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50. Internationales Wissenschaftliches Kolloquium
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Liquid dynamic viscosity measurement by ultrasonic wave mode conversion

ABSTRACT

This work presents a cell to measure the liquid dynamic viscosity using an ultrasonic wave mode conversion from longitudinal to shear wave and vice-versa. A prototype-measuring cell was constructed to test the proposed method. Measurements of the viscosity of automotive oils (SAE 90 and SAE140) were obtained in the frequency range from 1 to 10 MHz. These results are also compared with the Maxwell model with two relaxation times, showing the dependency of dynamic viscosity with the frequency of the shear wave. The experimental data are in good agreement with those provided by the Maxwell model.

INTRODUCTION

Viscosity is the main parameter that characterizes the flow of liquids in an industrial process, and its measurement provides information on the resistance to flow in tubes or in autoclaves during the molding operations. Besides, viscosity measurements are used to develop and to control the quality of the finished products, and to optimize product properties. So the knowledge of viscosity is crucial to many industrial processes in the chemical, food industry and so on.

Typical methods to measure the viscosity at low frequencies depend on the drag on an oscillating surface immersed in the liquid. Such methods are not appropriate for real-time process control. A more suitable method for real-time control employs ultrasonic waves to obtain the viscosity of liquids. The ultrasonic reflectance method was developed to measure the viscosity of liquids as early as 1949 by Mason *et al*. [1]. This method is based on the measurement of the complex reflection coefficient of a plane shear wave reflected in a solid-liquid interface at an oblique or normal incidence.

The cell discussed in this paper uses a piezoelectric transducer that generates longitudinal waves and a PVDF membrane that responds only to the longitudinal mode. The shear wave is generated by a mode conversion. Since the acoustic impedance of the shear waves for the solid part of the cell is known, the dynamic viscosity of the liquid can be obtained from the density of the liquid and the

complex reflection coefficient at the solid-liquid interface.

THEORY

In Fig. 1, the propagation of a harmonic shear wave along the *z*-axis in a viscoelastic isotropic medium (medium 2) can be described by:

$$\frac{\partial^2 u_x}{\partial z^2} = \frac{\rho_2}{G_2^*}\frac{\partial^2 u_x}{\partial t^2}, \tag{1}$$

where u_x is the transverse displacement in the x direction, G_2^* the complex shear modulus of medium 2, and ρ_2 the density of the medium 2. The complex shear modulus is defined as the ratio of shear stress to shear strain, $G_2^* = G' + jG''$, where G' is the storage modulus and G'' the loss modulus, which is related to the dynamic viscosity η_2 by the following equation:

$$\eta_2 = \frac{G''}{\omega}, \tag{2}$$

where ω is the angular frequency. The complex characteristic acoustic impedance Z_2^* for shear waves of the medium 2 is given by

$$Z_2^* = \sqrt{G_2^* \rho_2}\ . \tag{3}$$

Now considering the propagation of shear waves from the medium 1 (second buffer rod) to the medium 2 (sample), the complex reflection coefficient at the interface is given by

$$R_{12}^* = \frac{Z_2^* - Z_1}{Z_2^* + Z_1}, \tag{4}$$

where $Z_1 = \rho_1 c_1$ is the characteristic acoustic impedance of medium 1, a solid material with a known density ρ_1 and a propagation velocity to be determined c_1. In general, the solid introduces very little attenuation, and its impedance can be considered real. The medium 2 is the viscoelastic

medium whose viscosity is being measured and it has a complex impedance. Hence the complex reflection coefficient can be represented in an exponential form, $R_{12}^{*} = R_{12}e^{j(\pi+\theta)} = -R_{12}e^{j\theta}$, where R_{12} is the magnitude and $(\pi+\theta)$ the phase angle. If the medium 2 is an air sample (reference), $R_{12}=1$ and $\theta = 0$. Consequently, the reflected wave is 180^{o} out of phase with the incident wave. If medium 2 is a liquid sample, R_{12} is smaller than 1 and θ is the phase shift (a negative quantity). These quantities, R_{12} and θ, caused by the liquid, can be measured by comparing the reflected wave at the solid-liquid interface with that of the reference wave at the solid-air interface. The value of the dynamic viscosity is obtained by the following expression:

The value of the dynamic viscosity is obtained by the following expression:

$$\eta_2 = \frac{-4(1-R_{12}^2)R_{12}\text{sen}\theta}{(1+R_{12}^2+2R_{12}\cos\theta)^2}\frac{(\rho_1 c_1)^2}{\omega\rho_2}, \qquad (5)$$

where R_{12} and θ are the magnitude and phase of the complex reflection coefficient, ω is the angular frequency, ρ_1 and c_1 are the density and phase velocity of the medium 1, and ρ_2 is the density of the medium 2 [2].

MEASUREMENT CELL

The cell discussed in this paper, as shown in Fig. 1, consists of a piezoelectric ceramic transmitter, a PVDF (Poly-Vinylidene Fluoride) membrane receiver, PMMA (polymethyl-methacrylate) buffer rod, and an aluminum solid prism. The liquid sample is loaded on a face of the prism, which is opposite to an oblique face immersed in water. The transmitter emits a short longitudinal wave that travels through the PMMA buffer rod, the PVDF membrane and the water buffer, and reaches the prism oblique face. At this oblique water-solid interface, there is a wave mode conversion from longitudinal wave to shear wave. The shear wave propagates through the prism and reaches the solid-sample interface at normal incidence. At this interface, the shear wave reflects and returns to the receiver after back propagating through the prism and water. The reflected waves are measured in the longitudinal mode by the aperture PVDF membrane, which is sufficiently large to intercept the entire propagating pulse avoiding errors due to the acoustic diffraction effect and the lack of stability, in time, of the emitter and the associated electronic. The strategy used to obtain the

viscosity is based on the measurement of the complex reflection coefficient of shear waves at the solid-liquid sample interface, using the relative reflection method. The complex reflection coefficient (magnitude and phase) is obtained by normalizing, in the frequency domain, the solid-sample echo with respect to the solid-air echo recorded in a previous experiment [1], [2], [3].

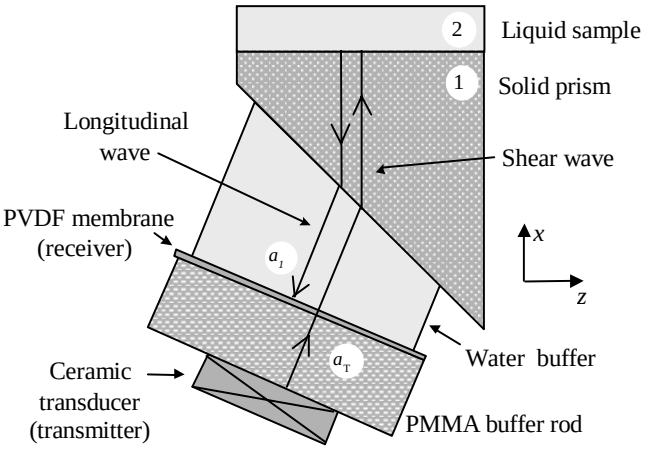

Figure 1. Schematic draw of the measurement cell.

The method employed in the measurement of the magnitude of the reflection coefficient and the phase is in reality a set of two measurements at the same temperature. First, an air sample is taken as a reference, obtaining the signals $a_{T(air)}$ and $a_{1(air)}$. The Fourier transforms at a selected frequency are calculated, resulting in the values $A_{T(air)}$ and $A_{1(air)}$. Then the measurement is repeated for the liquid sample, obtaining $A_{1(liq)}$ and $A_{T(liq)}$. The magnitude and the phase of the reflection coefficient can be calculated as the ratio of the second to the first measurements. To eliminate the problems with equipment drift [4] the relative reflection method employs a normalization with respect to $A_{T(liq)}$ and $A_{T(air)}$. The complex reflection coefficient is given by:

$$R_{12}^{*} = -\frac{A_{1(liq)} / A_{T(liq)}}{A_{1(air)} / A_{T(air)}}, \tag{5}$$

EXPERIMENTAL RESULTS

Figure 2 shows the viscosity versus frequency for the aluminum prism, these results are compared with the theoretical ones obtained by the Maxwell model (dashed line) and the Newtonian liquid model (solid line). Taking the values obtained by the measurement cells and comparing them with the measured values by the rotational viscometer (Newtonian liquid), the relative errors are in the range from 4% to 40% for SAE90 and from 20% to 50% for SAE140. The

large error is due to the elastic effect (non-Newtonian liquid) is not neglected to higher frequencies and to higher viscosity liquids.

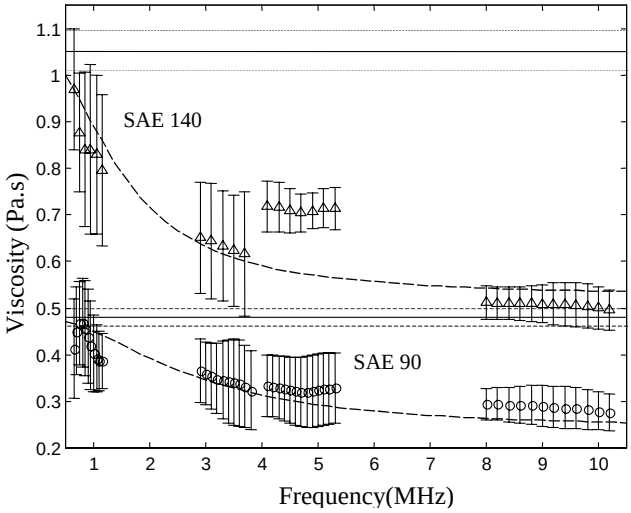

Figure 2. Viscosity versus frequency for the aluminum prism

CONCLUSION

A cell to measure the dynamic viscosity of liquids using wave mode conversion was presented. The experimental results are in good agreement when compared with the Maxwell model with two relaxation times, showing how the dynamic viscosity varies with frequency.

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