EXPERIMENTS ON VISCOSITY OF AQUEOUS GLYCEROL SOLUTIONS

Using a Tank-Tube Viscometer

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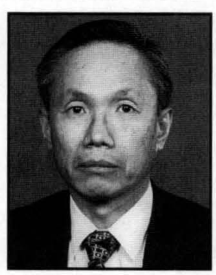
At Tuskegee University we have added a new laboratory experiment for the fluid mechanics and transport phenomena laboratory (the Unit Operations I Laboratory) that investigates the effects of both water concentration and temperature on the viscosity of aqueous glycerol solutions. The experiment is designed as an extension of the fluid mechanics course (offered to sophomore students), the engineering mathematics course (for juniors), and the transport phenomena course (offered to seniors).

We offer the course twice a year and it has an average student enrollment of twelve. The students are usually divided into three groups. The objectives of the course are to engage each student in active participation and experimentation and to have them analyze statistically the experimental data with the aid of a computer, to perform necessary calculations for tables and figures, and to prepare a written report using a word processor.

In this paper we will describe several experiments for measuring the viscosity of aqueous glycerol solutions using a tank-tube viscometer. Measuring the viscosity of highly viscous liquids with the tank-tube viscometer is easier than using other types of viscometers. This inexpensive viscometer generates numerous reproducible viscosity data of highly viscous aqueous glycerol solutions under given experimental conditions. The tank-tube viscometer consists of a large-diameter reservoir and a long, small-diameter, vertical tube.

Fabrication of the tank-tube viscometer is inexpensive since it does not need ancillary equipment such as a high-pressure pump, a pressure transducer, or an accurate flow meter. Our viscosity experiment provides an opportunity for students to apply mathematical and computational skills to analyzing statistically experimental data and to write a report using computer software. Mathematical and computational skills are learned through the mathematics courses as well as the basic engineering courses that are offered to our freshman and sophomore students. Our experiment also familiarizes students with the concept of viscosity of highly viscous Newtonian fluids, which they learned in the lecture class of the fluid mechanics course.

The main objective of the experiment is to demonstrate the effects of water concentration as well as temperature on viscosity by applying experimental data of accumulated amounts of aqueous glycerol solutions at various drain dura-



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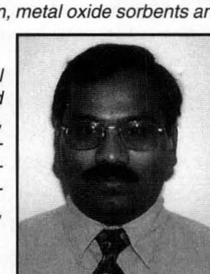

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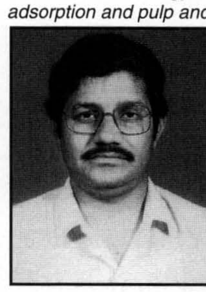

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The experiment is designed as an extension of the fluid mechanics course (offered to sophomore students), the engineering mathematics course (for juniors), and the transport phenomena course (offered to seniors).

tions to a newly developed viscosity equation for the fabricated tank-tube viscometer. The viscosity equation was developed under the assumptions that both the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid.

THEORY

Fluid mechanics is the study of forces and motions in fluids.[1] Treatment of fluid flow required understanding the physical properties of a fluid that affects the motion. The two most important fluid properties are density and viscosity, and the most important physical property of a fluid from the point of view of the study of fluid mechanics is the viscosity.[2] A fluid is a substance that undergoes continuous deformation when subjected to a shear stress; the resistance offered by a real fluid to such deformation is called its viscosity. All fluids have viscosity. This property causes friction.[3] The viscosity of a Newtonian fluid is constant if static pressure and temperature are fixed.

A chemical engineer is concerned with the transport of fluids from one location to another by pumping fluids through pipes over long distances from storage to reactor units.[4] Many intermediate products are pumped from one unit operation to another, and raw materials such as natural gas and petroleum products may be pumped very long distances to domestic or industrial consumers.

These industrial processes require determination of the pressure drops in both the pipeline and the individual units themselves, evaluation of the power required for pumping, and estimation of the most economical sizes of pipes and measurement of the flow rates. The viscosity value of a particular fluid flowing through pipes and individual equipment is an essential property in designing these industrial processes.

Viscosity values of a Newtonian fluid can be calculated using

$$\ell n\left(\frac{H+L}{h+L}\right)=\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{1}$$

if levels of a liquid in a reservoir tank of a tank-tube viscometer[5] at different drain durations are known. Equation (1) is developed based on the assumptions that both the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid.

The change in the level of a highly viscous liquid in the reservoir tank at a given drain duration is very small, however. Often it is difficult to read the change in the level of the liquid in the reservoir. Hence, the liquid level at a given duration of time is described in terms of accumulated amounts of the liquid drained from the reservoir tank (see Eq. 2). A mass balance of the liquid around the reservoir tank of the tank-tube viscometer produces

$$h = H - \frac{m}{\pi R^2 \rho} \tag{2}$$

We then obtain

$$-\ell n\left(1-\frac{m}{(H+L)\pi R^2\rho}\right)=\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{3}$$

by substituting the "h" value from Eq. (2) into Eq. (1). The left-hand side of Eq. (3) contains accumulated amounts of the liquid drained from the tank-tube viscometer, while the right-hand side contains drain durations. Therefore, Eq. (3) allows us to calculate the liquid viscosity if the total mass of the liquid out of the reservoir at a given drain duration is known.

The left-hand side of Eq. (3) is denoted as Y, as shown by

$$Y=-\ell n\left(1-\frac{m}{(H+L)\pi R^2\rho}\right) \tag{4}$$

The Y values of Eq. (4) are easily calculated by substituting both the amounts of aqueous glycerol solutions drained from the tank-tube viscometer and their density values. Densities of aqueous glycerol solutions were obtained with a densimeter. The "H" value in Eq. (3) is the same as the height of the reservoir when the reservoir tank is filled with a liquid. In this laboratory experiment, the reservoir is filled with aqueous glycerol solutions to avoid measuring the initial level of aqueous glycerol solutions in the reservoir. Otherwise, a possible experimental error source will be added to the experiment by measuring an initial level of aqueous glycerol solutions in the reservoir.

Equation (3) can be simplified to obtain

$$\left(\frac{m}{(H+L)\pi R^2\rho}\right)\cong\left(\frac{gR_o^4\rho}{8\mu R^2 L}\right)t \tag{5}$$

if the length of the vertical tube of the tank-tube viscometer is relatively longer than the initial level of a liquid in the reservoir and if amounts of the liquid drained from the reservoir are relatively small.

The viscosity of liquids decreases with increasing tem perature. An approximate empirical observation for the temperature dependency of viscosity for liquids is described by

$$\mu = Ae^{(B/RT)} \tag{6}$$

where A and B are empirical constants. This equation can be used with viscosity data for interpolation or modest extrapolation.[6] Since liquids are essentially incompressible, the viscosity of liquids is not affected by pressure.[7]

An average velocity equation for liquid flow in the vertical tube of the tank-tube viscometer is described as a function of accumulated amounts of aqueous glycerol solutions drained at a given drain duration. Combining the average velocity equation

$$v_m = \frac{\rho g R_o^2}{8\mu L}\left(H + L - \frac{m}{\pi R^2 \rho}\right) \tag{7}$$

with Eq. (3) gives

$$v_m = -\left(\frac{R}{R_o}\right)^2\left[\ell n\left(1 - \frac{m}{\pi R^2 \rho (H+L)}\right)\right]\left(H + L - \frac{m}{\pi R^2 \rho}\right)\frac{1}{t} \tag{8}$$

EXPERIMENTAL SETUP

A wide variety of viscometers (capillary, glass-tube, rotational, falling-ball, cup, and oscillatory[8]) is available for measuring viscosity. An inexpensive viscometer, the so-called tank-tube viscometer, was fabricated for the course (see Figure 1). It consists of a cylindrical reservoir and a long vertical tube. The radius and the height of the reservoir are 2.5531 cm and 14.7 cm, respectively. The radius and length are 0.1637 cm and 73.8 cm, respectively.

The reservoir is made of a transparent Plexiglas pipe, whereas the tube of the viscometer is made of stainless steel. The vertical tube is connected at the bottom of the reservoir. Aqueous glycerol solutions are chosen to test the fabricated tank-tube viscometer since glycerol is completely soluble in water, very viscous, and does not inflict any health hazards.[9] The bottom end of the vertical tube is initially closed with a rubber bulb and aqueous glycerol solutions are fed to the reservoir. An electronic balance placed beneath the bottom end of the vertical tube is used to measure accumulated amounts of aqueous glycerol solutions drained from the reservoir at a given drain duration.

EXPERIMENTAL PROCEDURE

The tank-tube viscometer is set up by placing an electronic balance beneath the bottom end of its vertical tube in a constant-temperature chamber, as shown in Figure 1. The cylindrical reservoir tank is filled with an aqueous glycerol solution that is allowed to flow through the vertical tube. When the vertical tube is filled with the aqueous glycerol solution by evacuating air from it, its bottom end is closed with a rubber bulb to stop the flow of solution. After closing

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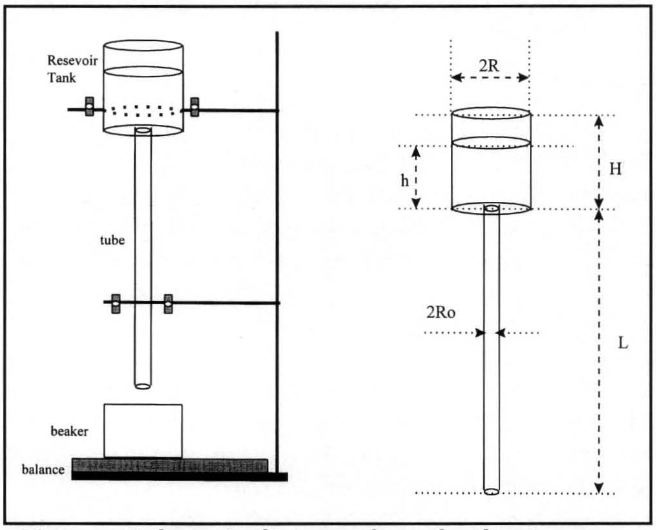

Figure 1. *Schematic diagram of a tank-tube viscometer.*

its bottom end, the cylindrical reservoir tank is again filled with the aqueous glycerol solution. Consequently, measurement of the initial level of the solution in the reservoir is not necessary since the it is equal to the height of the reservoir itself. The height of the reservoir is incorporated into Eq. (3).

An empty receiving beaker is placed on the electronic balance and tared. Reading accumulated amounts of aqueous glycerol solutions off the LSD digital indicator of the electronic balance starts when the rubber bulb from the bottom end of the tube is removed to allow the solution to flow into the beaker.

Accumulated amounts of aqueous glycerol solutions drained from the viscometer at random drain durations are read off the electronic balance, using a stopwatch. After the tank-tube viscometer is rinsed with distilled water for the next experiment, the reservoir tank is dried with paper towels and the vertical tube is dried with acetone.

ANALYSIS OF EXPERIMENTAL DATA

Experimental data of accumulated amounts of an aqueous glycerol solution drained from the reservoir of a tank-tube viscometer at various drain durations are obtained by using an electronic balance and a stopwatch. Several experimental data for aqueous glycerol solutions were obtained under controlled experimental conditions, such as concentrations of water in aqueous glycerol solutions and temperatures of aqueous glycerol solutions.

Each group of students obtained four different viscosity values of aqueous glycerol solutions with four different water contents at a controlled temperature during a 3-hour laboratory session. These experiments provide opportunities for students to learn the effects of water concentrations in aqueous glycerol solutions on viscosity values. Experimental results (performed at three different temperatures by three groups) are gathered and plotted after a complete rotation of this laboratory experiment to each group. These experimental results also provide opportunities for students to learn effects of temperature of aqueous glycerol solutions on viscosity values.

Personal computers, loaded with a FORTRAN program and Microsoft Professional Office, are used to process several series of experimental data of amounts of aqueous glycerol solutions drained from the reservoir at various drain durations. These data are applied to Eqs. (3) and (8) to calculate viscosity values and average velocity values with the aid of the FORTRAN program. Figures 2 through 8 are plotted using Microsoft Excel.

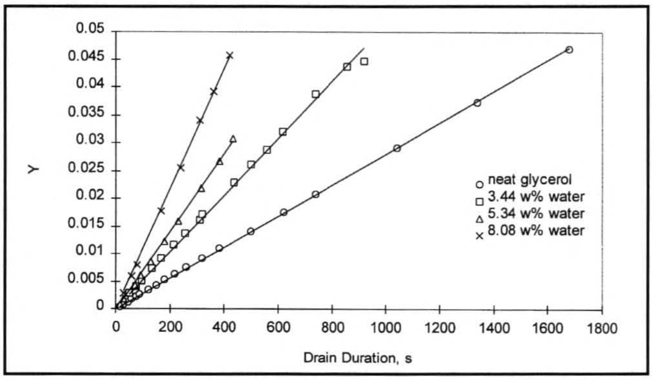

Figure 2. *Values of the left-hand side (LHS) of Eq. (3) at various drain durations and 27°C.*

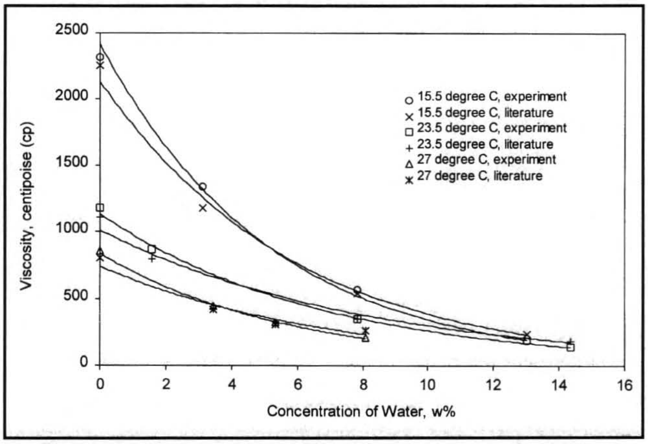

Figure 3. *Comparison of viscosity values of aqueous glycerol solutions at various temperatures from the experiment with those from the literature.*

A slope of the best-fit straight line passing through the origin of the rectangular coordinates is obtained through the linear least-squares method. A viscosity value is calculated by substituting a density value of aqueous glycerol solutions, the diameters of both the reservoir tank and the vertical tube, and the length of the vertical tube into the slope value (see Eq. 4). Consequently, these computations provide an opportunity for students to process experimental data with the aid of personal computers loaded with necessary computer software.

Students also obtain the slope values of the best-fit straight lines, their correlation coefficients, and their viscosity values using their hand calculators, rather than personal computers, when preparing a model calculation section of a laboratory report. The computer-generated data were used to examine whether or not their hand calculations were correct. As a result, they were able to enhance their computational skills. Computations by hand calculators also help students solve the written problems of a final examination since the answers to its problems are obtained with hand calculators.

A detailed derivation of Eqs. (3), (5), and (8) is discussed in the senior transport phenomena class, using the mathematical skills learned from the mathematics courses. Equation (3) is derived assuming that the quasi-steady-state approach and the negligible friction loss due to a sudden contraction between the reservoir tank and the tube are valid. Validity of the quasi-steady-state assumption is discussed in the transport phenomena class and the chemical reaction engineering classes by presenting the experimental results on viscosity of aqueous glycerol solutions. Deviation range of viscosity values obtained from the approximate equation (Eq. 5) from those from Eq. (3) is discussed in the engineering mathematics class by presenting the experimental results of this experiment.

Students prepare a report using a word processor. A typical laboratory report includes several sections, such as an abstract, an introduction, theory, the experimental set-up, experimental procedures, calculations, results, discussion, and conclusions. Figures and tables generated from a laboratory experiment and a schematic diagram on an experimental set-up are also include in the report. Figures and the schematic diagram must be drawn with the aid of computer software, whereas the calculation section should be handwritten.

RESULTS AND DISCUSSION

Left-hand side values of Eq. (4) are obtained with accumulated amounts of an aqueous glycerol solution drained from the reservoir at various drain durations, which are plotted against drain durations (see Figure 2). The slope of the best-fit line is obtained through the linear least-squares method. The viscosity value is calculated from the slope of the best-fit line by substituting the density value of the aqueous glycerol solution as well as the sizes of the viscometer into the right-hand side of Eq. (3). The sizes of the viscometer include the radius of the reservoir and the diameter and the length of the vertical tube.

The slope of this plot increases with increased concentrations of water in the aqueous glycerol solution. This observation shows that the viscosity of aqueous glycerol solutions decreases with increased concentrations of water. A good linear relationship between Y values and drain durations (see Figure 2) may indicate that the assumptions made in developing the viscosity equation for a tank-tube viscometer are valid.

Viscosity values of aqueous glycerol solutions obtained from this experiment are compared with those from the literature at various concentrations and temperatures (see Figure 3). The values obtained from this experiment are in agreement with those from the literature[10] over the range of water concentration and temperature explored, with an average deviation of 3.8% (see Figure 3). These observations also suggest that the validity of the assumptions made in developing the viscosity equation for a tank-tube viscometer are justified.

Viscosity values of aqueous glycerol solutions are plotted against concentrations of water in aqueous glycerol solutions at various temperatures (Figure 3). Viscosity values decrease drastically at relatively low concentrations (below 8 wt %) of water in aqueous glycerol solutions, while viscosity values decrease moderately at relatively high concentrations (above 8 wt %) of water.

Viscosity values are a strong function of temperature at relatively low concentrations (below 8 wt %) of water in aqueous glycerol solutions, whereas viscosity values are a moderate function of temperature at relatively high concentrations (above 8 wt %).

A series of viscosity values of neat glycerol at various temperatures is applied to Eq. (6) to find the Arrhenius relationship between viscosity values and temperatures of aqueous glycerol solutions (see Figure 4). A very good Arrhenius relationship

$$\mu = 1.4618 \times 10^{-8}\, e^{(7439/T)} \qquad (9)$$

is obtained over the temperature range of 15 to 27°C with a correlation coefficient value of 0.99.

Each viscosity value of aqueous glycerol solutions at its random drain duration is calculated using Eq. (3). This viscosity value is plotted against its accumulated amount of aqueous glycerol solution drained from the viscometer at random drain durations (see Figure 5). Viscosity values appear to be independent of accumulated amounts of aqueous glycerol solution drained at various drain durations. These results show that the solutions are Newtonian fluids and reproducibility of viscosity values of aqueous glycerol solutions obtained from the viscosity equation of the tank-tube viscometer appear to be excellent.

Viscosity values of aqueous glycerol solutions calculated with the approximate equation (Eq. 5) are compared with those from Eq. (3). Deviation percentages of viscosity values obtained from Eq. (5) in reference to those from Eq. (3)

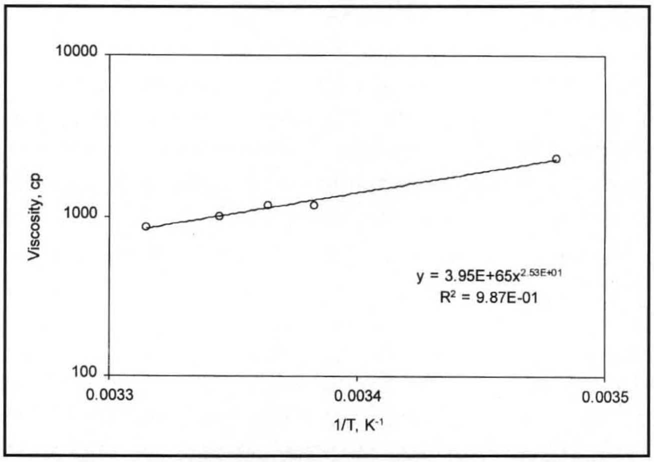

Figure 4. *Effects of temperature on viscosity of neat glycerol.*

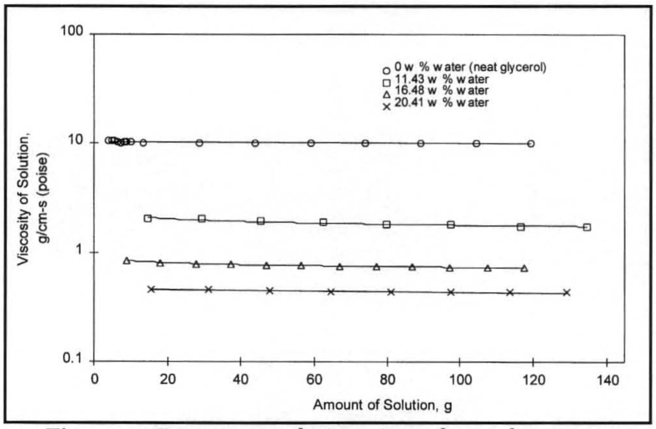

Figure 5. *Experimental viscosity values of aqueous glycerol solutions plotted against accumulated amounts of solution drained at 24.9°C.*

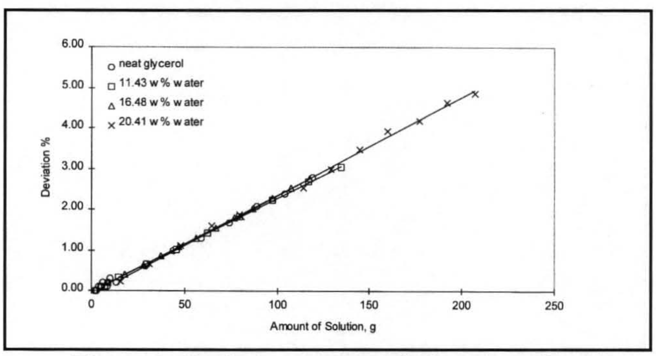

Figure 6. *Deviation percent of viscosity values obtained from Eq. (5) in comparison with those from Eq. (3) at 24.9°C.*

are evaluated at random drain duration. Deviation percentages increase with amounts of aqueous glycerol solutions drained from the tank-tube viscometer (see Figure 6) with a deviation range of 0 to 5%. Deviation percentages appear to be independent of water concentrations in aqueous glycerol solutions over the water concentration range from 0 to 20%. The maximum deviation error is 8.56% when the reservoir tank filled with aqueous glycerol solutions is completely drained.

Average velocities for flow of aqueous glycerol solutions in the vertical tube of the tank-tube viscometer are calculated at 24.9°C, using Eq. (8). Average velocities of aqueous glycerol solutions increase with increased water concentrations (see Figures 7 and 8). The standard deviation of average velocities decreases with decreased water concentrations over the drain duration range of 10 to 250 seconds. The mean values of average velocities and their standard deviations for the 20.41-, the 16.48-, and the 11.43-wt%-water glycerol solution, and the neat glycerol are 10.25±0.17 cm/s, 6.06±0.16 cm/s, 2.49±0.11 cm/s, and 0.468±0.024 cm/s, respectively. These observations may indicate that validity of the quasi steady-state approach is justified for the derivation of the viscosity equation of the tank-tube viscometer.

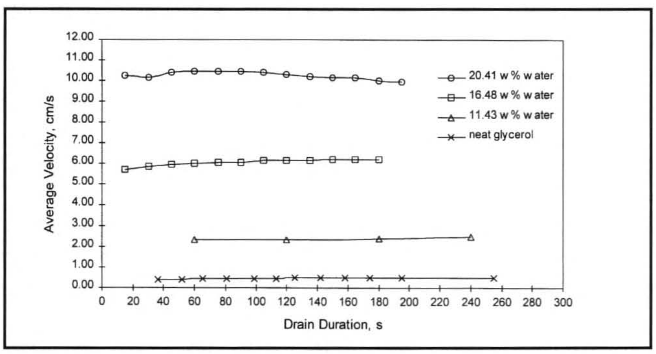

Figure 7. *Average velocity of aqueous glycerol solutions in the vertical tube of the tank-tube viscometer against various drain durations at 24.9°C.*

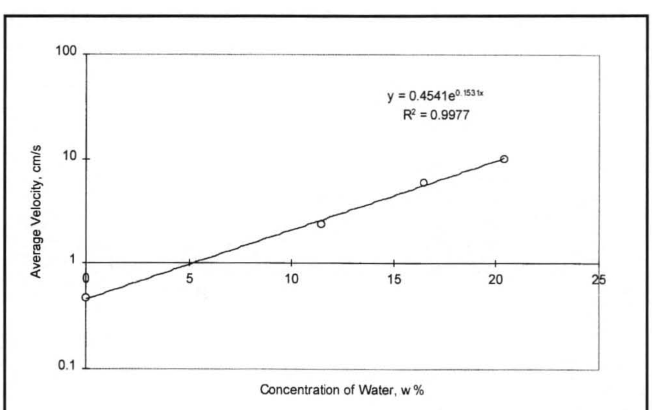

Figure 8. *Average velocity against various water concentrations in aqueous glycerol solutions at 24.9°C.*

CONCLUSIONS

An inexpensive tank-tube viscometer was fabricated to determine viscosity of highly viscous aqueous glycerol solutions, and a viscosity equation of a tank-tube viscometer was developed to calculate the viscosity of the solutions. This experiment introduces chemical engineering students to the concept of viscosity of a Newtonian fluid in fluid mechanics. It also provides an opportunity for the students to carry out experiments for the acquisition of experimental data, to apply their mathematical and computational skills as well as statistical analysis to interpreting experimental data with the aid of computer software, to survey the literature on viscosity, and to write a laboratory report using a word processor.

NOMENCLATURE

- cp centipoise
- g acceleration of gravity
- h level of a liquid in a reservoir tank at a drain duration t
- H initial level of a liquid in a reservoir tank or height of a reservoir tank when the reservoir tank is filled
- L length of a vertical tube
- LHS left-hand side values of Eq. (3)
- m accumulated amount of a liquid drained at t
- R inside radius of a cylindrical reservoir tank
- R_o inside radius of a vertical tube
- t drain duration
- T temperature of aqueous glycerol solutions, K
- v_m average velocity of a fluid flow in a vertical tube
- Y left-hand side value of Eq. (3)
- μ viscosity of aqueous glycerol solutions
- ρ density of aqueous glycerol solutions

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