

Laboratory 5

Viscosity

Objective:

The objective of this lab is for you to determine the flow properties of liquid phase materials by measuring the viscosities of a few common fluids. From the results, you will see how the viscosity varies with the concentration of a binary liquid mixture.

Preparation

- Read the references on viscosity (QCM-vis) and rheometry (ch3) posted in the Compass2g site. Refer to the viscometer operating manual if necessary.
- Read pp.29-32 of the QCM200 manual.
- Additional references on the Rule of Mixtures can also be found on the Compass website.

Equipment and samples

- Quartz crystal monitor and software
- Water, methanol, ethanol, propanol, butanol, polyethylene oxide in acetonitrile solution.

Laboratory Safety for Viscosity Experiment

Required PPE

- Long pants
- Closed toe shoes
- Safety Glasses
- Chemically resistant gloves

Safety Concerns

- Chemicals - potential for chemical exposure

Different alcohols will be tested using the QCM. Please read the safety data sheet for each of these chemicals (links below). Chemically resistant gloves must be worn when handling chemicals.

- MSDS Methanol (<https://www.sciencelab.com/msds.php?msdsId=9927227>)

- MSDS Ethanol (<http://www.sciencelab.com/msds.php?msdsId=9923955>)
- MSDS Propanol (<https://www.sciencelab.com/msds.php?msdsId=9924736>)
- MSDS Butanol (<http://www.sciencelab.com/msds.php?msdsId=9927115>)
- MSDS Poly(ethylene oxide) (<http://www.sciencelab.com/msds.php?msdsId=9926620>)

Introduction:

In this lab, you will study the transport coefficient for shear momentum in a fluid, i.e., the viscosity. (Viscosity is typically written as the Greek letter “eta” but “mu” is also common.) The ratio of the viscosity to the mass density is called the “kinematic viscosity” and, like thermal diffusivity and mass diffusivity, has units of m²/s. The MKS units of viscosity are Pa-sec but the cgs unit of poise is also commonly used. For example, the viscosity of water has a relatively strongly temperature dependence and crosses through 1 cP near room temperature: $\eta=1.8$ cP (centipoise) at $T=0^{\circ}\text{C}$; 1.0 cP at 20°C ; and 0.28 cP at 100°C . (1 cP= 0.001 Pa-sec = 1mPa-sec.)

According to the viscosity behavior, liquids are divided into two main categories:

- 1) Ideal liquids or incompressible liquids of very small viscosity.
- 2) Incompressible liquids of moderate viscosity.

The flow of ideal liquids or liquids of small viscosity is usually governed by what is called the equation of continuity and Bernoulli’s equation. However, the moderate viscosity of a non-ideal liquid causes a loss in energy during its flow. Accordingly, the total energy per unit volume, Bernoulli’s principle, is not constant along the path of such a viscous fluid. This means that we cannot apply Bernoulli’s equation to describe the flow of a viscous fluid.

Viscosity of a liquid may be measured by a pressure-driven or a drag flow system. In the pressure-driven system, a pressure gradient is applied to force the liquid flow through a capillary tube. By measuring the flow rate, the viscosity of the liquid, η , may be determined from the Poiseuille’s equation:

$$Q = \frac{\pi(P_2 - P_1)R^4}{8\eta L}$$

where R is the radius of the capillary tube, L, the length of the tube, P, the pressure, and Q, the flow rate. An example of the pressure-driven systems is the U-tube viscometer. In the drag flow system, an instrument head is used to start the liquid flow in a container and the drag force to the liquid flow is measured. There are three major types of viscometers based on the drag flow: rotational, vibrational and falling-sphere systems. In rotational viscometers, such as cone-plate and concentric cylinder, a thin layer of liquid is sheared at a given rotational speed while the torque required for rotational motion is recorded. The viscosity of a liquid is determined from the torque, angular speed, and geometric dimensions of the viscometer. For example, the viscosity of a liquid is obtained from the following equation for a cone-plate viscometer:

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{3M\beta}{2\pi R^3 \Omega}$$

where M is the torque or moment, Ω , the angular speed, R, radius of the cone, and β , the gap angle. In a falling sphere viscometer, the terminal speed of a sphere, v, falling through a liquid with a viscosity, η , is calculated from the Stokes' equation:

$$V_s = \frac{2}{9} \frac{r^2 g (\rho_p - \rho_l)}{\eta}$$

where r is the radius of the sphere, g, the gravitational constant, and ρ , the density of the particle or liquid.

In a vibrational viscometer, the liquid is subject to a vibrational motion at a given frequency and the vibrational response of the system containing the liquid is monitored. A quartz crystal monitor is such an example, where the frequency response of the crystal is used to measure the square root of the product of the viscosity and density, $\rho\eta$. (The analogous quantity in heat transfer is the thermal effusivity, $C\kappa$.) In MSE 307, you used the frequency shift of the oscillator to determine the mass of water per unit area adsorbed by a polymer film. The principle here is similar, only now the mass that is measured is the layer of the liquid that lies within the “shear-momentum diffusion length” from the surface of the quartz crystal. This momentum diffusion length L scales as

$$L \sim \sqrt{\frac{\eta}{\rho\pi f}}$$

where f is the frequency of the oscillator. Since the mass per unit area of the fluid layer is $L\rho$, the frequency shift of the oscillator scales as

$$\Delta f \propto \sqrt{\frac{\rho\eta}{\pi f}}$$

The complete equations are given in the operating manual for the quartz crystal monitor that is posted on Compass. These equations are only valid if the surface roughness of the quartz crystal is much smaller than L .

In many cases, transport coefficients and susceptibilities of mixtures and composites can be estimated from the properties of the pure components and effective medium theories. The simplest effective medium theory is a “rule of mixtures” where the property of the mixture is a weighted average of the properties of the two components. This rule of mixture can take many forms, but one of the simplest was determined by Arrhenius over one hundred years ago

$$\log \eta_s = N_1 \log \eta_1 + N_2 \log \eta_2$$

Where N represents the mole fraction of each component, and the subscripts s , 1 , and 2 refer to the solution, component 1 and component 2, respectively. However, not every system will be accurately described by the rule of mixtures.

Laboratory Procedure:

Using tweezers, place the crystal in the flow cell with the large circular electrode surface up and the electrodes on the bottom surface over the contact pins. Screw on the cap tightly. Adjust the null capacitance by switching the monitor to “Adjust” on the face of the unit. When the two null lights are steady, flip the switch back to “Hold” mode. Before a measurement with a new solvent is made, wash the cell thoroughly with methanol (or any other easily flushed liquid), to remove solvents used in the previous experiment and then dry in a stream of clean gas (air or nitrogen). Start the frequency measurements and when the frequency reaches a constant value, f_0 , fill the cell with the liquid under investigation. A few minutes are needed for stabilization of the frequency, f_L . The desired value is $\Delta f_\eta = f_L - f_0$.

First, establish the calibration curve using the liquids with known density and viscosity, such as methanol, ethanol, n-propanol, butanol, and water. Plotting the frequency shift for each liquid against the square root of its viscosity to obtain two calibration constants, A and B , in the following equation:

$$\frac{\Delta f_\eta}{\rho} = A - B \sqrt{\frac{\eta}{\rho}}$$

where ρ is the density of the liquid. After the calibration is completed, measure the frequency shift and density of the liquids to be investigated (mixtures of alcohols and mixtures of water and alcohol). From the calibration constants, calculate the viscosity of the experimental liquids using the equation above. Also calculate the expected viscosity for each solution using the rule of mixtures. Do all of the solutions follow the prediction, or are there some that have higher/lower viscosity than expected? What might cause this change in behavior?

A Brookfield rotational viscometer will also be used to measure the viscosity and flow behavior of a solution of polyethylene oxide in acetonitrile. The shear force experienced by a submerged spindle will be recorded as a function of rotational speed (0.5-100 RPM), and then converted to a viscosity. How the viscosity changes as a function of rotational speed can be used to determine certain characteristics of the fluid, including whether it is Newtonian in behavior or experiences shear thickening or shear thinning.

References:

1. Viswanath, D.S., Ghosh, T.K., Prasad, D.H.L., Dutt, N.V.K., Rani, K.Y., *Viscosity of Liquids: Theory, Estimation, Experiment, and Data*, Springer, 2007, ISBN: 978-1-4020-5481-5.
2. R. C. Reid, J. M. Prausnitz, and B. E. Poling, *The Properties of Gases and Liquids*, 4th ed. (McGraw-Hill, New York, 1987).