1
Fluid properties

1.1 Introduction

The engineer involved in water supply and sanitation deals with a variety of fluids including clean water, sewage and industrial wastewaters, sludges, gases (including air), biogas, chlorine, oxygen etc. Although the physical properties of these fluids and their flow characteristics vary widely, they are all classified as fluids in so far as they flow or continuously deform under the action of any unbalanced external force, no matter how small that force may be. Properties which influence the flow behaviour of all fluids include density, viscosity and surface tension. Where compressibility effects are significant, as is the case in the flow of gases under certain conditions, thermodynamic properties such as specific heat at constant volume or constant temperature, must also be known.

1.2 Viscosity

The viscosity of a fluid is a measure of its resistance to flow under conditions where turbulence is suppressed. A commonly used flow environment for the definition of fluid viscosity is illustrated on Fig 1.1. Consider the deformation of the fluid layer contained between the moving upper plate and the stationary lower plate. Assuming that there is no relative movement between the fluid and the plate surfaces, the movement of the upper plate at a uniform velocity v_p (ms^{-1}) results in a linear velocity gradient across the fluid. The force required to sustain the movement of the top plate can be expressed as a function of the velocity VP, the plate area A, and the distance Y between the plates:

$$F \propto \frac{Av_p}{Y} \qquad (1.1)$$

This proportional relationship may be written as an equation by introducing the correlating coefficient μ:

$$\frac{F}{A} = \mu \frac{v_p}{Y} \qquad (1.2)$$

where μ is the coefficient of **dynamic viscosity**. Equation (1.2) may be written in differential form as follows:

$$\tau = \mu \frac{dv}{dy} \qquad (1.3)$$

The units of μ are Nsm^{-2} i.e. stress/velocity gradient. Thus, in fluid flow, the maintenance of a velocity gradient requires the application of a shear force.

While the concept of velocity gradient is a very useful one in the general description of fluid flow, particularly in contexts such as mixing, flow can also be represented as a rate of shear deformation, as illustrated on the right hand side of Fig 1.1:

$$\frac{dv}{dy} = \frac{d\phi}{dt} \qquad (1.4)$$

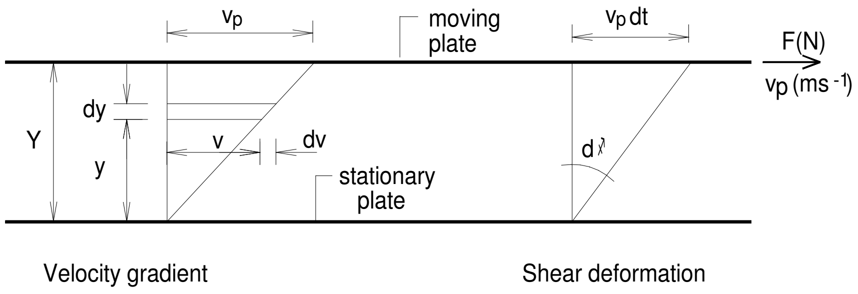

Fig 1.1 Viscosity definition diagram

where φ is the angular rotation of a fluid element subject to shear stress. Thus, the application of a shear stress to a fluid results in a **rate** of shear strain while its application to a solid causes a finite magnitude of strain or deformation.

Those fluids, which exhibit the foregoing deformation behaviour, are known as Newtonian fluids. They include waters, wastewaters and gases.

The magnitude of the coefficient of dynamic viscosity μ for liquids decreases with increase in temperature. Its value for water in the temperature range 0 to 100 °C is presented in Table 1.1.

Table 1.1 Physical properties of water.

Temperature (^oC)	Density (kgm^{-3})	Saturation vapour pressure ($Nm^{-2}x10^{-3}$)	Dynamic viscosity ($Nsm^{-2}x10^{3}$)	Surface tension ($Nm^{-1}x10^{3}$)
0	999.87	0.6107	1.787	75.64
5	999.99	0.8721	1.519	74.92
10	999.73	1.2277	1.307	74.22
15	999.13	1.7049	1.139	73.49
20	998.23	2.3378	1.002	72.75
25	997.07	3.1676	0.890	71.97
30	995.68	4.2433	0.798	71.18
35	994.06	5.6237	0.719	70.37
40	992.25	7.3774	0.653	69.56
45	990.24	9.5848	0.596	68.74
50	988.07	12.3380	0.547	67.91
55	985.73	15.7450	0.504	67.05
60	983.24	19.9240	0.467	66.18
65	980.59	25.0130	0.434	65.29
70	977.81	31.1660	0.404	64.40
75	974.89	38.5530	0.378	63.50
80	971.83	47.3640	0.355	62.60
85	968.65	57.8080	0.334	61.68
90	965.34	70.1120	0.315	60.76
95	961.92	84.5280	0.298	59.84
100	958.38	101.3250	0.282	58.90

(Source: CRC handbook of Chemistry and Physics, 67th edn, 1987)

The prevailing pressure has only a very minor influence on the dynamic viscosity value for water. At temperatures below 30 °C the dynamic viscosity of water slightly decreases with increase in pressure, reaching a minimum value and thereafter increasing with further increase in applied pressure. This minimum disappears at temperatures above 30 °C. The dynamic viscosity of gases increases with increase in temperature. Maitland and Smith (1972) proposed the following empirical correlation of gas viscosity with temperature for 11 common gases:

$$\ln\left(\frac{\mu}{S}\right) = A \ln \Theta + \frac{B}{\Theta} + \frac{C}{\Theta^2} + D \tag{1.5}$$

where μ is the dynamic viscosity (Nsm^{-2}) at temperature Θ (K), S is the dynamic viscosity (Nsm^{-2}) at a standard temperature of 293.2 K; and A, B, C and D are coefficients determined from a least-squares regression analysis. Note that Kelvin temperature K = °C + 273.1.

Recommended values for the foregoing coefficients for air, oxygen, nitrogen, methane and carbon dioxide are presented in Table 1.2.

Table 1.2
Dynamic viscosity coefficients for gases

Gas	A	B	C	D	S (Nsm^{-2}x10^{7})
Air	0.63404	-45.6380	380.87	-3.4500	182.0
Oxygen	0.52662	-97.5893	2650.70	-2.6892	203.2
Methane	0.54188	-127.5700	4700.80	-2.6952	109.3
Carbon dioxide	0.44037	-288.4000	19312.00	-1.7418	146.7

The linear correlation of shear stress and velocity gradient, characteristic of Newtonian fluids, prevails only in the absence of turbulence in the flow field. This type of flow environment is described as **laminar** flow and, for Newtonian fluids, is confined to situations where random bulk fluid movement is suppressed as, for example, flow in small bore pipes or through porous media or very close to solid boundaries. Where turbulence exists in the flow, however, the shear resistance is greatly increased and the associated shear stress can, for convenience, be correlated to the velocity gradient by an expression of the same form as that used to define dynamic viscosity:

$$\tau = \varepsilon \frac{dv}{dy} \tag{1.6}$$

where ε is the coefficient of eddy viscosity and is a characteristic of the flow, as distinct from μ which is a property of the fluid. The coefficient of eddy viscosity may be regarded as a coefficient of momentum transfer along the velocity gradient; its magnitude is dependent on the velocity gradient, shear stress, and other factors and is invariably much greater than the dynamic viscosity, μ.

Unlike water and gases, sludges, particularly at high concentration, typically exhibit non-Newtonian behaviour. Such behaviour, as illustrated in Fig 1.2, is characterised by a non-linear relation of shear stress and rate of shear strain and, in some fluids, by the existence of a yield stress which must be exceeded for flow to take place. The shear stress/rate of shear strain relation may be expressed in the form:

$$\tau = \tau_y + K\left(\frac{dv}{dy}\right)^n \tag{1.7}$$

where τ_y is the yield stress (Nm^{-2}), K is a consistency coefficient and n is a consistency index. These flow parameters are further discussed in Chapter 2. Newtonian and non-Newtonian flow behaviours are illustrated on Fig 1.2.

The ratio of fluid viscosity to fluid density, generally known as the kinematic viscosity, is a frequently encountered flow parameter in hydraulic computations:

$$\nu = \frac{\mu}{\rho} \tag{1.8}$$

where ν is the kinematic viscosity (m^2s^{-1}).

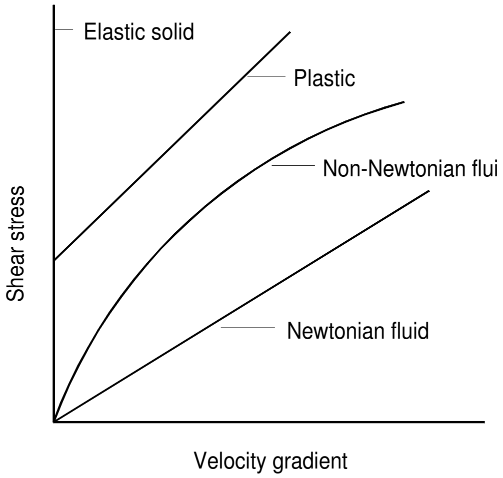

Fig 1.2 Fluid flow classification

1.3 Surface tension

The interfacial liquid at the boundary between a liquid and a gas behaves rather like a membrane, which possesses tensile strength. This membrane-like behaviour can be quantified as a strain energy per unit area i.e. Nm per m^2 or force per unit length (Nm^{-1}), denoted by the symbol σ. The surface tension influence is generally very small in most fluid flow problems encountered by civil engineers. However, in certain applications such as hydraulic modelling, where the model flow depth may be very small, the surface tension influence may be relatively of much greater significance in the model than in the prototype and thus distort model flow behaviour. Surface tension is also responsible for the capillary rise above the phreatic surface in fine-grained saturated soils and porous construction materials. When a liquid surface is penetrated by a solid object, surface tension causes the liquid surface in contact with the solid to be raised above the general liquid surface level in the case where the liquid "wets" the solid surface. On the other hand where the liquid does not wet the solid surface, the liquid surface in contact with the solid is depressed. The surface tension of water decreases with increase in temperature, as the data presented in Table 1.1 indicate.

1.4 Vapour pressure

When evaporation takes place from the surface of a liquid within an enclosed space or vessel, the partial pressure created by the vapour molecules is called vapour pressure. Liquid may, at any temperature, is considered to be in equilibrium with its own vapour when the rate of molecular transport through the separating gas-liquid interface is the same in both directions. The absolute pressure corresponding to this concentration of gas molecules is defined as the saturation vapour pressure of the liquid. The saturation vapour pressure of every liquid increases with increase in temperature. The temperature at which it reaches a value of 1 atm absolute is the boiling point, which for water is 100 ^oC. Data on the saturation vapour pressure of water in the temperature range 0 to 100 ^oC are presented in Table 1.1.

1.5 Thermodynamic properties

Thermodynamic properties are of particular relevance to gases. The equation of state for the so-called perfect gas is usually written in its general form as follows:

$$PV = mR_u\Theta \qquad (1.9)$$

where P is the absolute pressure (Nm^{-2}), V is the gas volume (m^3), m is the mass of gas (mole), R_u is the universal gas constant (J $mole^{-1}K^{-1}$) and Θ is the absolute temperature (K).

The perfect gas has an Ru-value of 8.3144 J $mole^{-1}K^{-1}$. The variation from this value for real gases is found to be less than 3 per cent (Daugherty and Ingersoll, 1954).

Changing from mole to kg, equation (1.9) may be written for individual gases in the form:

$$\frac{P}{\rho} = R\Theta \qquad (1.10)$$

where ρ is the gas density (kgm^{-3}) and R is the specific gas constant (J $kg^{-1}K^{-1}$), related to R_u as follows:

$$R = \frac{1000R_u}{w} \qquad (1.11)$$

where w is the molecular weight.

The constant R can be shown to be the difference between the specific heat capacity of a gas at constant pressure (C_p) and its specific heat capacity at constant volume (C_v). Values for these thermodynamic properties for a number of gases are given in Table 1.3.

Table 1.3
Thermodynamic properties of gases
(25 °C and 1 atm)

Gas	C_p ($Jkg^{-1}K^{-1}$)	C_p/C_v	R ($Jkg^{-1}K^{-1}$)
Air	1005.0	1.40	287.1
Oxygen	920.0	1.40	262.9
Nitrogen	1040.0	1.40	297.1
Methane	2260.0	1.31	534.8
Carbon dioxide	876.0	1.30	202.2

Source: CRC handbook of Tables for Applied Engineering Science, 2nd edn, 1976

The relationships embodied in eqns (1.9) and (1.10) may also be expressed in the forms:

$$PV^{\gamma} = \text{constant} \qquad (1.12)$$

Or

$$\frac{P}{\rho^{\gamma}} = \text{constant} \qquad (1.13)$$

where V is the gas volume (m^3) and γ is the so-called polytropic exponent. The value of γ depends on the process by which the gas undergoes volume change. For adiabatic processes (zero internal energy loss), γ is equal to the specific heat ratio C_p/C_v, whereas for isothermal processes (zero temperature change), γ is equal to unity. Thus, in real situations, the value of γ lies within the range 1.0 to C_p/C_v.

1.6 Compressibility

Compressibility may be defined as the susceptibility of a material to volumetric change on the application of pressure. The coefficient of compressibility K is defined as follows:

$$K = \frac{-\Delta P}{\Delta V / V} \qquad (1.14)$$

where K is the bulk modulus or coefficient of compressibility (Nm^{-2}), ΔP is the change in pressure (Nm^{-2}), ΔV is the change in volume (m^3) of the original volume V (m^3).

Liquids are highly incompressible; for example, the K-value for water at 10 °C is about 21.1 x 10^8 Nm^{-2}. Its value increases marginally with pressure and temperature up to a temperature of about 50 °C. Above 50 °C, there is a slight decrease with increase in temperature.

Gases are relatively highly compressible, their compressibility depending on temperature and pressure. The coefficient of compressibility K for a gas is given by the relation:

$$K = P\gamma \qquad ` \qquad (1.16)$$

where γ is the polytropic gas volume exponent, as previously defined and P is the absolute gas pressure in Nm^{-2}. Thus, gas compressibility decreases linearly with increase in pressure. Fluid compressibility has a key influence on the speed of transmission of elastic waves through fluid and is therefore an important fluid property in the analysis of unsteady flow phenomena such as waterhammer. Compressibility effects may also have to be considered in the steady flow of gases at high velocity.

1.7 Density

The density of a substance is defined as its mass per unit volume (kg m^{-3}). Temperature and pressure influence density. As may be deduced from the preceding data on fluid compressibility, liquids are highly incompressible and thus exhibit negligible change in density with change in pressure. Change in liquid density with variation in temperature is also slight. Density data for water in the temperature range 0 to 100°C is presented in Table 1.1. Gases, on the other hand, are highly compressible and hence subject to significant density change with changing temperature and pressure. Equation (1.10) may be used to compute gas density as a function of temperature and pressure.

References

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