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In-pipe coconut water rheological characterization with ultrasonic waves

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A B S T R A C T

We propose in this paper to use a simple and robust experimental protocol based on longitudinal ultrasonic velocity measurement in order to evaluate the viscosity of coconut water in a cylindrical stainless-steel pipe. Seven samples with Soluble Solids Content (SSC) ranging from 6.7 to 44.2°Brix were studied using conventional Couette viscometry and high-frequency ultrasonic methods. Calibration laws linking the ultrasonic velocity measured at 5 MHz to the shear viscosity and to the SSC are proposed. These laws are in very good agreement with previous measurements carried out several years ago using a plane 25 MHz transducer directly introduced into the coconut water with SSC of up to 60°Brix.

1. Introduction

Among the important rheological parameters, viscosity is certainly the most investigated because it reflects the flowing capacity of the material and thus provides a lot of data on the microstructure (Ferry, 1961). In particular, for sweet foods and beverages, the sugar content and sugar composition (glucose, fructose, sucrose …) is directly related to the viscosity (Telis et al., 2007). Moreover, this data is fundamental in many industrial applications as its understanding leads to control and optimization of manufacturing processes (Povey and Mason, 1998). Many experimental methods dedicated to viscosity evaluation have been developed. However, the most promising are the low-power ultrasonic approaches because they provide to a non-destructive measurement method and can be carried out through thick and opaque walls. The ultrasonic measurement is therefore possible through pipes during the filtration, concentration and processing of juices. In literature, many authors have described various ultrasonic methods dedicated to the characterization of fluids in food engineering (Contreras et al., 1992; Kuo et al., 2008; McClements and Gunasekaran, 1997; Resa et al., 2004; Saggin and Coupland, 2002). Most of the time, the measurement is carried out ex-situ. This means that a sample is extracted from the production line and analyzed in a specific device. It can be noticed that similar recent approaches are used in biomedical domain for blood analysis (Voleisis et al., 2017). In contrast, in other sectors such as the petroleum industry, there are many approaches dedicated to direct measurement in pipeline using either propagating waves in the oil or guided waves in the walls of the pipeline (Kazys and Rekuviene, 2011; Ma et al., 2007; Pavlakovic, 1998; Rose, 1998).

In the case of coconut water, to our knowledge, no, or only a few, scientific papers are dedicated to the link between ultrasonic parameters and viscosity or SSC. For instance, recently, Samuel (Samuel et al., 2015), described an ex-situ ultrasonic measurement using a commercial ultrasonic interferometer to evaluate the effect of laser exposure on a coconut water concentration. In fact, ultrasound are generally used to emulsify mixtures (Ramisetty et al., 2015), to treat coconut water from a chemical point of view (Rojas et al., 2017) or to extract components (Rodrigues and Pinto, 2007), but in these cases the ultrasonic intensity is high and it is not possible to consider these methods as non-destructive. Furthermore, viscosity is not measured. A comprehensive review of such approaches is given in the recent paper of Paniwnyk (2017). Finally, concerning viscosity measured with a rheometer as a function of SSC, one may refer to the work of Manjunatha (Manjunatha and

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Raju, 2013).

In a previous study (Laux et al., 2014), we published measurements of viscosity with the ultrasonic approach ex-situ using a 25 MHz ultrasonic transducer. Thanks to the measurement of longitudinal ultrasonic velocity and attenuation, the link between the longitudinal viscosity obtained by ultrasound and the shear viscosity (measured by rheometer) was established. In conclusion, our proposal was to further adapt the ultrasonic measurements to cylindrical geometry in order to carry out in-line measurements directly on pipes. Therefore, in this new communication we first described an experimental protocol dedicated to longitudinal measurements in cylindrical tubes. The specific signal processing based on a double Fast Fourier's Transform (FFT) was detailed and its robustness was tested on simulated signals. New results obtained on seven coconut water solutions with SSC up to 44° Brix were then presented. We only focused our attention on longitudinal velocity and on the relationship between this velocity, the shear viscosity measured with a Couette rheometer and the SSC.

2. Materials and methods

2.1. Samples

Seven samples were prepared as follows. Coconut water was extracted from 15 immature coconut fruits harvested from the Green Dwarf variety of Thailand (Cock Brand, Thailand). Immature coconut water (CW) extracts were collected and the juice was dispatched in 1 L glass bottles prior to immediate freezing at −50 °C and stored at −18 °C until processing. CW concentration was carried out using a rotary evaporator under controlled pressure conditions. Soluble solids content (SSC) was measured on native and concentrated samples using a digital hand-held PAL refractometer 0–85° Brix (ATAGO Corp., LTD, Japan). CW samples were concentrated 5–10-fold, resulting in Brix values from 6.7 to 44.2°Brix. After concentration, the samples were stored at −18 °C in 20 mL sterile containers. Prior to viscosity measurement, the samples were thawed at 20 °C.

2.2. Flow tests

Shear viscosity was measured using the same protocol as described in our previous study and measurements were carried out using a Physica MCR301 Rheometer (Anton Paar© France, Courtaboeuf, France). A Couette flow measuring cell DG27/T2000/SS was again used. All measurements were carried out at 20 ± 0.1 °C using a Peltier system to control the temperature and a fluid circulator Viscotherm VT 2 controlled directly from the Physica MCR. After 5 min of thermal stabilization, each 11 mL sample was submitted to a flow test in the 10 to 400 s^{-1} shear rate range. The rheological behavior identified was Newtonian and consequently, the viscosity was directly calculated from the ratio between the shear stress and the shear rate. For the seven samples the viscosity ranges between 1.4 and 10.27 mPa s.

2.3. Ultrasonic approach

2.3.1. Ultrasonic high-frequency longitudinal waves in cylindrical pipes

Measurement of the sound velocity in a cavity is a widely investigated subject in literature. Among the works referring to such measurements in liquids in rectangular or cylindrical geometry, we can cite the works of Sinha (Sinha and Kaduchak, 2001). For measurements in gases a large study was carried out by Rosenkrantz (Rosenkrantz, 2007; Rosenkrantz et al., 2009). In cubic cavities it is possible to consider that the ultrasonic waves are plane. Thus, in order to evaluate the velocity of propagation, it is sufficient to divide the distance traveled by the travel time also called time of flight. For cylindrical shells the problems is more complex and is theoretically well known (Rose, 1998). But, if the frequency is high enough to consider that the wavelength is small with respect to the radius of curvature of the cylindrical pipe, it is possible to measure the celerity in a simple way as for plane waves in infinite medium. This point is clearly detailed by the authors previously cited. Thus, the elementary relationship "distance = velocity x time of flight" remains valid. Concerning the measurement of the attenuation, Sinha (Sinha and Kaduchak, 2001) describes two approaches: one in the temporal domain and one using a frequential approach. In order to correct diffraction effects and to take into account the transfer function of the experimental device, a pre-calibration with a known liquid is necessary (Blahova, 2010). As we preferred to avoid such a calibration, we only focused our attention on the ultrasonic velocity evaluation.

2.3.2. Ultrasonic echograms simulation

In order to simulate the ultrasonic signal after propagation in a small cell, the "easier" method is to use the convolution between a typical echo pattern and a reflectivity. This method is generally used in seismic research for blind deconvolution methods testing. In a first approximation the echo pattern can be defined as a sine function multiplied by a Gaussian trend. The reflectivity is defined as a succession of Dirac spikes regularly spaced in temporal domain according to the time of flight. An exponential decay can be added in order to simulate damping due to viscosity. Finally, white noise can also be superimposed. This procedure is illustrated in Fig. 1. The regular space between the echoes is equal to $2d/C_L$ whereby C_L represents the longitudinal ultrasonic velocity in the fluid and d the cell size.

2.3.3. Experimental method

A classical broadband plane Sonaxis© transducer (central frequency 5 MHz – Bandpass 2 MHz) excited with an Olympus© 5800 pulse generator was used and coupled to a stainless-steel tube filled with coconut water. The coupling between the transducer and the tube was ensured using a specific stainless-steel adapter in order to convert plane waves into a cylindrical ultrasonic field (see Fig. 2). The use of this low-cost homemade adapter enabled optimization of the coupling between the transducer and the tube. Secondly, if the diameter of the tube is modified the adapter can easily be reworked. Honey was introduced at the interfaces (transducer/adapter) and (adapter/pipe) and acted as coupling fluid. It would also have been possible to work with a specific ultrasonic

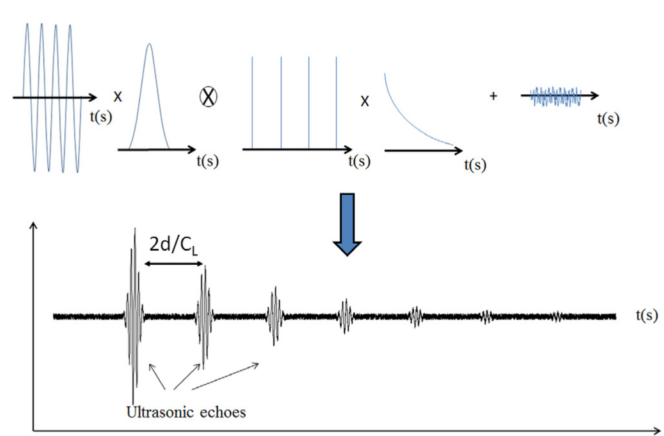

Fig. 1. Numerical generation of ultrasonic echoes.