FLUID FLOW

for Chemical Engineers

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Preface

This book is a basic undergraduate text in fluid flow. It is a summary of the fluid flow content of the chemical engineering degree course at the University of Salford. The book is written throughout in SI units and is divided into two parts. Part 1 is a conventional treatment of fluid flow and contains a minimum of mathematics. Part 1 is suitable for use in Higher National Certificate and Higher National Diploma courses in chemical engineering. Part 2 makes use of vector analysis and more sophisticated mathematics. Part 2 deals with the flow of Newtonian liquids with reference to rectangular and cylindrical coordinate systems. The treatment of non-Newtonian flow in rectangular and cylindrical coordinate systems requires the use of tensors. Tensors are only used in Master's degree courses at Salford and are consequently omitted from this text. It can readily be seen that the transport phenomena approach used in Part 2 is far more powerful than the largely empirical approach used in Part 1. Nevertheless a clear understanding of physical boundary conditions and the engineering aspects of a problem are essential if the transport phenomena approach is to be used effectively. Parts 1 and 2 together are suitable for use in honours degree courses in chemical engineering. Part 1 and much of Part 2 are also suitable for use in ordinary degree courses in chemical engineering.

The material in this book is also used in the one week refresher courses in fluid mechanics, which are periodically run by the Department of Chemical Engineering at the University of Salford, for the Institution of Chemical Engineers. It is hoped that the book will also be useful for chemists, mechanical engineers and other technical people concerned with the flow of fluids.

The author believes that there is no substitute for wide reading in a subject. However, this can be done more effectively with reference to a basic framework. This book, which is largely a collection of lecture notes with the emphasis on brevity, is designed to provide such a framework.

The author would like to express his gratitude to Miss Barbara Buckley for typing the manuscript and to his colleague, Mr F. A. Watson, for checking the material and reworking the calculations. He also greatly appreciates the valuable help given by Mr J. Swolkein and Mr P. Diggory with the drawings.

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Nomenclature

a	blade width, m
A	area, m^2
b	width, m
C	Chezy coefficient $\sqrt{g/j_f}$, $\mathrm{m}^{\frac{1}{2}}/\mathrm{s}$
C	constant, usually dimensionless
C	solute concentration, $\mathrm{kg/m}^3$
C_d	discharge or drag coefficient, dimensionless
C_p	heat capacity per unit mass at constant pressure, J/(kg K)
C_v	heat capacity per unit mass at constant volume, J/(kg K)
d	diameter, m
d_{e_p}	equivalent diameter of annulus $D_i - d$ for pressure drop, m
d_{e_q}	equivalent diameter of annulus $(D_i^2 - d_0^2)/d_0$ for heat transfer, m
D	diameter, m
$\dfrac{D}{Dt}$	substantial time derivative, $\dfrac{\partial}{\partial t} + v_x \dfrac{\partial}{\partial x} + v_y \dfrac{\partial}{\partial y} + v_z \dfrac{\partial}{\partial z}$ in Cartesian coordinates, s^{-1}
E	efficiency function $\left(\dfrac{1}{P_A/V}\right)\left(\dfrac{1}{t}\right)$, m^3/J
E	total energy per unit mass, J/kg or $\mathrm{m}^2/\mathrm{s}^2$
f	Fanning friction factor, dimensionless
F	energy per unit mass required to overcome friction, J/kg
F	force, N
g	gravitational acceleration, 9.81 $\mathrm{m/s}^2$
G	mass flow rate, $\mathrm{kg/(s\ m^2)}$
h	head, m
H	height, m
H	enthalpy per unit mass, J/kg
$\mathbf{i}$	unit vector, dimensionless
I_T	tank turnovers per unit time in equation (5.2–6), s^{-1}
$\mathbf{j}$	unit vector, dimensionless
j_f	friction factor, dimensionless
k	exponent in equation (6.2–8), dimensionless
k	proportionality constant in equation (5.1–1), dimensionless
$\mathbf{k}$	unit vector, dimensionless

K	consistency coefficient, $\mathrm{kg/(s^{2-n}m)}$
K	parameter in equation (2.5–3), dimensionless
K	proportionality constant in equation (2.9–10), dimensionless
K_c	parameter in Carmen Kozeny equation, dimensionless
K_p	consistency coefficient for pipe flow, $\mathrm{kg/(s^{n-2}m)}$
KE	kinetic energy flow rate, W
L	length of pipe or tube, m
L	mixing length in equation (2.9–8), m
ln	$\log_e$, dimensionless
log	$\log_{10}$, dimensionless
m	mass of fluid, kg
m	number, dimensionless
M	flow rate of fluid, kg/s
(MW)	molecular weight, kg/kmol
n	number, dimensionless
n	power law index, dimensionless
n'	flow behaviour index in equation (3.1–1), dimensionless
N	rotational speed, rev/s
N_C	compressibility factor in equation (6.2–5), dimensionless
N_{FR}	Froude number, dimensionless
N_{HE}	Hedstrom number, dimensionless
N_M	Mach number, dimensionless
N_P	power number, dimensionless
N_{RE}	Reynolds number, dimensionless
N_{WE}	Weber number, dimensionless
N_Y	yield number for Bingham plastics, dimensionless
$NPSH$	net positive suction head, m
p	pitch, m
P	pressure, $\mathrm{N/m^2}$
P_A	agitator power, W
P_B	brake power, W
P_E	power, W
q	heat energy per unit mass, J/kg or $\mathrm{m^2/s^2}$
Q	volumetric flow rate, $\mathrm{m^3/s}$
r	blade length, m
r	pressure ratio, dimensionless
r	radius, m
r_f	recovery factor in equation (6.6–8), dimensionless
R	shear stress, $\mathrm{N/m^2}$
R_G	gas constant, 8.3143 kJ/(kmol K)
s	distance, m
s	scale reading in equation (8.5–1), dimensionless
s	slope $\sin\theta$, dimensionless
s	parameter in Laplace transform, $\mathrm{s^{-1}}$
S	cross-sectional flow area, $\mathrm{m^2}$
S_o	surface area per unit volume, $\mathrm{m^{-1}}$
t	time, s
T	temperature, K
T_o	stagnation temperature in equation (6.6–7), K
TS	tip speed, m/s
u	mean linear velocity, m/s
u_p	terminal settling or falling velocity, m/s
U	internal energy per unit mass, J/kg or $\mathrm{m^2/s^2}$
v	linear velocity, m/s

V	volume, m^3
V	volume per unit mass, m^3/kg
w	weight fraction, dimensionless
W	work energy per unit mass, J/kg or m^2/s^2
x	distance, m
x	exponent in equation (5.4–5), dimensionless
x_v	volume concentration of solids, dimensionless
X_{tt}	Lockhart Martinelli parameter in equation (7.2–8), dimensionless
y	distance, m
y	exponent in equation (5.4–5), dimensionless
Y_1	expansion factor in equation (6.7–16), dimensionless
z	distance, m
α	velocity distribution factor in equation (1.6–7), dimensionless
α	reciprocal of holding time Q/V, s^{-1}
γ	ratio of heat capacities C_p/C_v, dimensionless
$\dot{\gamma}$	shear rate, s^{-1}
δ	thickness of boundary layer, m
ε	roughness of pipe, m
ε	voidage fraction, dimensionless
η	kinematic viscosity, m^2/s
η	efficiency factor in equation (5.2–2), dimensionless
θ	angle or slope, dimensionless
μ	dynamic viscosity of fluid, kg/(s m) or N s/m^2
ρ	density of fluid, kg/m^3
σ	surface tension, N/m
τ	torque, N m
ϕ	power function in equation (5.4–6), dimensionless
ϕ	Lockhart Martinelli parameter in equation (7.2–9), dimensionless
ψ	correction factor in equation (9.1–10), dimensionless
ω	angular velocity, rad/s
Δe	per cent error in equation (8.5–5), dimensionless
∇	del, $\mathbf{i}\frac{\partial}{\partial x} + \mathbf{j}\frac{\partial}{\partial y} + \mathbf{k}\frac{\partial}{\partial z}$ in Cartesian coordinates, m^{-1}
∇^2	Laplacian operator, $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ in Cartesian coordinates, m^{-2}

Subscripts

a	referring to apparent
A	referring to agitator
b	referring to packed bed
B	referring to yield stress
c	referring to coarse suspension, coil, contraction, or critical
d	referring to discharge side
D	referring to displacement
e	referring to eddy, equivalent, or expansion
f	referring to friction
G	referring to gas
i	referring to inside of pipe or tube
L	referring to liquid
m	referring to manometer liquid, mean, or a number

M	referring to mixing
n	referring to a number
o	referring to outside of pipe or tube or a reference level
p	referring to pipe or solid particle
r	referring to reduced
s	referring to sonic, stream, suction side, or system
t	referring to time or transient
T	referring to tank or total
vp	referring to vapour
V	referring to volume
w	referring to pipe or tube wall
W	referring to water

Part one BASIC FLUID FLOW

1

Fluids in motion

1.1 Units and dimensions

Mass, length and time are commonly used primary units. Their dimensions are written as M, L and T respectively. Other units are derived in terms of mass, length and time. In the Système International d'Unités, commonly known as the SI system of units, the primary units are the kilogram kg, the metre m and the second s. A number of derived units are listed in Table (1.1–1).

Although the SI unit for the amount of substance is the mole, the kmol has been used in this text for convenience and consistency.

TABLE (1.1–1)

quantity	derived unit	symbol	relationship to primary units
force	newton	N	kg m/s^2
work, energy, quantity of heat	joule	J	N m
power	watt	W	J/s
area	square metre		m^2
volume	cubic metre		m^3
density	kilogram per cubic metre		kg/m^3
velocity	metre per second		m/s
acceleration	metre per second squared		m/s^2
pressure	newton per square metre		N/m^2
surface tension	newton per metre		N/m
dynamic viscosity	newton second per metre squared		N s/m^2 or kg/(s m)

1.2 Flow patterns

In general, fluids in motion have different velocities at different points in a line perpendicular to the direction of flow. The particular distribution of velocities depends on the nature of the flow which in turn is a function of the geometry of the container, the physical properties of the fluid, and its mass flow rate.

For the most part, flow can be characterized either as laminar or as turbulent flow.

Laminar flow. This is also called viscous or streamline flow. In this type of flow, layers of fluid move relative to each other without any macroscopic intermixing. Laminar flow systems are commonly represented graphically by streamlines. There is no fluid flow across these lines. A velocity distribution results from shear stresses which in turn are present because of viscous frictional forces.

Turbulent flow. In turbulent flow, there is an irregular random movement of fluid in directions transverse to the main flow. This irregular fluctuating motion can be regarded as superimposed on the mean motion.

Consider fluid flow with reference to an ordinary rectangular Cartesian coordinate system x, y, z. A point velocity at any instant in the x direction can be written as

$$v_x = \bar{v}_x + \bar{v}'_x$$

where $\bar{v}_x$, the mean point velocity, is defined as

$$\bar{v}_x = \frac{1}{\Delta t}\int_0^{\Delta t} v_x \, \mathrm{d}t \qquad (1.2\text{–}1)$$

In equation (1.2–1), Δt is a time interval which need be only a few seconds, since the irregular fluctuations are extremely rapid. If the mean velocity $\bar{v}_x$ is constant with time, the motion in the x direction is said to be in steady state. If motions exist in the y and z directions, they can similarly be expressed as the sum of a mean and a fluctuating velocity.

1.3 Newton's law of viscosity and momentum transfer

Consider two parallel plates of area A distance $\mathrm{d}z$ apart shown in Figure (1.3–1). The space in between the plates is filled with a fluid. The lower plate travels with a velocity v and the upper plate with a velocity $v - dv$. The small difference in velocity dv between the plates results in a resisting force F acting over the plate area A due to viscous frictional effects in the fluid.

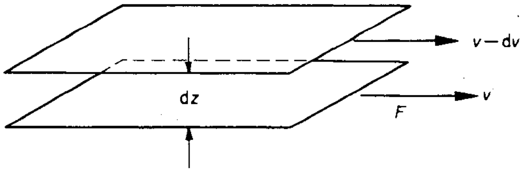

Figure (1.3–1)
Shear between two plates.

Thus a force F must be applied to the lower plate to maintain the difference in velocity dv between the two plates.

The force per unit area F/A is known as the shear stress R.

Since the velocity v decreases as the distance z increases, the velocity gradient is written with a negative sign as $-dv/dz$.

Newton's law of viscosity states that the shear stress R is proportional to the velocity gradient $-dv/dz$ in the fluid. The constant of proportionality is known as the coefficient of dynamic viscosity μ. Newton's law of viscosity can be written

$$R = -\mu \frac{dv}{dz} \qquad (1.3\text{–}1)$$

Fluids which obey this equation are called Newtonian fluids. Fluids which do not obey this equation are called non-Newtonian fluids.

In terms of velocity in the horizontal x direction, equation (1.3–1) can be rewritten for a point in the z direction in the form

$$R_{zx} = -\mu \frac{dv_x}{dz} \qquad (1.3\text{–}2)$$

or for a point in the radial r direction in the form

$$R_{rx} = -\mu \frac{dv_x}{dr} \qquad (1.3\text{–}3)$$

Newton's law of viscosity holds for Newtonian fluids in streamline flow. For Newtonian fluids in streamline flow, the velocity gradient $-dv/dz$ is also the shear rate conventionally written as $\dot{\gamma}$.

Newton's law of viscosity is commonly written in one of the following three forms:

$$R = \mu\dot{\gamma} \tag{1.3–4}$$

$$\dot{\gamma} = \frac{R}{\mu} \tag{1.3–5}$$

or

$$\mu = \frac{R}{\dot{\gamma}} \tag{1.3–6}$$

i.e.

$$\text{dynamic viscosity} = \frac{\text{shear stress}}{\text{shear rate}}$$

In a fluid in laminar flow, fast moving molecules diffuse into slow moving streams and vice versa, resulting in a transfer of momentum in a direction perpendicular to the direction of flow. The rate of momentum transfer is the same as the shear stress R_{zx} given by equation (1.3–2).

Equation (1.3–2) may also be written as

$$R_{zx} = -\eta\rho\frac{\mathrm{d}v_x}{\mathrm{d}z} \tag{1.3–7}$$

where $\eta = \mu/\rho$, the viscous diffusivity or kinematic viscosity.

In turbulent flow, momentum transfer takes place by the movement of eddies imposed on the ordinary molecular motion. The rate of momentum transfer through regions of turbulent flow is given by the equation

$$R_{zx} = -(\eta + \eta_e)\rho\frac{\mathrm{d}v_x}{\mathrm{d}z} \tag{1.3–8}$$

where η_e is the eddy viscous diffusivity. In turbulent flow, the eddy viscous diffusivity η_e is much greater than the molecular viscous diffusivity η. Thus large shear stresses exist in turbulent fluids.

1.4 Non-Newtonian behaviour

For Newtonian fluids a plot of shear stress R against shear rate $\dot{\gamma}$ on Cartesian coordinates is a straight line having a slope equal to the coefficient of dynamic viscosity μ. For many fluids a plot of

R against $\dot{\gamma}$ does not give a straight line. These are the so-called non-Newtonian fluids. Plots of R against $\dot{\gamma}$ are experimentally determined using a viscometer.

The term viscosity has no meaning for a non-Newtonian fluid unless it is related to a particular shear rate $\dot{\gamma}$. An apparent viscosity μ_a can be defined as follows:

$$\mu_a = \frac{R}{\dot{\gamma}} \tag{1.4–1}$$

When the apparent viscosity μ_a decreases with an increase in shear rate $\dot{\gamma}$ as in Figure (1.4–1) the fluid is said to be pseudoplastic. When

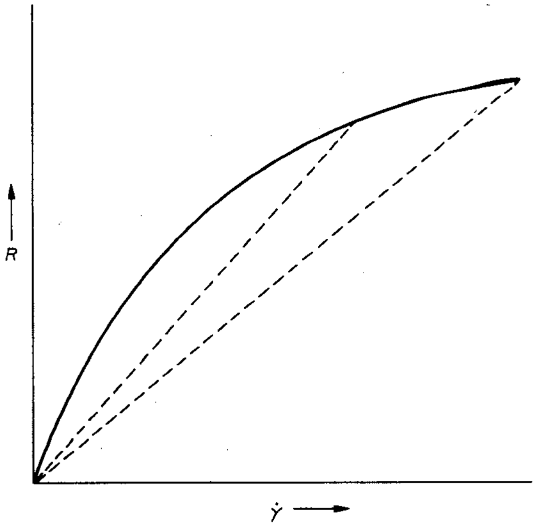

Figure (1.4–1)
Shear stress R against shear rate $\dot{\gamma}$ for a pseudoplastic fluid.

μ_a increases with an increase in $\dot{\gamma}$ as in Figure (1.4–2) the fluid is said to be dilatant.

Another type of non-Newtonian fluid is the Bingham plastic. A plot of R against $\dot{\gamma}$ on Cartesian coordinates for a Bingham plastic shown in Figure (1.4–3) is a straight line having an intercept R_B on the shear stress axis called the yield stress. R_B is the stress which must be exceeded before flow starts. The fluid at rest contains a three dimensional structure of sufficient rigidity to resist any stress less

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