A “New” Viscosity Instrument and Exercise

Tim Cooley
Purdue University, School of Technology

Introduction

Although mathematical derivations can explain the individual parameters, and many commercial devices are available to accurately measure the behavior, students still seem to have difficulty understanding the physical implications of viscosity; the interaction between shear stress and strain rate. To assist in overcoming this conceptual hurdle, the author designed and built an inexpensive and versatile experimental device and accompanying laboratory exercise for Mechanical Engineering Technology students. It combines the basic aspects of a traditional rotary viscometer with a purely mechanical measurement system that allows students to clearly visualize and experience first-hand the reaction to viscous shear stress on a stationary drum in response to a concentric rotating cup containing the test fluid. This paper describes important design features of the device, constructed from an “antique” Garrard turntable, and the major conceptual topics students must understand in order to complete their laboratory exercise.

The Rotary Viscometer System

The rotary viscometer system combines a Garrard turntable, used in a previous lifetime to experience and enjoy LP albums, with a custom designed support structure containing an adjustable cam-style gravimetric force indicator. The force indicator is based entirely on visible mechanical principles to assist student analysis and understanding of the concept of fluid viscosity. Refer to Figure 1.

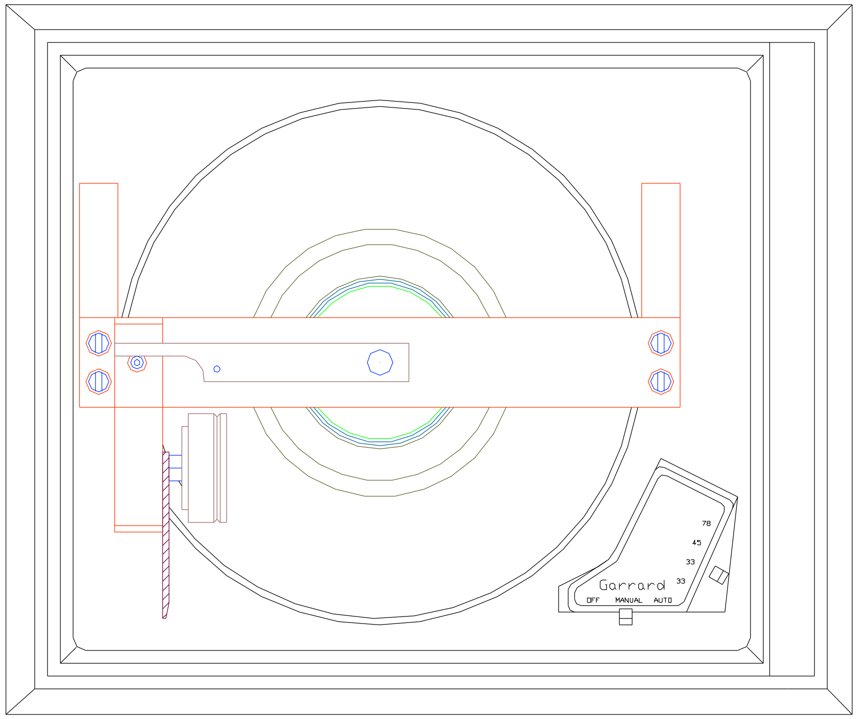

Figure 1 – Garrard Rotary Viscometer (Top View)

The turntable portion of the system, minus its tone arm and changer mechanism, serves as the rotary platform holding the fluid cup. Being from the 1970s era, the platter has speeds of 33, 45, and 78 rpm. With removal of the arm and changer mechanism the base is also large enough to mount a complete support structure for the drum and mechanical force indicator.

In a previous life the fluid cup was a stainless steel 35 mm film developing can. It has an inside diameter of 3.44 inches with a precision of ±0.005 inches from top to bottom. The cup is located at the center of the platter using a sealed white oak base having a 0.001 inch interference fit to insure accuracy about the spindle axis.

The 3.28 inch diameter drum is also made of white oak. It was sanded to a smooth finish with 400-grit paper, sealed, and waxed to provide a perfectly smooth, impervious surface capable of long-term exposure to most water and oil-based liquids. The drum is mounted on a twin-bearing spindle for support against potential vertical (buoyancy) thrust forces without affecting rotational force transmission. To simplify analysis the lower surface of the drum is held above the cup base approximately 0.75 inches to minimize its torque contribution (and simplify mathematical modeling). It is coupled to the spindle with a sleeve nut to facilitate disassembly and removal of the cup and drum without affecting any other components of the system.

The mechanical force measurement system was designed specifically to enhance visualization and tactile investigation by students. It can be explained with simple lever and mechanical-advantage concepts and the sine component of a common gravity-force scale. All components were designed to be large enough to allow students to observe motion and "feel the pull" of the fluid at all times.

This mechanical force measurement system consists of the following components. Refer to Figure 2. Fluid torque on the drum is applied to a 3.38 inch (radius) lever mounted on the drum spindle immediately above its bearings. Torque is then transmitted to a 2.00 inch diameter pulley by a thread made of cotton to minimize stretch. The thread pulley is on a twin-bearing shaft for frictionless rotation, and connected to a balanced weight-arm. The weight-arm has a 5.12 gram weight hook at a radial distance of 3.00 inches. This hook is designed to allow additional weights to be added in the event highly viscous fluids are tested. The support structure for this mechanical system also contains a half-degree precision protractor mounted immediately behind the thread pulley so accurate measurements of its angular position can be determined.

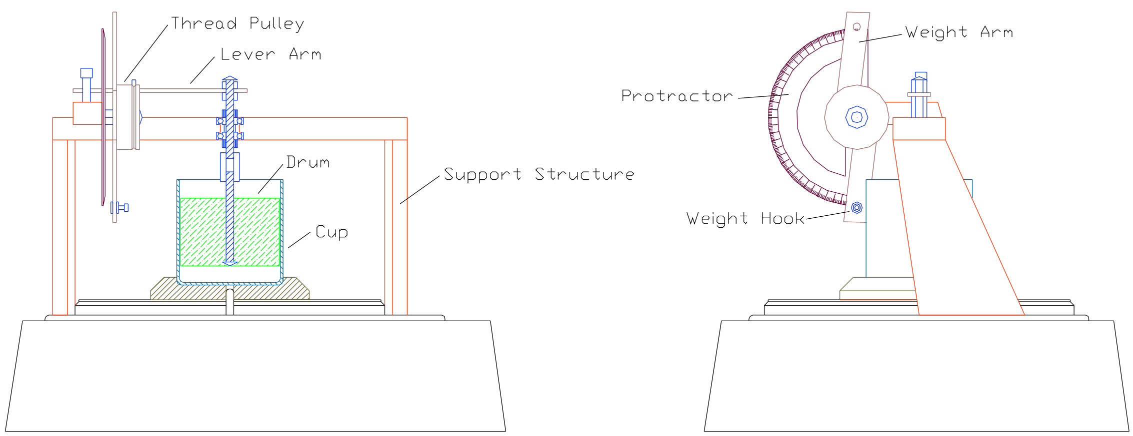

Figure 2 – Garrard Rotary Viscometer

The total cost for the above system was less than $20. If the turntable and film developing can had not already been available, they could probably have been acquired at a local garage sale for an additional $20 or so.

The Laboratory Exercise

The laboratory exercise students use to explore viscosity consists of the following components: 1) lecture examination of the variables associated with viscosity, 2) discussion and analysis of the forces and geometric variables of the rotary viscometer associated with measuring viscosity, 3) research and experimental measurement of a documented fluid such as SAE 30W motor oil, 4) design and completion of a spreadsheet for calculating effective viscosity, and 5) classroom discussion of variables such as temperature and rotational speed on the results obtained.

1) Viscosity

Students at the engineering technology level are not concerned with the process of deriving Newton's equation for viscosity.

For this reason the exercise starts with Newton's equation $\mu = \tau / (dv/dy)$ and progresses to the more-usable form $\mu = (Fy) / (Av)$. The shear stress variable (τ) is reduced to F/A to represent the shear force (drum torque) divided by surface area (drum surface area). This is generally considered acceptable when a concentric-cylinder arrangement is constructed such that the gap space is small compared to drum diameter, as in this case. [(1)] Similarly, the strain rate variable (dv/dy) is reduced to a linear velocity difference (v/y) with respect to the stationary surface, (viscometer drum). Again, the large ratio of drum circumference to gap space (128.8:1) allows us to make this generalization. [(1)]

In this manner Newton's original equation has been reduced from its original differential form to fundamental physical components that can be easily visualized and understood; F is the force applied to the drum surface by the fluid through the action of viscosity, A is the surface area of the drum receiving the force, v is the rotational speed of the cup with respect to the stationary drum, and y is the fluid gap between the drum and the cup. By design (the 0.75" gap), the torque contribution at the base of the drum is minimal compared to sidewall forces and is therefore neglected in the interest of analytical simplicity.

2) Forces & Geometry

At this point the analysis of the viscometer's geometry begins. Through visualizations such as the one below in Figure 3 (and references to a prerequisite Statics class), the following relationships are presented.

$$F = W * (La/Rd) * (R2/R1) * \sin\theta$$

$$A = 2\pi * Rd * Ld$$

$$v = 2\pi * Rc * RPM$$

$$y = (Rc - Rd)$$

The final equation then becomes:

$$\mu = \frac{[W * La * R2 * \sin\theta * (Rc - Rd)]}{[0.65797 * Rd * Rd * Ld * Rc * R1 * RPM]}$$

with units of pounds force seconds per square foot. Students are also given the exercise of units conversion from the above viscometer-dependent units to strengthen their understanding of the universality of viscosity between measurement systems.

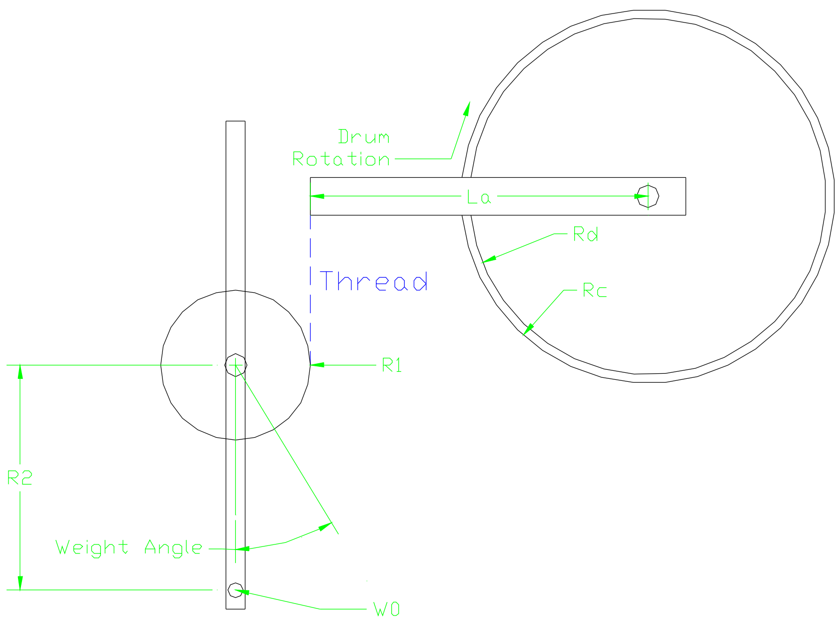

Figure 3 – Viscometer Geometry

3) Test Fluid

For the purpose of calibration a common, published fluid, SAE 30W motor oil is used.(2) It has the following viscosity properties; 0.350 Pa s @ 68F and 0.019 Pa s @ 176F. As the spreadsheet below shows, performance of this design was shown to be quite good. Deviation ranged from -3.3% to -8.5% depending on the speed tested. For the purposes of the student laboratory exercise the performance of the viscometer against this standard is first determined, before other fluids are used.

4) Spreadsheet Analysis

As part of the exercise students are required to design a spreadsheet similar to the one below. See Figure 4. This facilitates a more thorough examination of the effects of dimensional variability on apparent viscosity. In this way students can examine the effects of changes in torque, fluid gap, rotational speed, etcetera on their determination of a fluid's apparent viscosity.

Garrard Rotary Viscometer

DIMENSIONS	VARIABLE	SYMBOL	VALUE	UNIT	VALUE	UNIT
	Cup Radius (inside)	Rc	1.72	inches	0.143	feet
	Drum Radius	Rd	1.64	inches	0.137	feet
	Drum Length	Ld	2.28	inches	0.190	feet
	Lever Arm Radius	La	3.38	inches	0.282	feet
	Thread-wheel Radius	R1	1.00	inches	0.083	feet
	Weight-wheel Radius	R2	3.00	inches	0.250	feet
	Arm Weight (initial)	W0	5.46	grams	0.012	pounds force
PERFORMANCE	Turntable Speed	RPM	33	RPM	33	RPM
	Added Weight	Wa	2.140	grams	0.005	pounds force
	Total Weight	W = W0 + Wa	7.603	grams	0.017	pounds force
	Weight Angle	Theta	40.5	degrees	40.5	degrees
	Turntable Speed	RPM	45	RPM	45	RPM
	Added Weight	Wa	5.120	grams	0.011	pounds force
	Total Weight	W = W0 + Wa	10.583	grams	0.023	pounds force
	Weight Angle	Theta	38.0	degrees	38.0	degrees
	Turntable Speed	RPM	78	RPM	78	RPM
	Added Weight	Wa	10.160	grams	0.022	pounds force
	Total Weight	W = W0 + Wa	15.623	grams	0.034	pounds force
	Weight Angle	Theta	45.0	degrees	45.0	degrees
	Test temperature		77.0	F	77.0	F
PUBLISHED	SAE 30W @ temp	68	0.350	Pa s	0.007310	Lbf s / ft2
VALUES		176	0.019	Pa s	0.00040	Lbf s / ft2
		Temperature constant	k	-0.011716		

RESULTS	Viscosity as tested (lbf s / ft2)	rpm	Measured Viscosity	(Corrected to 68F)	Deviation from Published Value
		33	0.005545	0.007069	-3.3%
		45	0.005366	0.006840	-6.4%
		78	0.005249	0.006691	-8.5%

Figure 4 – Data Spreadsheet

5) Discussion of Variables

Depending on the depth desired, several categories of potential variability can be discussed. Categories typically include a) geometric aspects of the viscometer used, b) temperature effects on apparent viscosity, and c) concepts associated of Newtonian behavior.

a) Within the category of geometric and dimensional aspects of the viscometer, examinations can be undertaken on the effects of cup speed accuracy and precision, the impact of measurement accuracy and precision of cup and drum diameter, and the effect of degree of lever rotation on the force transmission vector. The use of a spreadsheet to examine these variables makes this a straightforward exercise for most students. Through manipulation of each variable students can quickly grasp the influence each variable in the above equation has on the measurement of apparent viscosity.

b) The impact of temperature on viscosity is primarily accomplished through the inclusion of Viscosity Index, and derivation of the temperature constant for the oil in question, as shown in the example spreadsheet above. Students are guided through this analysis in an adjacent lecture and encouraged to include this information in a comparison between published and measured values.

c) The author has found that certain topics within the domain of Newtonian behavior can be effectively included for students with a more theoretical appreciation for the behavior of fluids. The most obvious aspect to discuss is the linear relationship between rotational speed (dv) and torque (τ) Newtonian fluids exhibit. The above apparatus allows students to investigate this behavior at 33, 45 and 78 RPM in order to confirm the linear nature of most commonly used motor oils.

Correlation with Published Information

As noted above, this rotary viscometer device has been shown to have good correlation with published values for SAE 30W motor oil.

Conclusion

The rotary viscometer described above was designed for the expressed purpose of enhancing student understanding of the nature of fluid viscosity. It uses purely mechanical principles to measure viscosity that are easy for mechanical engineering technology students to visualize and understand. It demonstrates the applicability of Newton's original differential equation as well as commonly used simplifications students can readily relate to.

Bibliography

(1) Holman, J. P., Experimental Methods for Engineers, Third Ed., McGraw-Hill Book Company, New York, 1978, page 328

(2) Mott, Robert L., Applied Fluid Mechanics, Fifth Ed., Prentice Hall Inc., New Jersey, 2000, page 30