

Characteristics and Analysis for Mechanical Instrumentation Used to Measure Fluid Viscosity

Mohammad Quqazeh, Hasan A. Aldabbas, Monzer M. Krishan, Nabil Musa

Abstract: The task of development of the measurement procedure and the general-purpose control equipment which can allow us to analyze fluid rheological properties and to ascertain the dependence of the stress tensor of the sample on the deformation tensor over a wide range of strain rates is urgent nowadays. At the same time the question of providing the continuous inspection of the product properties under the condition of high precision and measuring automation is a matter of principle.

Keywords: viscosimeter, measuring automation.

M : moment of resistance
M : torque
C : proportionality constant
R, r : radiuses of the external and of the internal cylinder
L : the rotating fluid height

Greek symbols

ω : angular velocity

I. INTRODUCTION

The study of the fluid rheological properties is an important task in many sectors of industry such as manufacturing, automotive, chemical industry, and medicine. Different changes of the rheological properties of the material, products or their components in the process of the equipment functioning or their production can have a significant influence on operating parameters of manufacturing processes, finished product quality, and finished product functioning. At the same time the question of providing the continuous inspection of the product properties under the condition of high precision and measuring automation is a matter of principle.

Viscosity is a property of fluid to offer resistance to the movement of one layer of the fluid over another. The viscosity of some liquid materials at 20°C is shown in Table 1.1. The instruments used to measure the viscosity of a fluid are called viscosimeters. The conditions under which the studies are made and the methods and devices used are determined by the assigned task. In accordance with it the devices used for measuring the rheological properties of materials can be divided into four groups:

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1. Industrial instruments set directly to manufacturing machines which record mass flow properties used for consecutive and continuous measurement of viscosity under industrial conditions.
2. Laboratory instruments for mass assignment to provide an accelerated control for the manufacturing process. Such instruments should be used in technological laboratories of enterprises.
3. Instruments which make possible the conduction of for precision measurement of Newtonian fluids viscosity and for fluid and materials rheological properties studying.
4. Instruments used for investigation purposes, e.g. for measurement of some specific materials properties.

Table 1.1. Dynamic viscosity of some liquids

Liquid	Viscosity, $\mu 10^{-3} \text{Pa} \cdot \text{s}$
Water	1
Engine oil	26 – 35
Vegetable oil	8 – 100
Kefir	400 – 600
Chocolate	800
Kerosene	1.7
Milk	1.8
Normal blood viscosity	4 – 5

Instruments of each group have their own requirements. The instruments used for scientific researches should primarily satisfy such requirements as possibility to change the limits of effective range of the viscosity in the process of one wide range test; possibility to measure viscosity of a large number of different materials; wide operating temperature range; possibility to subject a sample to different loads (shift, distension, oscillatory motion, continuous stress or constant shear rate providing etc). Industrial viscosimeter should satisfy the following main requirements: high reliability; stability and measurement accuracy; possibility of measurement under static pressure; linearity of response and proportionality of the output signal to viscosity; possibility of an easy instrument adjustment to different measurement subrange under the condition of wider general range of measurements; being explosion-proof; standard output; high degree of unification and of standardization of blocks, units and components, low laboriousness and ease of production, use and maintainability; general industrial assignment, i.e. possibility of applying for measurement and control of viscosity of mediums with different properties in a wider range of industrial sectors.

The instruments used for rheological properties studying



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can be subdivided into absolute, relative and conditional according to their physical and mathematical validity. The first group instruments give values of studied characteristics in absolute units. When working with the instrument from the second group, we make their predetermined calibration using reference materials, the characteristics of which according to the conditions of the test are known beforehand. As a result of the experiments relative values are received, and then they can be easily converted to absolute values with regard to calibration charts. The third group instruments make it possible to get some conventional values typical for the instrument. These conditional characteristics can be used for a comparison of different mass and for the study of the influence which technology and other factors can produce on test materials in the production process. Conditional characteristics have only qualitative character and cannot be used for the equipment calculation. The data received with the help of the instruments of the first two groups which are theoretically substantiated can be successfully applied both for the assessment of the material qualitative indexes and for the calculation of the machine production structure and for the choice of optimum process conditions. Rheological test methods and instruments can be also classified as integral which makes it possible to determine the flow additive

effect and as differential used for observing the deformation in each particle of disperse system when it flows in time. What is more, measurement technology instruments are divided into devices with a homogeneous and inhomogeneous stress and strain field. Homogeneous stress field can be obtained for small cross-section samples using one type stress. If not, inhomogeneous stress and strain field is obtained. Dividing rheological instruments into integral and differential is relative as it depends on their purpose and construction. The viscosimeter's Mode of functioning is based upon the dependence of output signals on molecular mechanical properties of the liquid analyzed and also upon the signals' dependence on molecular mechanical phenomena of the controlled liquid. Mechanical viscometers are intended to measure the viscosity and structure-mechanical properties of different fluids. The classification of instruments used to measure the viscosity of fluids according to their measuring method is shown in Figure 1.1.

In modern production there is a wide range of methods and technologies used for rheological properties estimation and controlling based in the majority of cases on indirect measurements. Now let us examine the main well-known measuring methods in detail.

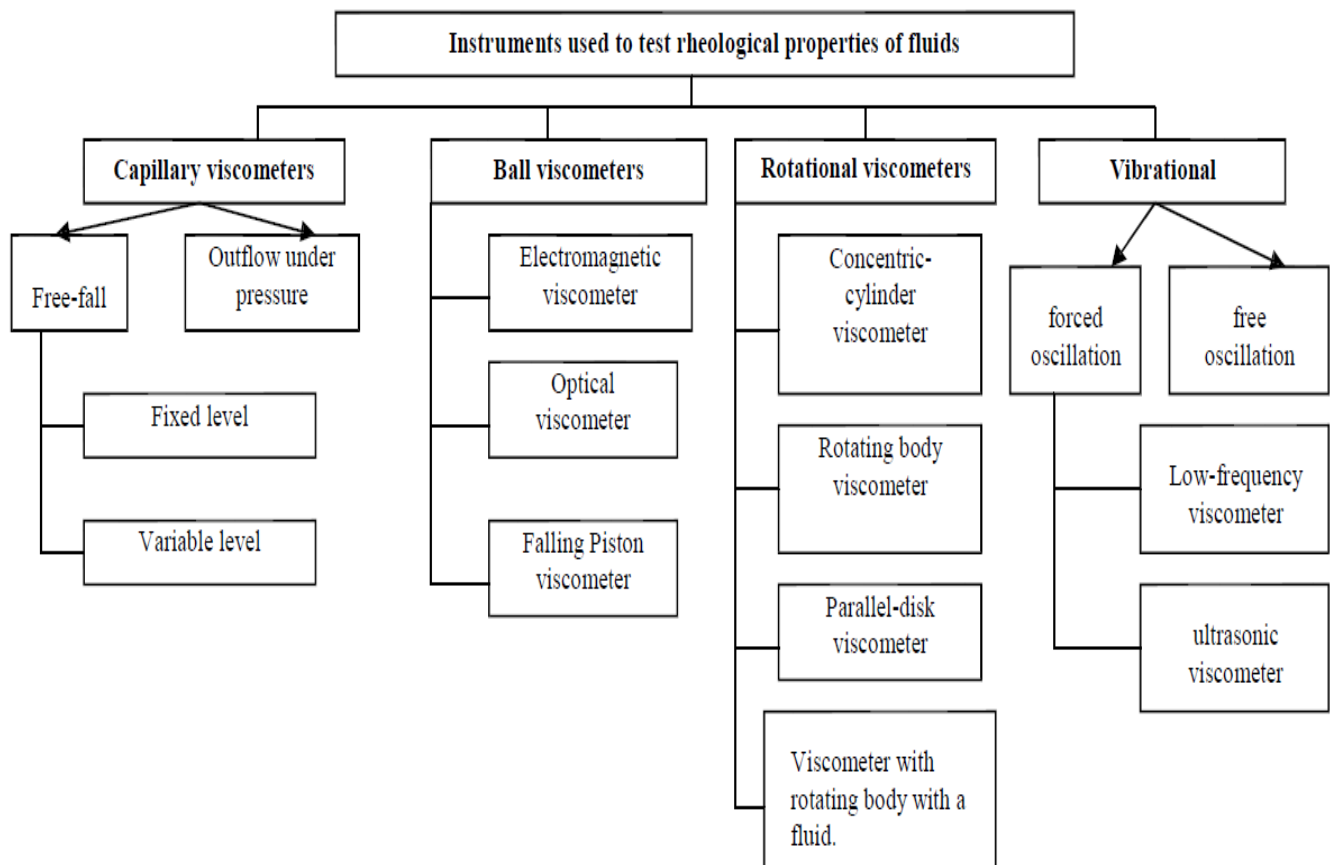


Figure 1.1 Classification of Instruments used to Measure the Rheological Properties of a fluid

Capillary viscometers Capillary viscometer method is one of the oldest and well-studied methods. For the first time this method was used in the time of Newton and Poiseuille (about 1840). Capillary viscometers became widely spread in laboratory practice due to their high precision (errors in measurements: 1-2% for low viscosity, more than 10% for

high viscosity), wide range of measurements and relative simplicity. The instruments of such type have no defects which are common, for example, to rotational viscometers: in the capillary the incoming liquid is

uninterruptedly shifted and the heating generation is removed with the material. Ostwald viscometer and Ubbelohde viscometer are widely spread.

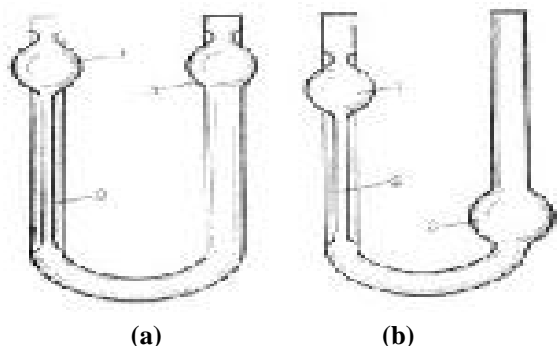


Figure 1.2. Diagram of capillary viscometers: a Ubbelohde viscometer; b) Ostwald viscometer; 1 a vessel used to measure the amount of the fluid which flows through the capillary; 2 the capillary; 3 a vessel for fluid collection.

Capillary viscometers are U-shaped tubes in one arm of which there is a capillary. In Ubbelohde viscometer (Fig. 1.2., a) it is necessary to produce a forced pressure and depression in one of the arms in order to make the fluid outflow; in Ostwald viscometer (Fig. 1.2., b) the fluid flows from one arm to another under the influence of hydrostatic pressure.

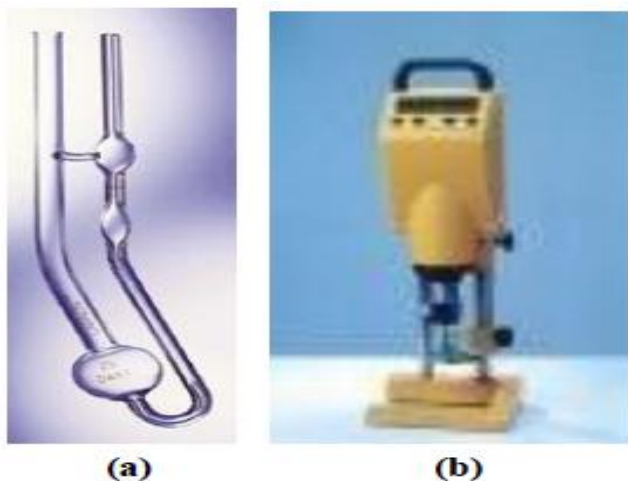


Figure 1.3. Modern constructions of capillary viscometers a. Glass capillary viscometer Cannon-Fenske Routine, Petrotech

b) Automatic capillary flow viscometer LK-10, Partech Modern capillary viscometers are microprocessor control instruments held in a built-in bath with a programmed temperature. Viscometers can work both off-line and with any other laboratory equipment controlled by a special program or PC. Outflow viscometers use is limited due to the following drawbacks of the capillary viscometer method:

- The method can be applied only for laminar flow regimes.
- They are applied basically to measure lower viscosities.
- The necessity to introduce a lot of corrections connected with the peculiarities of the fluid flow in the capillary and its going out from the reservoir, e.g. corrections for hydrostatic pressure of the test material column, taking

into account non-perfect form of the capillary, surface tension etc.

- The method has high inaccuracy when the rheological properties of non-Newtonian high-viscosity fluids are determined.
- Narrow temperature range of measurements.
- Low reliability connected with the possibility of the capillary sealing and clogging.
- The method virtually cannot be used for metal baths due to the difficulties connected with the capillary material choice, production, and means of recording of baths moving in an opaque viscometer.

II. BALL VISCOMETERS

Measuring with the help of the method based on the body moving in a fluid, applied to rolling ball viscometers, is relatively common to manufacturing industry, chemical and petrochemical industry to measure the viscosity of both transparent and nontransparent liquids. The mode of functioning of such viscometers is based on measuring the traverse speed of the sphere of known size and density in the liquid analyzed being its viscosity function. The rolling ball method can be applied for fluids and is based on law for slow stationary flow past a sphere.

The system can be said to use force of gravitational attraction for measuring and as the value of the gravitational attraction is stable, the fall time should only be measured. Such sensors are located in systems with paint venting (bypasses) which is delivered to the measuring module under low pressure. The capacity is 2-3 measuring per minute.

In Figure 1.4. we can see Hoppler viscometer diagram; in the viscometer the fluid is located in an inclined tube, then a ball is put there; there is a small slot between them. The investigated characteristics determination is based upon the determination of the time the ball needs to transverse a definite distance. A drawback of the device is that it is impossible to reproduce the results in 2 successive experiments due to the structure destruction.

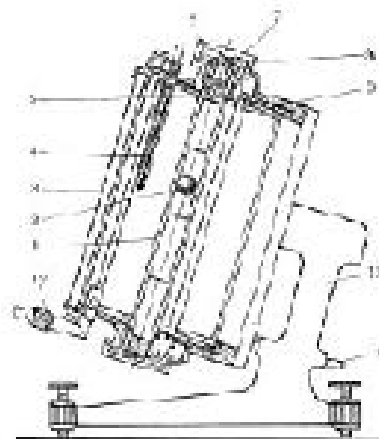


Figure 1.4. Hoppler viscometer

1. glass tube; 2. ball; 3. thermostat liquid cylinder; 4. thermometer; 5. rubber cap for excess liquid removal; 6. union nut; 7. cave for excess liquid; 8. seal ring; 9. cover;

10. base; 11. adjusting screw; 12. water supply choke.

There are several main types of this method.

1. The ball is rolling with a constant speed. The peculiarity is that some time is needed for the ball to roll with a constant speed; when calculating it is necessary to take into account the shocks affecting the sinking ball, moreover, the ball when rolling can diverge from the axial direction.
2. The ball has uniformly accelerated motion. In this case the main calculation difficulty is that it is obligatory to take into account inertia forces subjecting the ball.
3. The ball is drawn from the fluid under a certain load. It is difficult to measure the viscosity of a fluid due to surface tension forces subjecting the thread and fluid elements sticking to the thread accounting which presents some difficulties.
4. At present there are also industrial falling ball viscometers on the basis of the measuring method connected with keeping the ball in a certain position while the analyzed fluid around it is passing relative to it, that can be achieved through the automatic fluid speed control while its viscosity is measured. The limit of effective range of such devices is from 0.5 till 2.5 Pa*s, the relative error is no more 3-4%.

There are two more factors which determine the application of Stocks' Method. They are the ball's mode of rolling and the boundary layer character of the fluid; i.e. the ball is to plunge with a terminal velocity and the boundary layer of the fluid should not touch the vascular walls. These three factors determine the material choice criteria for the unit creating (The ball's radius, distance to the first sensor, the vascular diameter).

Among general drawbacks of the method we can mark out the following:

- The resistance force expression given can be used only with very small values of Reynolds' number;
- Correction for edge effect;

- The sphere passes a long distance until its velocity stabilizes;
- Temperature limit;
- It is difficult to observe the sphere in nontransparent liquids.

Total uncertainty of the method is 6-8%. Viscosity measuring range is 0.001-10 MPa*s.

III. ROTATIONAL VISCOMETERS

Rotational instruments based on measuring moments of resistance or drag torques, given to the detecting element by the fluid analyzed, being the fluid viscosity function, have become widely spread to measure the viscosity of a fluid.

According to some data among all the determined control systems of the viscosity up to 80% we can find rotational viscometers.

In viscometers with rotating cylinders, especially with a small clearance between them, the material flow is close to the shear flow.

Chief companies in the sphere of producing rotational viscometers producing are BROOCKFIELD ENGINEERING, HAAKE, ANTON PAAR, BAKER, BOHLIN, VISCO BASIC etc.

The appearance of some rotational viscometers constructions can be seen in Figure 1.2. While the sphere is rolling in a viscous medium a counter moment appears which is conditioned by the resistance of the medium. If the rotation has a constant velocity, the moment makes torque and is proportional to the dynamic viscosity:

$$M = C \cdot \omega \cdot \mu, \tag{1.1}$$

where M – moment of resistance, H·m;

C – proportionality constant, m³;

ω – angular velocity, rad·s⁻¹.



(A) Haake Viscotester VT6L/R (B) Rotational viscometer VISCO BASIC (C) Analog model of viscometer Brookfield BDRV

Figure 1.5 Examples of modern rotational viscometer constructions.

This method uses a number of types (types of what? the main peculiarity of which is a body (or several bodies) rotating relative to the fluid analyzed. Here are some prototype models which are very popular.

A). the devices with concentric cylinders plunged into the fluid analyzed are widely spread. The viscometer with concentric cylinders (Fig. 1.3. a) has two cylinders with the fluid analyzed between them. Cylinder 2 rotates with a

constant velocity, the fluid passes from electric motor 1 to the stationary rotational motion and gives the torque to internal cylinder 3. For keeping cylinder 3 at rest it has equal in magnitude but opposite in sign moment of force.

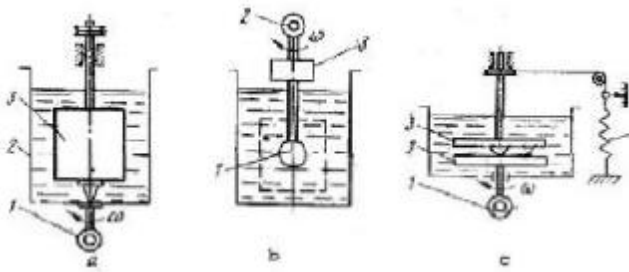


Figure 1.6 Block diagrams of the main types of rotational viscometers

The principle of operation of the viscometer with concentric cylinders (Fig. 1.4.) is the following.

The measured material is located in the clearance of the measuring system. The rotor rotates with a constant predetermined velocity, and the measured fluid due to its viscosity offers resistance to the rotation. The moment M_{xp} of resistance to the rotor rotation is measured.

The built-in microcomputer based on the values of rotational velocity, torque and measuring system geometry (systemic factor) calculates the viscosity, velocity gradient, and shear stress. At the same time either the internal cylinder's rotating with rotating with the internal cylinder fixed is possible. The external cylinder fixed or the external cylinder's

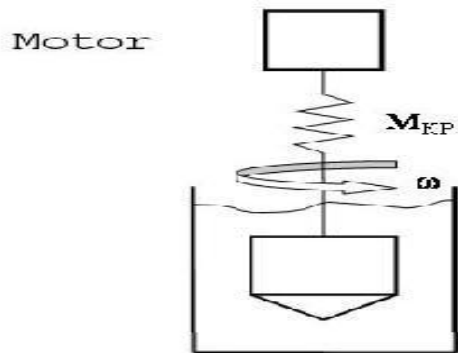


Figure 1.7 Principle of operation of the viscometer with two concentric cylinders

For the laminar flow regime the fluid viscosity and the moment of resistance are connected in the following relation [24]:

$$\mu = \frac{M \cdot (R^2 - r^2)}{4\pi\omega L \cdot R^2 r^2} \quad (1.2)$$

where M – torque, H·m;

R, r – radiuses of the external and of the

internal cylinder, m;

ω – angular velocity, $\text{rad} \cdot \text{s}^{-1}$;

L – the rotating fluid height, m.

The concentric cylinders method is widely used in production for testing both Newtonian fluids and materials of a complex structure. One of the main reasons of the decreased accuracy of this method is difficulties of counting changeable friction force in the viscometer's bearings which leads to the lower limit Restrictions (10 MPa*s), Moreover, the medium's structure disturbance occurs in the clearance.

Certain difficulties can be caused by heating generation of a layer of the tested material which is situated in the narrow annular clearance. Different structure methodical approaches for concentric cylinders viscometers development had been offered for a long period of time; they are still in great demand.

2) The body rotation in a fluid. The viscometer with a rotating body plunged into the fluid (Fig. 1.3, b) is made in the form of a ball-shaped or cylindrical rotor 1 which is actuated by electric motor 2 which has a constant rotating velocity. The value of the resistance of the fluid to the rotor rotation can be measured by angle of torsion of the resilient spring with the help of a special instrument 3 or any other method, e.g. by the current strength the driving motor consumes, by measuring the reactive moment of the stator rotation etc.

The increase of viscosity determination accuracy entails the calculation complications by introducing corrections which depend on the body size. Another problem is difficulties to support the required coincidence of axes of cylinders with a small clearance between them which is necessary for adherence of the condition of homogeneity of the stress field of the shear of the deformed fluid.

3) Rotating disk viscometer (Fig. 1.3, c) has parallel disks 2 and 3 plunges into a fluid. Disk 2 starts steady rotation being actuated by electric motor 1. Due to the viscosity of the fluid analyzed disk 3 gets torque proportional to the fluid viscosity; the disk is balanced with an indicating device with the help of cylindrical calibrated spring 4 or any other way. Constant coefficients for rotational viscometers are determined analytically and more often experimentally on a standard working fluid.

The main technical characteristics of such viscometers are the following:

- The range of measurements of the dynamic viscosity of Newtonian fluids is $0.001 \dots 10^7 \text{ Pa} \cdot \text{s}$.
- Inaccuracy of viscosity measurement is no more + 2.5%.
- Shear rate is under $100 \text{ rad} \cdot \text{s}^{-1}$.
- Specific power consumption is $800 \text{ W/Pa} \cdot \text{s}$.
- Overall sizes: about $700 \times 500 \times 700 \text{ mm}$. The main advantage of rotational viscometers is that rheological properties of mediums are determined with the direct method, not with the indirect method due to the examination of the cross shear flow of the medium in the annular clearance between the cylinders. Main drawbacks of rotational viscometers are:
- Lower limit restrictions of the viscosity measured (as the moment is small big errors appear).
- Errors due to the fact that the fluid flow in the bearing face of the moving cylinder is not counted.
- Fluid viscosity change due to the mechanical effect of the moving parts of the viscometer that can lead to big Errors in their rheological properties determination. Errors in rheological properties determination of the analyzed samples with the help of the rotational method can also appear due to the fact that the dynamic processes which take place while a fluid is flowing in the annular channel of the viscometer under the

centrifugal force field influence occurred during the rotor rotation are not taken into account. Great inaccuracy of measuring often appear in cases of measuring rheological properties of a fluid and other material types over the range of low shear rates. It is connected with technical complexity, impossibility or unreasonableness to receive low rotating frequency of the rotor proceeding from the considerations of keeping the angular velocity stable. This can lead to great inaccuracies when the rheological dependences in rapid response areas are found; it is typical of pseudo plastic fluids.

The most leading-edge technology of the viscosity measuring is using two rotating rotors actuated by independent drives (the so-called birotor principle). The main advantages of the usage of instruments with such a construction are wider range of functionality due to supplying with practically any shear deformation of the material and intensity of centrifugal force fields that makes it possible to measure the rheological properties of a fluid under the conditions close to working conditions.

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