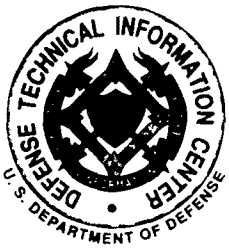

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A NEW ORBITAL BALL TYPE OF VISCOMETER

by Albert Abnett,[1] and Ray Garvey[2]

Abstract: This paper describes a new "orbital ball" type of digital viscometer designed for use in maintenance departments to measure viscosity of lubricants and hydraulics. A steel ball placed in a small cup containing the test oil is caused to rotate around the inner wall of the cup by electromagnetic action. The speed of the ball is measured with a microcomputer and viscosity of the fluid is computed. The operator has the option of easily cleaning the cup, or discarding the cup and ball for little cost. Other advantages are low cost, ruggedness, small sample volume, wide range, high repeatability. Equations governing the operation are developed, and experimental results are presented. Temperature of the fluid is measured and results can be extrapolated to standard conditions.

Key Words: Digital, electromagnet, lubricant, oil, hydraulic, temperature, viscosity, viscometer

INTRODUCTION: A digital viscometer was designed and developed for use in-plant by maintenance mechanics and technicians, enabling them to measure the viscosity of lubricants and hydraulic fluids. The digital viscometer is intended to be used in conjunction with other on-site instruments which measure fluid quality, contamination, and wear debris. The primary purposes of this device are

- to detect misapplication of lubricant (e.g., wrong or mixed oils),
- to detect fuel dilution in liquid fueled engine applications,
- to establish the lubricant viscosity for purposes of trending,
- and setting parameters for further tests which have viscosity dependent characteristics.

Misapplication of lubricants is a common problem that can normally be detected quite easily by measuring viscosity. The problem occurs whenever someone inadvertently selects the wrong lubricant when topping off or refilling a machine. Most often the difference between right and wrong lubricant is simply a matter of viscosity -- ISO grade 32 was used instead of the correct ISO grade 68. This oversight can lead to significant damage when the lubricated machinery reaches design loads at peak operating temperatures.

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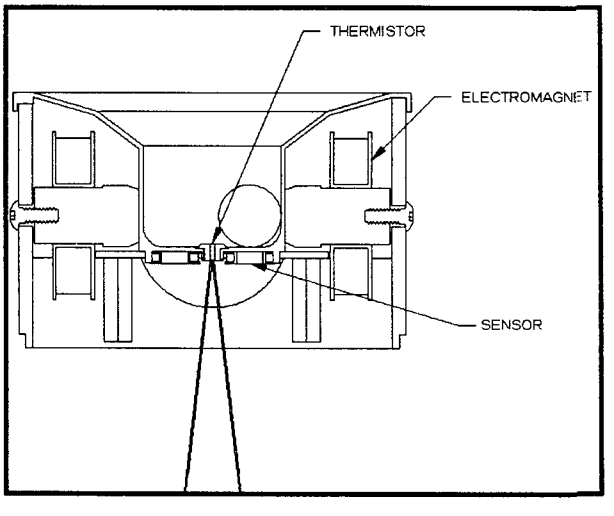
Fuel dilution can lead to rapid and severe wear problems for diesel and gasoline engines. The problem normally originates from a leaky fuel injector. Truck operators have termed this condition "making oil" because the dip stick may show more oil after operation than before. It does not take very much fuel to seriously compromise lubrication. Since lubricant viscosity is the primary factor affected by fuel dilution, viscosity can be a very simple and direct measure of the problem. In a blind test performed by the author with 300 diesel engine oil samples, the 7 samples exhibiting fuel dilution were correctly identified using viscosity measurement. All of those with fuel dilution showed in excess of 10% drop in viscosity as compared to a new oil sample. In all of these cases, the viscosity drop due to fuel dilution overpowered viscosity increases due to other factors such as oxidation or soot loading.

Third on the list of priorities for in-shop viscosity measurement is to measure and trend viscosity. It is well known that viscosity is one of the most important characteristics of a lubricant. As such it is a good idea to measure and trend this parameter, watching for adverse conditions to appear. Unfortunately, just about everything affects viscosity and as such, it becomes quite difficult to determine what, if anything, is wrong with a lubricant simply using viscosity. Temperature is possibly the greatest variable. For example the percent drop in viscosity due to heating from room temperature (20 to 25 C) to machine operating condition can be 70% if the machine operates around 40 C, or it can 95% if the machine operates around 100 C. Some other variables that affect lubricant viscosity include oxidation (typically increases viscosity, although some synthetics may drop in viscosity after chemical oxidation), soot loading (typically increases viscosity), and moisture contamination (this can increase viscosity until saturation occurs, then drop viscosity). For these reasons, viscosity trending can be a valuable confirmation of a suspected problem, detected using another instrument.

Finally, some of the other instruments used for on-site oil analysis suggest viscosity classification to determine flow rates, settling rates, or dilution requirements. In these cases, the digital viscometer is a convenient accessory.

DESCRIPTION: The principle of operation of this new "orbital ball" viscometer is simple and produces results consistent with the falling ball type of manual instrument. A small cup holds a sample of the test fluid. See Figure 1. Electromagnets spaced around the circumference of the cup create a rotating magnetic field, similar to a D.C. motor. A steel ball is immersed in the fluid and its position is reported by proximity sensors acting like the commutator on a motor. As each sensor detects the ball position the "next" magnet is turned on, pulling the



ball around the inner wall of the cup. The speed of this orbital motion is determined by the strength of the magnetic force and the viscosity of the fluid. For a constant field, higher rotation speeds result from lower viscosities. As will be shown, at low Reynolds numbers the motion is independent of extraneous effects and depends only upon fluid viscosity at the viscometer operating temperature.[3] Once it is calibrated, the digital viscometer can be used to measure viscosity of most fluids (10 cp or cSt to 1000 cp or cSt) at ambient temperature. Narrowing from "most fluids" to "most lubricants," the viscosity-temperature equation, ASTM D-341, is used to calculate viscosity values at 40 C.

The actual test volume is 12 ml. Tests typically take approximately 1 minute. Fluid is discarded at the end of a test. The orbital ball viscometer is convenient to use due to its ease of cleaning. The cup can be readily cleaned with a shop rag in the field.

EQUATIONS OF MOTION: The ball will rotate at a velocity such that the force due to the magnetic field is exactly balanced by the viscous drag force. The accepted formula for drag of an object moving through a fluid is:

$$F_d = C_d \bullet A \bullet p \bullet V^2 / 2 \qquad (1)$$

C_d is drag coefficient
A is cross section of ball
p is fluid density
V is relative velocity

The drag coefficient is a function of the Reynolds Number, N_R , and has been found empirically to follow the graph reported by Vennard .[4] Stokes has shown that for Reynolds Numbers less than 1, C_d is a linear function of N_R. In order to arrive at motion equations for a wide range of viscosities, this curve was further divided into three regions: Reynolds Numbers less than 1, 1 to 10, and 10 to 1000. Equations for drag coefficients in each region were derived by simple curve fitting.

Reynolds Number less than 1:

$$C_d = 24 / N_R \qquad (2)$$

Reynolds Number 1 to 10:

$$C_d \approx 24 / N_R^{3/4} \qquad (3)$$

[3]First disclosed in U. S. Patent 5,394,739, issued to Computational Systems, Inc.

[4]Elementary Fluid Mechanics, by Vennard, 2d edition published 1949 by John Wiley, graph of drag coefficients vs Reynolds numbers, page 297

Reynolds Number 10 to 1000:

$$C_d \approx 12 / N_R^{1/2} \quad (4)$$

The Reynolds Number can be calculated from:

$$N_R = pVD/\mu \quad (5)$$

p is fluid density (kg/m^3)
V is velocity (m/s)
D is ball diameter (m)
μ is fluid absolute viscosity (kg/m•sec)

Substituting equations 2 - 5 into equation 1, and plugging in actual dimensions of the 9/16 inch ball, gives three equations of motion for the orbital viscometer:

Reynolds Number less than 1:

$$T_{perRev} = (.135 / F_{mag}) \bullet \mu \quad (6)$$

Reynolds Number 1 to 10:

$$T_{perRev} = (.086 / F_{mag}^{4/5}) \bullet \mu^{3/5} \bullet p^{1/5} \quad (7)$$

Reynolds Number 10 to 1000:

$$T_{perRev} = (.040 / F_{mag}^{2/3}) \bullet \mu^{1/3} \bullet p^{1/3} \quad (8)$$

T_{perRev} is 1/V and is time in seconds for one revolution of ball
F_{mag} is magnetic force in Newtons to overcome drag
μ is viscosity in kg/m•sec (1000 centipoise)
p is fluid density in kg/m^3

Equation 6 shows that the time per revolution is linearly proportional to fluid viscosity. This linear relationship between revolution time and viscosity is born out by experimental data of higher viscosity fluids (from 50 to 5000 centipoise) if the ball velocity is kept low. For one specific design of viscometer with a 1.125" diameter cup, a 9/16 inch ball, and using .9 for fluid density, the Reynolds number is seen to be:

$$N_R = 640 \bullet \text{Revolutions per Second / Centipoise} \quad (9)$$

So for $N_R \leq 1$, Revs per second must be kept slower than Centipoise / 640. This is accomplished by the microprocessor controlling the electromagnet current. However, for low viscosity fluids (< 50 centipoise), it is not practical to run with the very low magnetic force. In this case it is necessary to accept the non-linear relationship, and to plug in fluid density; this is not considered a limitation in a computer controlled instrument.

The magnetic force on the ball is given by:

$$F_{mag} = \beta^2 A / \mu_0 \qquad (10)$$

The magnetic field, β, is determined primarily by exciting current and air gap, and is:

$$\beta = N \bullet I \bullet \mu_0 / l_{air\ gap} \qquad (11)$$

Substituting (11) into (10) and using specific constants for this viscometer:

$$F_{mag} = 32.2 \bullet 10^{-6} (I / l_{air\ gap})^2 \qquad (12)$$

F_{mag} is force, in Newtons
I is magnet current in amperes
$l_{air\ gap}$ is in meters

If all were simple, equation 12 could be substituted into equations 6, 7, or 8, and the revolution time of the ball could be calculated for a given fluid viscosity. There are additional factors that come into play when computing F_{mag}, however. First, the air gap is not constant; because of the geometry the air gap "tends" toward a fixed number because as the ball approaches one pole it is leaving the previous pole, so when between poles the air gap is nearly constant. But the magnets must switch before the ball gets between poles, so it starts with a larger gap. This means that the velocity is not constant but goes through a max and min every quarter revolution. So the average flux is between the extremes. Second, the magnetic flux is diverted from the exciting pole toward the other free poles as well as through the ball, another dilution. Both effects tend to reduce the useful magnetic flux. Only a fraction of the calculated peak energy contributes to ball motion.

Just to get a feel for the equations a specific example will be considered. In one experiment an oil of 525 cp and a magnet current of .65 amps produced a ball revolution time of 3.8 seconds. Equation 9 shows this is a Reynolds number of .32 so equation 6 can be used. The magnetic air gap was seen to vary from about .5 inches to .8 inches. According to 12, this should produce a force excursion of .028 to .072 Nt, or an average of .05 Nt. If all the flux went to ball motion, equation 6 shows a revolution time of:

$$T = (.135/.05)\ (525/1000) = 1.4 \text{ seconds}$$

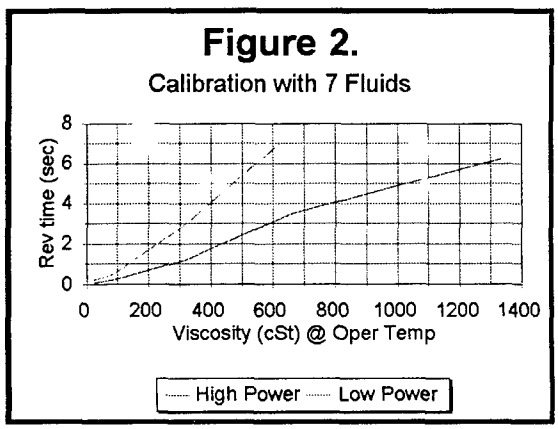
The "wasted" flux is proportional to the square root of the time ratio, or $(1.4/3.8)^{.5} = .61$. So 39% of the magnetic flux is not producing ball-viscous energy. This is a geometry constant so when the viscometer is calibrated with known fluids all later readings will produce correct results. A program in the host computer facilitates calibration.

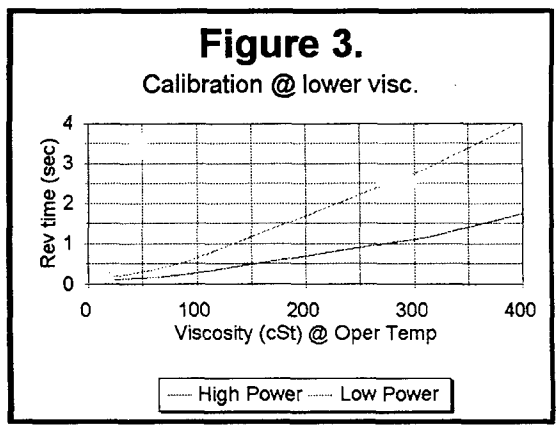
EXTRANEOUS EFFECTS: There are two obvious concerns of variables which might affect ball speed: rolling friction of the ball, and surface roughness effects of fluid flow. An accepted formula for rolling friction[5] is:

$$F_f = k \bullet W / r \qquad (13)$$

W is normal force
r is ball radius
k is coefficient of friction (approx .01 for steel on plastic)

The normal force is the vector sum of the weight of the ball in liquid, and centrifugal force. Because of low speeds and buoyancy of fluid the friction forces are less than 1% of the viscous forces down to 1 cp conditions. It has been shown[1] that fluid flowing through a pipe is unaffected by surface finish of the inner walls of the pipe so long as laminar flow conditions are maintained, i.e. the Reynolds number is kept below 2300. It seems consistent that the same conditions apply to a ball rolling around the wall of a cup filled with a fluid. Thus the speed of the ball's rotation is seen to be independent of surface finish of the cup wall and of the ball itself.





CALIBRATION: A piecewise linear interpolation curve, similar to that shown in Figure 2 and Figure 3, is used to calibrate the digital viscometer. These graphs show the calibration test results for various fluids representing the overall viscosity range. The viscosities shown reflect the actual viscosity at operating or ambient temperature.

VISCOSITY-TEMPERATURE COMPENSATION: Since the primary purpose of the digital viscometer is to measure viscosity for in-plant oil analysis, it is critical that the measurements be translated into units which are convenient for the user. The industry norm for lubricant viscosity measurement is to report results in centistokes (cSt) at 40 C and 100 C. The authors have found that although the digital viscometer physically measures centipoise, if it is calibrated with mineral based fluids in centistokes, the results can be reported in centistokes with reasonable accuracy as shown below. The following methodology has been developed and demonstrated to provide reasonable results in units of cSt at 40 C for a wide range of lubricants.

The temperature of the fluid is measured by means of a thermistor in the bottom of the cup. Using this thermistor, the viscosity of a *known* lubricant can be calculated at any temperature using the following equation from ASTM D-341 can be used down to 2 cSt [4]:

$$\log \log (\mu + .7) = A - B \bullet \log K \qquad (14)$$

μ is in centistokes (cSt)
K is temperature in Kelvin
A and B are constants to be determined

Rearranging terms, the constants for a specific lubricant are given by:

$$A = \log \log (\mu_1 + .7) + B \bullet \log K_1$$
$$B = [\log \log (\mu_2 + .7) - \log \log (\mu_1 + .7)] / [\log K_1 - \log K_2]$$

where K_1, K_2, μ_1, μ_2 are measured values

A convenient method for determining the "A" and "B" constants for a particular type of lubricant is to make use of the 40 C and 100 C viscosity values which are readily available from a lubricant data sheet or fluid analysis report. In this case K_1 and K_2 are 313.16 and 373.16 K respectively, and μ_1 and μ_2 are as reported on the lubricant data sheet or lab oil analysis report.

Once these constants have been determined then the viscosity for the *known* lubricant can be determined at any temperature from equation 15:

$$\mu|_{Temp} = 10^{10^{[A - B \bullet \log(K)]}} - .7 \qquad (15)$$

Equation 15 was used with *known* lubricants to calculate the true viscosity values at operating temperatures as shown in Figures 2 and 3 above. To measure the 40 C viscosity of an *unknown* oil, the following procedure can be used.

First, the operator the 40 C and 100 C viscosity values measured from a new sample of the particular lubricant. If the operator does not input these, then default selection is automatically

applied, sacrificing measurement accuracy while still giving good repeatability. These inputs are then used to compute the "A" and "B" constants for new or "reference" lubricant.

Next, approximately 12 ml of used oil is added to the sample cup and a test is run. The digital viscometer automatically operates through high, then low, power settings. If the viscosity is extremely high causing revolution time to be longer than about 4 seconds per revolution, the viscometer will stop after the high power setting.

The average revolution time for the orbital viscometer is converted directly to viscosity at operating temperature using data from Figures 2 or 3. This measurement is defined as V1

A separate calculation of viscosity at this particular temperature is performed using equation 15. The calculated viscosity for the reference lubricant at actual operating temperature is defined as V2.

Finally, the temperature compensated viscosity measurement is computed using the following equation:

$$V_{40}used = V_{40}reference * (\frac{V1}{V2}) \qquad (16)$$

where,

$V_{40}used$ = 40 C viscosity for used oil

$V_{40}reference$ = 40 C viscosity for reference

V1 = measured viscosity at operating temperature

V2 = reference viscosity at operating temperature

In an alternate method, the orbital viscometer may be used to measure the viscosity at two temperatures. Typically the lower temperature is at ambient and a second higher temperature is achieved through self-heating of the electro-magnets. Then the constants, A and B are calculated and used to calculate viscosity at any desired temperature. For instance, the viscosity at 40 C is computed by:

$$\mu|_{40_C} = 10^{10^{[A - B \bullet \log(313.16)]}} - .7 \qquad (17)$$

TEST RESULTS: Figures 4 and 5 show results using the digital viscometer to measure viscosity for multiple fluids at two different power settings. These 40 C viscosity results were obtained by applying measured revolution time to calibration curve to obtain viscosity at operating (ambient) temperature then compensating this viscosity value to 40 C using equations 15 and 16.

CONCLUSIONS: The "orbital" digital viscometer is designed for field use in measurement of lubricant viscosities. It is capable of identifying misapplication of lubricants, liquid fuel dilution, and viscosity measurement for the purpose of trending. It is also suitable for use with other in-shop oil analyzers which are use viscosity as a basis for setting flow rates, settling rates, and dilution parameters.

The digital viscometer uses a patented orbiting ball to measure viscosity. The speed of the ball is determined by the physical geometry of the cup, by the power settings for the electromagnets, and by the viscosity of the fluid in the sample cup. By controlling the geometry and electromagnet power, viscosity is directly related to ball speed. Testing is done using approximately 12 ml of fluid. Tests take approximately 1 minute.

To convert measured lubricant viscosity at a the test temperature to that which would be measured at 40 C, the standard viscosity-temperature equations from ASTM D-341 are used.

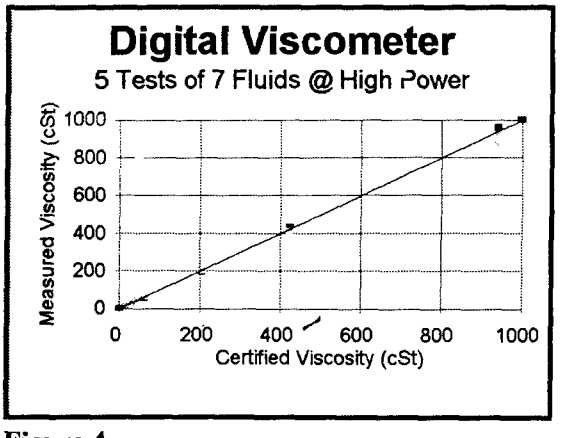


Figure 4

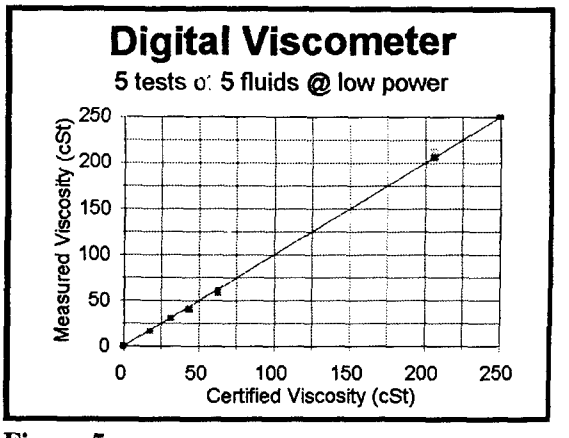


Figure 5

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