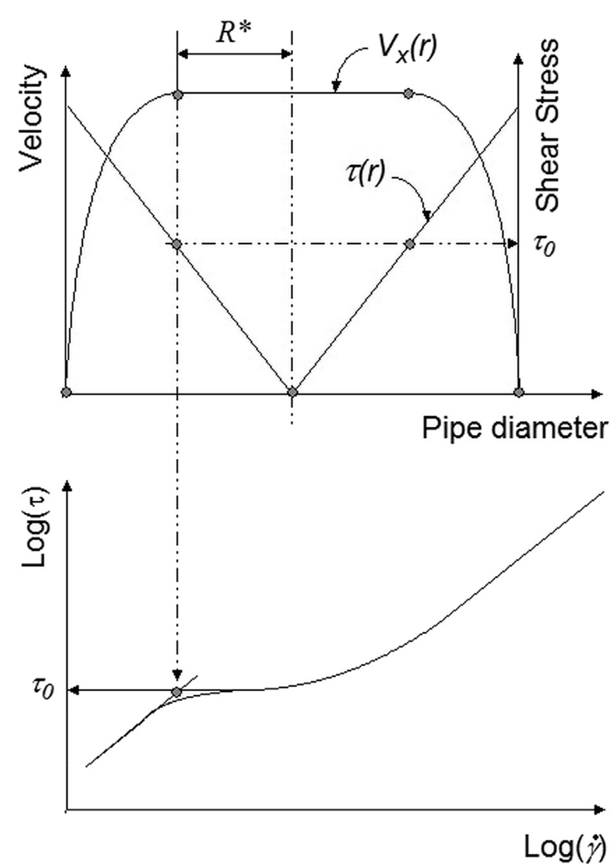

Fig. 1. Schematic illustration of yield stress estimation from the plug velocity profile, and the corresponding rheogram.