Viscosity of Newtonian and non-Newtonian liquids (rotary viscometer)

Related topics

Shear stress, velocity gradient, internal friction, viscosity, plasticity.

Principle and task

The viscosity of liquids can be determined with a rotation viscometer, in which a motor with variable rotation speed drives a cylinder immersed in the liquid to be investigated with a spiral spring. The viscosity of the liquid generates a moment of rotation at the cylinder which can be measured with the aid of the torsion of the spiral spring and read on a scale.

Equipment

Rotary viscometer		18221.93	1
Support base -PASS-		02005.55	1
Support rod, stainl. steel, 500 mm		02032.00	1
Right angle clamp		37697.00	1
Magn. heating stirrer w. temp.con		35711.93	1
Magn.stirring bar 30mm, cyl.		46299.02	1
Separator f. magnetic bars		35680.03	1
Glass beaker, short, 600 ml		36015.00	3
Glass beaker, tall, 250 ml		36004.00	2
Glass rod, boro 3.3, l = 200 mm, d = 5 mm		40485.03	1
Digital thermometer		07030.00	1
Immersion probe NiCr-Ni, -50/1000C		13615.03	1
Glycerol	250 ml	30084.25	2
Liquid paraffin	250 ml	30180.25	1
Castor oil	250 ml	31799.27	2
Acetone, chem. pure	250 ml	30004.25	3

Fig. 1: Experimental set up: Viscosity of Newtonian and non-Newtonian liquids (rotary viscometer).

Problems

1. Determine the gradient of the rotational velocity as a function of the torsional shearing stress for two Newtonian liquids (glycerine, liquid paraffin).
2. Investigate the temperature dependence of the viscosity of Castor oil and glycerine.
3. Determine the flow curve for a non-Newtonian liquid (chocolate).

Set-up and procedure

The experimental set-up is presented in Fig. 1. The rotary viscometer must be adjusted until it is exactly vertical. Use the adjustment screws to do this: they are located on the base of the support stand. There is a box level on the viscometer which allows one to check the exactness of the set-up's adjustment.

Screw the rotary cylinder on carefully (left-handed threads). Subsequently, lower the viscometer until the surface of the liquid exactly reaches the calibration mark on the rotary body in each case. Stir low viscosity fluids while heating to the desired measuring temperature with the aid of a magnetic stirrer and a magnetic stirring rod to rapidly achieve a uniform heat distribution. The temperature should always be measured in the immediate vicinity of the immersion cylinders. After the experimental temperature has been reached, turn off the heater. The temperature should remain constant for several minutes before measurements are begun, as the immersion cylinder must be in thermal equilibrium with the liquid. When thermal equilibrium has been reached, switch off the magnetic stirrer and determine the viscosity of the liquid. Since the moments of rotation which are measured in this experiment are very small, it is necessary to study the operating instructions of the rotary viscosimeter carefully and to follow them exactly.

After the measurement has been made, always clean the bar of the viscometer and the rotary cylinder carefully with water or acetone.

For glycerine and liquid paraffin, determine the dependence of the moment of rotation on the frequency in the range between 0.1 Hz and 1.0 Hz.

For glycerine and castor oil, determine the dependence of the viscosity on the frequency in the temperature range between approximately 290 K and 350 K. For chocolate, determine the dependence of the moment of rotation of the frequency in the range between 0.1 Hz and 1.0 Hz at a temperature of approximately 303 K.

Other substances which are appropriate for investigation are:

Newtonian substances: oils, ethylene glycol, etc.

Non-Newtonian liquids: paints (structural colour, hammer effect enamel), syrup, lubricants, chocolate spread, etc.

Theory and evaluation

If a liquid is between two plates and a force F acts along the plate in the direction of the x axis, the plate moves with velocity v. For Newtonian liquids the corresponding component of the shearing stress τ

$$\tau = \frac{F}{A} \qquad (1)$$

is linked with the velocity gradient $\frac{dv}{dx}$ as follows:

$$\tau = \eta \frac{dv}{dx} \qquad (2)$$

(η is the viscosity of the liquid and A the area of contact between the plate and the liquid.)

A number of substances (suspensions, emulsions) show a complex correlation between T and the integral velocity gradient D (non-Newtonian liquids). Hysteresis is also possible.

Rotary viscometer

A rotary viscometer consists of an inner and an outer cylinder. The liquid to be investigated is located between them. At low rotational velocity the moment of rotation which is exerted on a cylindrical layer of liquid with a radius rand a height h conforms to the following relationship as a result of the rotation of the outer or inner cylinder:

$$T(r) = \tau \cdot 2\pi r h \cdot r \qquad (3)$$

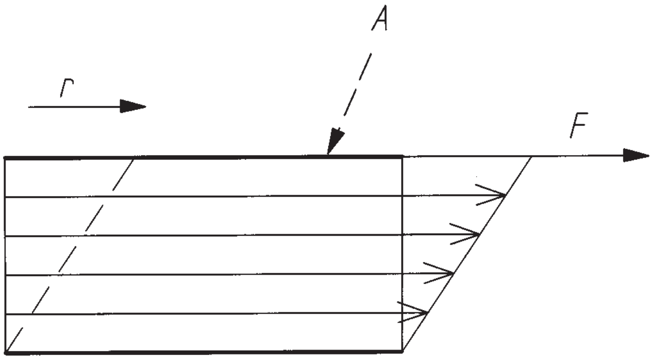
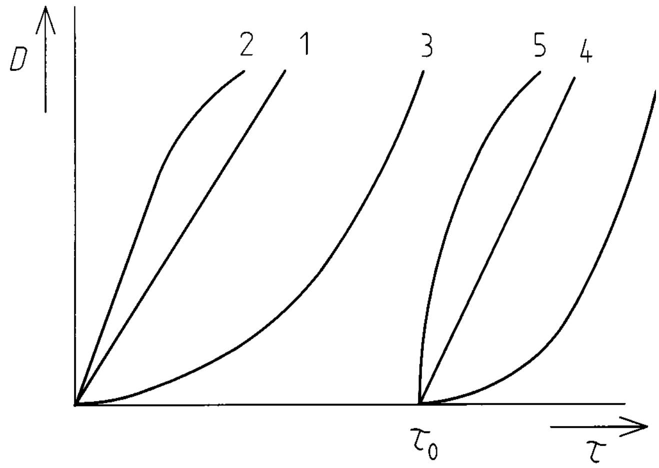


Fig. 2: Velocity gradient and shearing stress.

Fig. 3: Viscous and plastic flow of different substances
1. Newtonian (pure viscous) liquid
2. Dilatant liquid
3. Psuedoplastic liquid
4. Bingham (pure plastic) liquid
5./6. Quasiplastic liquid.



The shearing stress can be expressed by the measurable moment of rotation:

$$\tau(r) = \frac{T}{2\pi r^2 h} \qquad (4)$$

In this case, the velocity gradient D is as follows:

$$D(r) = r\frac{d\omega}{dr} \qquad (5)$$

ω is the angular velocity.

For Newtonian liquids eqn. (2) or eqn. (3) can be substituted in eqn. 1. Integration with the following limiting conditions:

$\omega = 0$ for $r = R_1$

$\omega = f$ for $r = R_2$

(R_1 and R_2 are the radii of the two cylinders) gives the following relationship between the measured moment of rotation and the angular velocity:

$$T = \frac{4\pi R_1^2 R_2^2 h}{R_2^2 - R_1^2}\eta f = C\eta f \qquad (6)$$

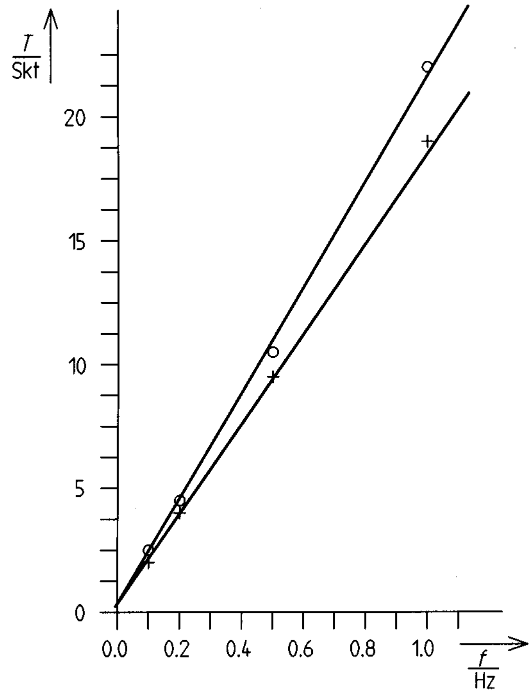
where C is a device constant.

The above expression must be further corrected due to edge effects so that C becomes an empirical constant.

It is customary to use the average shearing stress acting on the surface of the two cylinders (2), which is obtained from the geometric or arithmetic mean of the shearing stresses (τ_{mg} or τ_{ma}).

$$\tau_{ma} = T\frac{R_1^2 + R_2^2}{4\pi h R_1^2 R_2^2} \qquad (7)$$

Fig. 4: Moment of rotation as a function of the frequency for a Newtonian liquid
+ Glycerine
o Liquid paraffin



or

$$\tau_{mg} = T \frac{1}{2 \pi R_1 R_2 h} \qquad (8)$$

Using Expression (4) the following is obtained for D

$$D_{ma} = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2} \cdot f \qquad (9)$$

or

$$D_{mg} = \frac{2 R_1 R_2}{R_2^2 - R_1^2} \cdot f \qquad (10)$$

For non-Newtonian liquids T is no longer directly proportional to f nor is τ proportional to D. There is an approximation formula which describes a relationship between T and τ and between D and f.

For many liquids, the viscosity changes exponentially with the temperature T_{abs}:

$$\eta = A e^{b/T_{abs}} \qquad \text{(Andrage)} \qquad (11)$$

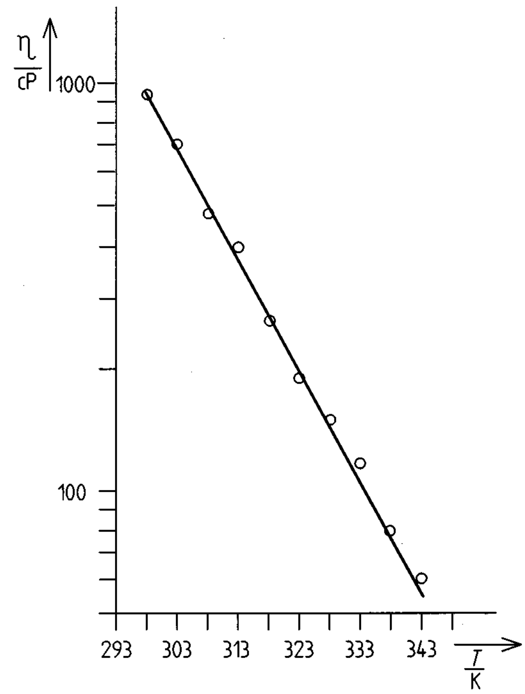
or

$$\log \eta = \frac{T_{abs} + b}{T_{abs} + c} \qquad \text{(Vogel)} \qquad (10)$$

At 303 K the viscosity of glycerine was calculated to be

$$\eta = 680 \text{ cP}$$

Fig. 5: Temperature dependence of the viscosity of glycerine.



Data

Glycerine η_{293} = 1499 cP
η_{303} = 624 cP

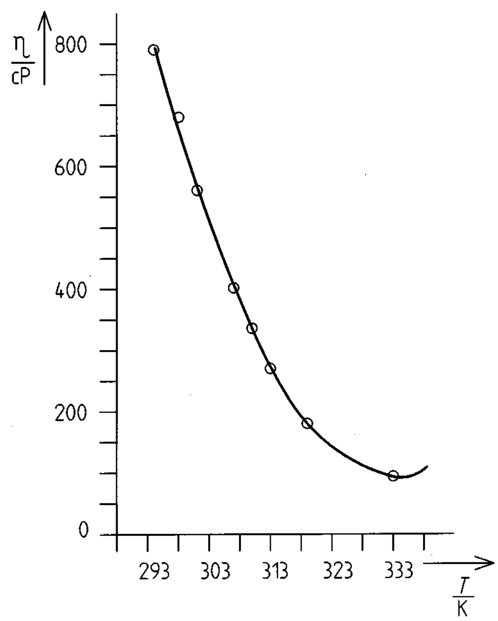


Fig. 6: Temperature dependence of the viscosity of castor oil.

Fig. 7: Moment of rotation as a function of frequency for a non-Newtonian liquid (chocolate at 302 K).