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Design, Construction & Performance Test of a Rotational Digital viscometer

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ABSTRACT

A coaxial cylindrical rotational viscometer is such a type in which a solid (inner) cylinder is rotated inside a hollow cylinder which contains test sample of liquid. The torque experienced by the solid cylinder due to viscous effect of the test sample is measured and hence viscosity can be calculated. The design, construction and performance of a coaxial type rotational viscometer have been performed with locally available materials in order to measure the viscosity of different liquids at different temperatures which have been presented in the paper. The inner cylinder has been made from aluminum, rotated by a dc motor and outer cylinder has been fabricated from GI sheet. A temperature controlling bath has been provided in order to maintain a constant temperature in the test sample. The bath has been constructed with GI sheet and having 1 cm insulation of glass wool. An arrangement has been made to show the temperature of sample liquid and its viscosity digitally. The test has been carried out within the temperature range 35 ^oC to 80 ^oC for water, diesel and kerosene. But there is a remarkable deviation of the measured viscosity from the actual. In order to minimize the deviation a correction coefficient '*C*' has been introduced and multiplied with the measured value. With the help of curve fitting, empirical equation of correction coefficient for water, diesel and kerosene has been determined. Finally it can be said that when multiplying the value of *C* from empirical equation with measured value, the deviation from actual viscosity has been greatly reduced. Though equation of correction coefficient for each sample has been developed using data within the range 35 ^oC to 80 ^oC, it can be applied to any temperature since trend of the best fit curve of correction coefficient vs. temperature is very close to the actual curve.

Keywords: Viscometer, Viscosity, Materials, Temperature, Correction Coefficient.

1. Introduction

The Viscometer is a device by which the viscosity of fluids is measured. Rotational viscometer is such a type where a solid shaped body named cylinder or spindle is rotated immersing in the fluid whose viscosity is to be measured. A typical rotational viscometers work on the principle that the torque required to turn an object in a fluid is a function of the viscosity of that fluid. From the measurements of rotational speed of the solid body and the required torque, the viscosity is calculated [1].

Rotational viscometer has several advantages over others. The measurement of fluid viscosity is very important in many practices such as chemistry, chemical industry, and many types of manufacturing practices. So, viscosity should be measured properly and correctly. A typical viscometer is not always preferable in some cases where values with precision and time saving measurement of fluid viscosity are important factors. Hence developments on a typical rotational viscometer are necessary. This will eliminate all sorts of possible errors in the existing viscometer like improper alignment of inner cylinder and driving motor shaft.
The interest to design a digital rotational viscometer with locally available materials that could be used in the measurement of viscosity of different fluids, due to the listed reasons below:

- *Unavailability of the instrument in the local market.*
- *High cost of the instrument for the importation.*
- *Use of local technology and skills for the construction of the device.*

The objectives of this project are:

- *To construct a digital co axial rotational viscometer*

2. Rotational Viscometer and Digitalization of its measuring system.

2.1 Dimensions

In this project, the diameter of the inner cylinder was assumed as 3 cm. Generally height is to be taken as twice the diameter [2].

So height of the inner cylinder was taken as 6 cm. So we can conclude the dimension of the inner cylinder as below.

Diameter of inner cylinder = D_i=3 cm

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Height=h= 6 cm

Diameter of outer cylinder= D_o=6cm

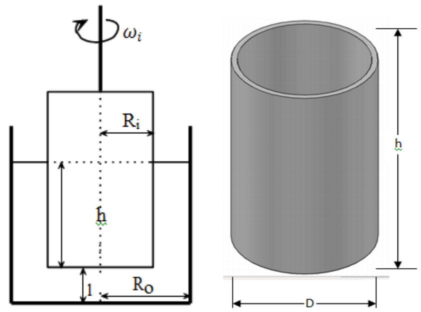


Fig.1 Basic structure of a coaxial cylinder viscometer

2.2 Material:

The material, whose heat transfer capacity is low, can be used to fabricate the temperature bath to reduce heat loss to the outside. In this project two layer GI sheet has been used and insulation has also been provided.

2.3 Insulation:

Insulation is used to reduce heat loss to the outside. In this project, an insulation of 1 cm thickness to all sides of the temperature bath has been provided. Glass Wool has been be used as insulating material since it has lower thermal conductivity and its numerical value is .04 *W/(m.K).*

2.4 Heater:

Two heaters each having capacity of 500W, are used in control temperature bath. Each heater operates at 220-240V.

2.5 Specification of motor:

The specification of motor is listed below

Type: DC

Capacity: 25W

Operating voltage: 6-12V

Operating current: upto 2 amp

Rpm at free load: 1800

2.6 Structural view

The device of the project has been developed in that manner below.

Fig.2 Shaft Coupler

The joint had been made by a screw mechanism. The main shaft is drilled to allow the motor shaft to enter in it and then a screw is set to have rigid coupling.

Fig.3 Adjustable Motor Base

To ensure proper alignment of motor and the main shaft an adjustable motor base is provided. The motor is rigidly attached to the base and the base is movable relative to the frame.

Fig.4 Adjustable Cylinder Base

A new cylinder base was constructed for outer cylinder which is adjustable within the heating bath. By placing the outer cylinder to the appropriate position, the required co-axial alignment of the two cylinders can be set.

Fig.5 Revolution Counter Plate

2.7 Theory and Evaluation for coaxial cylinder viscometer:

When a thin film of a liquid is held between two glass plates, moving the plates relative to each other requires the application of force. The liquid layers that are directly adjacent to each the plate surfaces are held to them by forces of adhesion, and forces of cohesion act between the molecules of the liquid. On movement, a linear velocity gradient is formed within the liquid between the two plates.

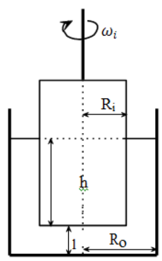


Fig6. Basic structure of a coaxial cylinder viscometer

When a fluid is held between two surfaces and a linear velocity gradient is formed within the fluid then we have according to Newton's law of viscosity from equation [3]

$$\tau = \frac{F}{A} = \mu \frac{dv}{dy}$$

where,

μ = Viscosity

τ = Shear stress

$\frac{dv}{dy}$ = velocity gradient

F = Force required to move liquid layers

A = Area of contact between the plate and the liquid

At low rotational velocity the moment of rotation or torque *T(r)* which is exerted on a cylindrical layer of liquid with a radius r and a height h conforms to the following relationship as a result of the rotation of the inner cylinder [4]

$$T = F \times r$$

$$=> T = \tau A \times r$$

$$=> T = \tau(2\pi rh)r$$

$$=> \tau = \frac{T}{2\tau hr^2} \text{ --------------------------------------(1)}$$

Combining equation (2.1) and (2.4), we have

$$\frac{dv}{dy} = \frac{T}{2\tau\mu hr^2}$$

$$=> dv = \frac{T}{2\tau\mu hr^2}\, dy$$

Replacing $dy = -dr$ since r decreases with the increase of y where 'y' is the distance from outer cylinder

$$=> dv = -\frac{T}{2\tau\mu hr^2}\, dr \text{ ------------------------------(2)}$$

Considering

v_i = Velocity of inner cylinder

v_o = Velocity of outer cylinder = 0 (since it is stationary)

ω_i = Angular Velocity of inner cylinder

ω_o = Angular Velocity of outer cylinder (since it is not rotating)

R_i = Radius of inner cylinder

R_o = Radius of outer cylinder

Integrating equation (2.5) within the limit v_o to v_i and R_o to R_i

$$\int_{v_o}^{v_i} dv = \frac{T}{2\pi\mu h} \int_{R_o}^{R_i} \left(-\frac{dr}{r^2}\right)$$

$$=> v_i - v_o = \frac{T}{2\pi\mu h} \left({}^{1}/_{R_i} - {}^{1}/_{R_o}\right)$$

Here,

$v_0 = 0$ since outer cylinder is stationary

$v_i = \frac{2\pi N_i}{60} \times R_i$ where N_i is rpm of inner cylinder

So we have,

$$=> \frac{2\pi N_i}{60} \times R_i = \frac{T}{2\pi\mu h} \left({}^{1}/_{R_i} - {}^{1}/_{R_o}\right)$$

$$=> \mu = \frac{T \times 60}{4\pi^2 N_i h} \left({}^{1}/_{R_i^2} - {}^{1}/_{R_i R_0}\right) \text{ ----------------(3)}$$

This is the desired equation by which viscosity of a fluid can be measured. The equation is valid for those case in which shear is proportional to velocity gradient.

2.8 End Effects:

The main concern with the coaxial cylinder viscometer is the end effects. The equation has been derived without considering the end effects. End effects are the resistances offered by the test sample at the base and top of the inner cylinder. End effect at the top may be avoided by ensuring that the wetted height will not be higher than the height of the inner cylinder. Several scientists have been working to determine end effect. In this section, various approaches for end effect at the base will be discussed.

Couette and Hatschek modified the design to eliminate end effects by the use of guard rings [5].

Mallock suggested that the inner cylinder can have a concave base in which a bubble of air could be trapped to reduce the drag on the base. However, the difficulty of trapping the same volume of air during each measurement prevented its wide range use [6].

Lindsley and Fisher found that the end effect is negligible in the range of 1 to 150 poise, but the viscosity must be corrected when it is below 1 poise [7].

Lindsley and Fisher, and Highgate and Whorlow suggested that modification of the design may not be adequate to account for the end effects. Therefore experimental measurements and theoretical analysis were proposed by a number of researchers to correct the viscosity for end effects [8].

Kobayashi provided end corrections for several combinations of bob (inner cylinders) and cup(outer cylinder) design. For rotating bob viscometer system, the end correction appears to increase for Reynolds numbers above 10, even for low viscosity. A conical end of the inner cylinder and a wide gap between the inner and outer cylinder give a larger end correction. But wide gap between inner and outer cylinder tends to break linearity of velocity potential in the gap [9].

In this project, end effect will be compensated by carrying out experiment of different sample. Finally a correction coefficient will be provided which will take into account end effect and other instrumental error.

2.8 Digitalization of the Device

The measuring procedure is fully automatic. A microcontroller will control all the steps orderly according to the program. The input values are determined by high precision semiconductor devices (IR LED, temperature Sensor etc.) and feed to the microcontroller. To convert AC current into DC current bridge rectifier and regulator ICs are used. The motor speed is properly measured by IR LED and precisely controlled by microcontroller. To determine fluid temperature, temperature sensor is used and so microcontroller is able to switch off the heater when desired temperature is reached.
The following circuit elements have been used in the project:

1) Resistor
2) Capacitor
3) Diode
4) LED
5) Regulator IC
6) Transistor
7) MOSFET
8) IR Emitter
9) IR Absorber
10) Temperature Sensor
11) PCB

2.8.1 Main Circuit Board

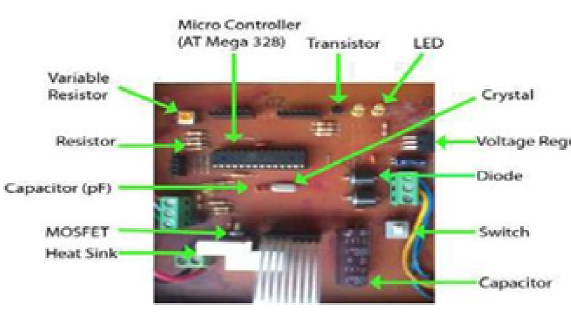
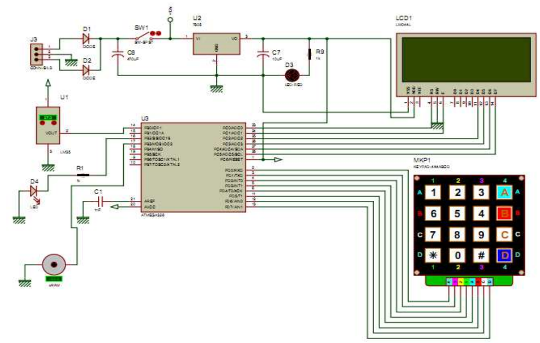


Fig7. A photograph of circuit board

2.8.2 Simulation of the project



2.9 Operation

At first the device will ask for setting (PWM) Pulse Width Modulation. After setting PWM, DC motor will start rotating. The microcontroller circuit will read no load power and the motor rpm and calculate no load torque. The motor will be switched off by a button of keypad then. Sample liquid will be poured into the outer cylinder. The heater will be started . The temperature sensor will show liquid temperature. Then decision will be taken to switch off the heater. Now for the same PWM , the microcontroller will read the motor rpm, power and calculate torque at load condition. The program will calculate the difference between load torque and no load torque and finally show the viscosity of the sample liquid at that temperature.

3. Experimentation

In order to carry out the experimentation of the digital viscometer, viscosity of few samples will be measured by the viscometer. Then the measured viscosity will be compared with the actual viscosity. Finally a correction coefficient will be provided. In order to obtain the actual viscosity, measured viscosity will be multiplied by the correction coefficient.

3.1 Parameter Measured In The Test

Rpm of inner cylinder at load = N_L
Rpm of inner cylinder at no load = N_{NL}
Ampere of the DC input = I in amp
Voltage of the DC input = V in volts

3.2 Equation Used In Calculation

Power at the motor shaft,
P_m = VI in Watt-------------------------------------- (4)

Ampere of the DC input = I
Voltage of the DC input = V

Torque of the motor shaft at no load,

$T_{NL} = \frac{P_m \times 60}{2\pi N_{NL}}$ in Nm---------------------------------- (5)

Torque of the motor shaft at load,

$T_L = \frac{P_m \times 60}{2\pi N_L}$ in Nm----------------------------------- (6)

Torque offered by the test sample,

$T = T_L - T_{NL}$--- (7)

From equation (3), viscosity can be expressed as

$$\mu = \frac{T \times 60}{4\pi^2 N_i h}\left(1/R_i^2 - 1/R_i R_o\right)$$

Here,

$R_i = 1.5\text{ cm} = .015\text{ m}$

$R_o = 3\text{ cm} = .030\text{ m}$

$h = 6\text{ cm} = .06\text{ m}$

$N_i = N_L$

By putting this value in above equation we get,

$\mu = 45031 \times \frac{T}{N_L}$------------------------------------- (8)

3.3 Experimental Value of Viscosity

Table 1 Viscosity of water at different temperatures.

Temperature (°C)	Measured viscosity (Pa.s)	Actual Viscosity (Pa.s)
35	2.32×10^{-3}	0.723×10^{-3}
40	2.1×10^{-3}	0.656×10^{-3}
45	1.85×10^{-3}	0.599×10^{-3}
50	1.62×10^{-3}	0.549×10^{-3}
55	1.43×10^{-3}	0.506×10^{-3}
60	0.89×10^{-3}	0.469×10^{-3}
65	0.76×10^{-3}	0.436×10^{-3}
70	0.53×10^{-3}	0.406×10^{-3}
75	0.42×10^{-3}	0.380×10^{-3}
80	0.26×10^{-3}	0.357×10^{-3}

Table 2 Viscosity of kerosene at differenttemperatures.

Temperature (°C)	Measured viscosity (Pa.s)	Actual Viscosity (Pa.s)
35	6.85×10^{-3}	1.95×10^{-3}
40	6.25×10^{-3}	1.766×10^{-3}
45	6.01×10^{-3}	1.583×10^{-3}
50	5.4×10^{-3}	1.4×10^{-3}
55	5.3×10^{-3}	1.32×10^{-3}
60	4.95×10^{-3}	1.24×10^{-3}
65	4.69×10^{-3}	1.16×10^{-3}
70	4.28×10^{-3}	1.08×10^{-3}
75	3.83×10^{-3}	1×10^{-3}
80	3.45×10^{-3}	0.98×10^{-3}

4. Results

4.1 Presentation of Result

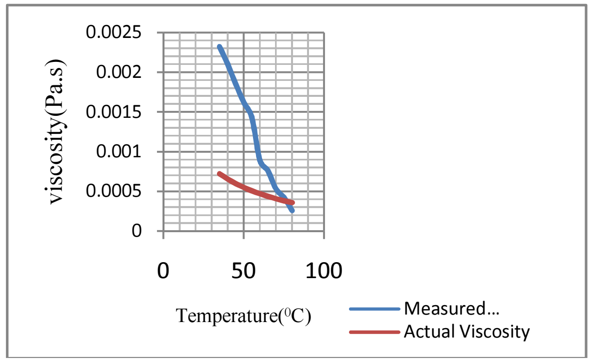


Fig8. Actual Viscosity and Measured Viscosity(Multiplying Correction coefficient) of water at different temperatures.

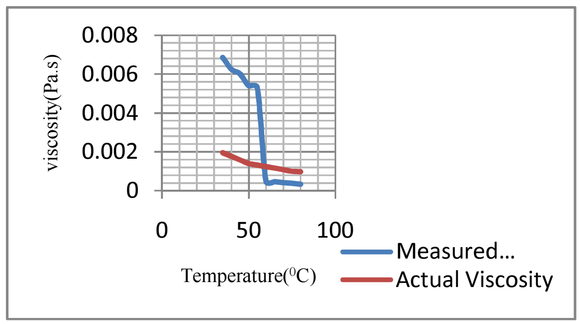


Fig9. Actual Viscosity and Measured(Multiplying Correction coefficient) of kerosene at different temperatures.

4. Discussion

The determination of viscosity of fluid was carried out on two samples at different temperatures.
The samples were water and kerosene and the tests were done in the temperature range 35-80°C.
with each at 5. intervals (i.e. 35 °C,40 °C,45 °C, 50 °C, 55 °C, 60 °C, 65 °C, 70 °C, 75 °C and 80 °C).
First, viscosity was calculated from equation (4.5). In the test, it was seen that this measured viscosity was not conformed to the actual viscosity.This can be corrected by introducing a Correction Coefficient. This is the usual practice what every viscometer manufacturer does. For every viscometer, manufacturer provides a correction coefficient. It has been observed that measured viscosity decreases with the increase of temperature which validates the properties of a liquid.

When water was taken as sample the values of Water viscosity at temperature 35. was measured 2.32×10-3 Pa.s. In comparison of the actual viscosity (0.723×10-3 Pa.s) it gives almost three times. Some other values like at 60. the measured value is doubled of actual value which signifies that temperature has an effect on correction factor.

When kerosene was taken as sample the viscosity measured digitally varies in 3.2 to 4 times of the actual value still signifying the effect of temperature on correction factor. The actual viscosity of kerosene at 55. is 1.32×10-3 Pa.s where the digitally measured value is 5.3×10-3 Pa. s which is almost 4 times.

The correction coefficient. C.=1.8401-0.0698ϴ+0.0008ϴ^2 for water

C=0.4979-0.0084ϴ.+0.00007ϴ^2 for kerosene

were suggested for our experimented value.

5. Conclusion

A coaxial cylindrical rotational viscometer has been developed and digitalized in this project. The provision for the measurement of viscosity of liquids at different constant temperatures has been provided with the instruments. The tests are carried out for water kerosene within the temperature range from 35℃ to 80℃ and observed as follows.

- At 80℃ actual viscosity of water is 0.357×10^{-3} Pa.s where measured viscosity is 0.26×10^{-3} Pa.s So there is a deviation between the actual and measured viscosity. In order to minimize the deviation, a correction coefficient has been introduced and multiplied with the measured value. Using curve fitting, an equation for the correction coefficient has been developed in terms of temperature. The value of C at 80℃ is 1.3761 and multiplying with the measured value finally viscosity of water at 80℃ is 0.3577×10^{-3} Pa.s which is very close to the actual value.
- At 80℃ actual viscosity of kerosene is 0.98×10^{-3} Pa.s where measured viscosity is 3.45×10^{-3}. The value of C at 80℃ is 00.3579 and multiplying with the measured value finally viscosity of kerosene at 80℃ is 1.235×10^{-3} Pa.s which is very close to the actual value.
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NOMENCLATURE

C : Correction coefficient: Helmholtz function, kJ
D_i : Diameter of the inner cylinder
D_o :Inner diameter of the outer cylinder
h : Height of the inner cylinder
I : Moment of Inertia
N_{NL} : rpm of inner cylinder at no load
N_L :rpm of inner cylinder at load
T : Torque
R_i : Radius of the inner cylinder
R_o : Inner radius of the outer cylinder
μ : Dynamic coefficient of Viscosity
τ : Shear stress
ω_i : Angular velocity of the inner cylinder

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