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INTRODUCTORY MEMORANDUM ON THE VISCOSITY OF LIQUIDS AND THE CLASSIFICATION OF LUBRICATING OILS

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**INTRODUCTORY MEMORANDUM ON THE
VISCOSITY OF LIQUIDS AND THE
CLASSIFICATION OF LUBRICATING OILS**

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INTRODUCTORY MEMORANDUM ON THE VISCOSITY OF LIQUIDS AND THE CLASSIFICATION OF LUBRICATING OILS

1. NOTATION

M	molecular weight
m	mole fraction, see Section 5.3.2
p	absolute pressure
T	absolute temperature
u	velocity
v	volume fraction
W	weight
y	co-ordinate normal to direction of local fluid flow
η	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress

2. INTRODUCTION

This Item supersedes Item No.65001 "Introductory memorandum on the viscosity of liquids".

The main aims of the Item are

- (i) to serve as an introduction to a series of Data Items giving information on the viscosity of specific liquids*;
- (ii) to present the factors required to convert viscosity data obtained from the literature into common working units;
- (iii) to discuss the effects of temperature and pressure on viscosity and to indicate how approximate values of viscosity may be estimated, particularly in the absence of direct data;
- (iv) to indicate major sources of numerical data on viscosity;
- (v) to give information on a number of commonly used classification systems for lubricating oils, based on viscosity and the effect of temperature on viscosity.

Consideration of the viscosity of gases and of non-Newtonian liquids (e.g. suspensions, greases and emulsions) is outside the scope of this Memorandum.

* Numerical data for the viscosity of liquids are not included in this Memorandum. The reader who requires quantitative information on the viscosity of a particular liquid should consult Section 7 of this document, where a selected list of sources of viscosity data is given.

3. DEFINITIONS AND DIMENSIONS

3.1 Viscosity

When relative motion takes place between adjacent layers of a fluid, internal shear stresses arise which oppose the motion. This property of a fluid, its resistance to shearing motion through internal stresses, is termed viscosity. In this Section definitions of the basic terms in the field of viscosity are given. Throughout this Memorandum the use of such terms has been rigorously followed to avoid ambiguity.

3.2 Newtonian Fluid

A fluid is described as a Newtonian fluid when the shear stress, arising from or causing motion of the fluid, is directly proportional to the rate of shear (i.e. to the velocity gradient normal to the plane of shear).

3.3 Dynamic Viscosity

For the laminar flow of a Newtonian fluid, the shear stress, τ , and the rate of shear, du/dy , are related by the expression

$$\tau = \eta \frac{du}{dy}, \quad (1)$$

where the constant of proportionality, η , is known as the dynamic viscosity of the fluid. This constant is sometimes referred to as the coefficient of viscosity, absolute viscosity or, simply, viscosity, but these terms should be avoided because ambiguity may arise from their use.

The dynamic viscosity can also be defined by reference to the relative motion of two parallel planes separated by a fluid and unit distance apart. The dynamic viscosity of the fluid is the tangential force on unit area of either of the two planes, when one of the planes moves relative to the other with unit velocity in its own plane. (This definition assumes no slip at the fluid-plane interfaces.)

The dimensions of dynamic viscosity are, when using force units, $[\text{Force}][\text{Time}]/[\text{Length}]^2$, where $[\text{Force}] = [\text{Mass}][\text{Length}]/[\text{Time}]^2$ or, when using mass units, $[\text{Mass}]/[\text{Length}][\text{Time}]$.

3.4 Kinematic Viscosity

In many instances of fluid motion, viscous and inertia forces must be considered simultaneously and often the ratio of the dynamic viscosity, η , to the density, ρ , appears in the study of such motions. This ratio, in which both of the fluid properties are evaluated at the same conditions of temperature and pressure, is known as the kinematic viscosity and is denoted by ν . Thus

$$\nu = \frac{\eta}{\rho}. \quad (2)$$

Kinematic viscosity has the dimensions $[\text{Length}]^2/[\text{Time}]$.

The kinematic viscosity is sometimes called viscosity, but the qualification "kinematic" should always be retained to avoid any confusion with dynamic viscosity.



The gravitational force on a specified volume of a fluid is proportional to its density and, provided the flow is laminar, the force resisting the flow of a fluid through a constriction is approximately proportional to the dynamic viscosity. Hence the time taken for the flow of a specified volume of fluid through a constriction under the influence of gravity is approximately proportional to the ratio of dynamic viscosity to density, i.e. to the kinematic viscosity. A number of standardised industrial viscometers are in use which are based on the application of this principle.

4. UNITS OF MEASUREMENT

4.1 Dynamic Viscosity Units

Units of length, time and mass (or force) are required to express dynamic viscosity.

In the International System (SI) or metre-kilogramme-second (MKS) system the unit is the newton second/metre squared, sometimes called the poiseuille (Pl).

$$1 \text{ SI unit} = 1 \text{ N s/m}^2 = 1 \text{ kilogramme/metre second (1 kg/m s)}.$$

In the centimetre-gramme-second (c.g.s.) system the unit of dynamic viscosity is the poise (P).

$$\begin{aligned} 1 \text{ poise} &= 1 \text{ dyne second/centimetre squared (1 dyn s/cm}^2\text{)} \\ &= 1 \text{ gramme/centimetre second (1 g/cm s)}. \end{aligned}$$

It is customary to work in terms of the centipoise (cP) where

$$\begin{aligned} 1 \text{ cP} &= 10^{-2} \text{ P} \\ &= 10^{-3} \text{ N s/m}^2. \end{aligned}$$

Other systems are based on:

the kilogramme-force (kgf) as the unit of force and the metric technical unit of mass*, or
the poundal (pdl) as the unit of force and the pound (lb) as the unit of mass, or
the pound-force (lbf) as the unit of force and the slug as the unit of mass.

The units of length and time may also be varied. Conversion factors for the commonly used units are given in Table I and the relationships between the newton second/metre squared and other units are given in Table II.

4.2 Kinematic Viscosity Units

Units of length and time are required to express kinematic viscosity.

The unit in the International System is the metre squared/second.

$$1 \text{ SI unit} = 1 \text{ m}^2/\text{s}.$$

In the c.g.s. system the unit of kinematic viscosity is the stokes (St).

$$1 \text{ stokes} = 1 \text{ centimetre squared/second (1 cm}^2/\text{s)}.$$

* The metric technical unit of mass is sometimes called the hyl. 1 hyl = 9.8066 kg.

It is customary to work in terms of the centistokes (cSt).

$$\begin{aligned} 1 \text{ cSt} &= 10^{-2} \text{ St} \\ &= 10^{-6} \text{ m}^2/\text{s}. \end{aligned}$$

Feet or inches may be employed as the units of length and hours may replace seconds. Conversion factors for the commonly used units are given in Table III.

When kinematic viscosity is reported as a number of seconds (e.g. Redwood No.1 seconds, Saybolt Universal seconds) this refers to the time of efflux from a standard viscometer which must, together with the temperature, be specified. Degrees Engler ($^{\circ}\text{E}$) is the ratio of the time of efflux at the temperature of the test from a standard Engler viscometer to the time of efflux of distilled water at 20°C .

Kinematic viscosities, in centistokes, equivalent to degrees Engler and to efflux times for various viscometers are given in Table IV*.

5. THE ESTIMATION OF VISCOSITY

5.1 Effect of Temperature

An increase of temperature causes a rapid decrease in the dynamic and kinematic viscosities, the magnitude of the effect depending on the pressure. Bridgman's⁶ measurements at 30°C and 75°C show that the temperature effect at 10 000 atmospheres can be as much as four times greater than at atmospheric pressure. The effect of change of temperature on viscosity is also dependent on the structure of the molecule of the liquid. In general, liquids with more complex molecules exhibit larger variations of viscosity with temperature¹⁸.

Over the years, many empirical relations have been developed to represent the effect of temperature on the viscosity of liquids and, as the subject has developed, the treatment of oils has become distinct from the treatment of other liquids. Thus for oils the variation of kinematic viscosity with temperature is usually considered whereas for other liquids the dynamic viscosity is usually considered, although there is no fundamental reason for the different methods of handling the two cases.

Of the many relations expressing the variation of dynamic viscosity with temperature, the following combines the qualities of simplicity and reasonable accuracy:

$$\log_{10} \eta = A + \frac{B}{T} \quad (3)$$

A and B are constant for a specific liquid at a particular pressure and, for many liquids, remain valid over a considerable range of absolute temperature.

The values of the constants A and B can always be deduced from two known values of dynamic viscosity, and Equation (3) then allows interpolation and limited extrapolation to be used with confidence.

* This table may be used to convert cSt to Engler, Saybolt or Redwood values, or to convert the last three among themselves. Because of the much higher accuracy of the methods for determining kinematic viscosity in fundamental units, exact conversion to cSt from commercial viscometer measurements is not realistic. So long as it is remembered that the conversion is not exact, the table can be used to obtain approximate equivalents of the other results in cSt, however.



For water, in common with other highly polar* compounds, B is a function of temperature.

Perry³⁴ gives a chart from which values of dynamic viscosity, to within about 10 per cent accuracy, may be quickly assessed for about 150 listed fluids in the range -30°C to $+200^{\circ}\text{C}$.

For most petroleum products the variation of kinematic viscosity with temperature may be determined with very good accuracy when values are known at any two temperatures. To facilitate interpolation and extrapolation to other temperatures two graphical methods have been devised, namely: the "ASTM" (American Society for Testing and Materials) and "Refutas" methods. Standard charts are available†.

Both methods employ a relationship of the form

$$\log_{10} \log_{10} (\nu + a) = n \log_{10} T + b, \quad (4)$$

where n and b are constants for a particular product. For ν in centistokes, the Refutas method uses $a = 0.8$ whereas in the ASTM method a is a function of ν and varies between 0.60 and 0.72.

A relationship similar in form to Equation (4), but expressed in terms of dynamic viscosity, has been found to be applicable for a wide range of liquids although it was originally derived³⁵ for lubricating oils. For η in centipoises and T in degrees Kelvin the relationship is

$$\log_{10} \log_{10} (\eta + 0.631) = n \log_{10} (T - 138) + b, \quad (5)$$

where n and b are constants for a particular liquid.

5.2 Effect of Pressure

The dynamic viscosity of liquids increases with pressure (except for water under certain conditions of pressure at temperatures below about 30°C). The magnitude of the effect appears to depend to a large extent on the complexity of the molecule of the liquid. This is difficult to define quantitatively, but it may be said that the pressure effect increases on proceeding to higher members of a structural series, and that branched-chain isomers** tend to have larger variations with pressure than their normal straight-chain counterparts. Liquids such as lubricating oils, which have complex molecules, have appreciable changes of viscosity under pressure whereas for most liquids the effect is less than one per cent in the range 1-10 atmospheres.

For pressures below 500 atmospheres, the effect of pressure on dynamic viscosity can be expressed approximately by an equation of the type

$$\eta_2 = C(p_2 - p_1) + \eta_1, \quad (6)$$

* A polar compound is one whose molecules tend to orientate under the influence of an applied electric field.

† Seven different ASTM charts are available, covering different ranges of kinematic viscosity and temperature and of varying sizes depending on the above ranges. These charts are obtainable in the United Kingdom from the Institute of Petroleum, 61 New Cavendish Street, London, W1M 8AR. The Refutas Chart is available from Baird and Tatlock, Freshwater Road, Chadwell Heath, Essex. Another chart using a value of $a = 0.8$ is produced by the British Petroleum Company and is available from John Hartley and Partners Ltd, 36 Great James Street, London, W.C.1.

** Isomers are compounds which have the same molecular weight and percentage composition, but have different molecular structures.