FLUID MECHANICS

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Theory, worked examples and problems

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PREFACE

The purpose of this book is to present the fundamental laws of fluid mechanics and illustrate them by application to a wide range of worked examples and problems.

The level is suitable for first and some second year fluid mechanics work on degree and diploma courses in mechanical and civil engineering. The book should also be useful to students preparing for CEI examinations.

The presentation is based on a logical teaching order in preference to grouping the examples under convenient topic headings. A feature of the book is the rigorous treatment of fundamentals in the introductory theory to each chapter. This is necessary because of the wide range of principles involved in fluid mechanics and my belief that the assumptions, on which the principles are based, should be examined. It is also important to consider the range of validity of derived relationships before they are applied to the worked examples.

The actual derivation of the relationships is not considered appropriate in this book and the practice of deriving basic theory in the examples is generally avoided, although there are occasions when it is desirable to link a particular aspect of derived theory with numerical work. It is assumed that the reader will cover the derivations in the lectures of an engineering course, or refer to the books listed in the bibliography.

I attach great importance to the link between certain topics covered in both fluid mechanics and a parallel course in thermodynamics. For this reason, thermodynamic concepts are summarised in Chapter 1. The principle of conservation of energy is treated in Chapter 4 and the important relationship between the Bernoulli equation and the steady-flow energy equation is discussed in detail.

In some chapters, the general three-dimensional flow case is treated, even though the subsequent discussion and examples are restricted to one or two-dimensional flow. This treatment is included for the benefit of students proceeding to an advanced study of fluid mechanics.

Vector methods are used in certain topics, particularly those in the chapter on the dynamics of fluids. Vectors are now taught at an early level and a modern book on fluid mechanics should include vector treatment where appropriate. However, the reader who is unfamiliar with vectors, or the student who prefers to avoid them, should have little difficulty in following the theory and worked

examples. Scalar equations are always given, in addition to vector equations, and the majority of the examples are solved using scalars.

It is customary in books to denote vector quantities by bold-face type. This is impossible in the present work and vector quantities are denoted by an underscore. For example, F denotes a scalar force and $\underline{F}$ denotes a vector force.

The notation adopted for velocity is particularly important because it is necessary to distinguish between resultant vector velocities in two and three-dimensional flow, and mean velocities used in one-dimensional flow. The symbol used for velocity, throughout this book, is u . The resultant vector velocity at a point is $\underline{u}$, with u , v and w as velocity components in the x , y and z -directions, respectively. The mean velocity in duct or channel flow ($\dot{V}/A$) is denoted by $\bar{u}$. Other velocities are defined by an appropriate subscript e.g. u_r and u_θ are radial and tangential velocity components, respectively.

The symbols used in this book conform wherever possible to the recommendations of the British Standards Institution and the Royal Society. All problems are set in SI units and the general method of numerical solution involves the substitution in physical equations of base SI units (i.e. kg, m, N, etc.) and multiples of ten. This method obviates the need for any special techniques such as the Stroud convention.

My thanks are due to the Director of the North Staffordshire Polytechnic and the Council of Engineering Institutions for permission to include questions from their examination papers. I accept sole responsibility for the solutions to the questions.

I wish to express my gratitude to Mrs Kay White for her expert typing of the manuscript and her patient interpretation of my rough notes.

Finally, I wish to thank my wife and children for their encouragement and help during the writing of the manuscript.

Stafford
May 1978

H. C. Lowe

SYMBOLS AND UNITS

<i>Symbol</i>	<i>Quantity</i>	<i>Preferred Units</i>
A	area	m ²
$\underline{A}$	area (vector)	m ²
a	linear acceleration	m/s ²
a	radius of circular cylinder	m
a	sonic velocity	m/s
B	width of liquid surface	m
b	breadth of weir, spillway, etc.	m
C	a constant	
C	Chézy coefficient	
C _c	contraction coefficient	
C _D	drag coefficient	
C _d	discharge coefficient	
C _f	mean skin coefficient	
C _L	lift coefficient	
c	velocity (celerity) of wave propagation	m/s
c _f	local skin friction coefficient	
c _p	specific heat at constant pressure	kJ/kg K
c _v	specific heat at constant volume	kJ/kg K
D	diameter	m
D _e	equivalent diameter (4A/P)	m
d	differential operator	
E	internal energy	kJ
E _k	kinetic energy	kJ
E _p	potential energy	kJ
e	specific internal energy	kJ/kg
F	force	N
$\underline{F}$	force (vector)	N
F _D	drag force	N
F _L	lift force	N
Fr	Froude number $u/\sqrt{gL}$	
f	friction factor	
f	frequency of vortex shedding	s ⁻¹
g	acceleration of free fall	m/s ²
H	enthalpy	kJ
H _O	Bernoulli head $(p/\rho g + \bar{u}^2/2g + z)$	m
H _s	specific head $(\bar{u}^2/2g + y)$	m

h	specific enthalpy	kJ/kg
h	depth below free surface of liquid	m
K	a constant	
K_s	isentropic bulk modulus	$\text{Pa} \equiv (\text{N/m}^2)$
K_T	isothermal bulk modulus	Pa
k	surface roughness height	m
L	length	m
ℓ	length	m
ln	natural logarithm (i.e. to base e)	
log	logarithm to base 10	
M	total mass	kg
M	Mach number u/a	
m	mass	kg
$\dot{m}$	mass flow rate	kg/s
m	strength of source or sink ($Q/2\pi$)	m^2/s
N	rotational speed	rev/min
n	rotational speed	rad/s
n	frequency of vortex shedding	s^{-1}
n	Manning roughness coefficient	
n	polytropic index	
P	wetted perimeter	m
P	power	W
p	pressure	$\text{Pa} \equiv (\text{N/m}^2)$
p_a	atmospheric pressure	Pa
p^*	piezometric pressure ($p + \rho gz$)	Pa
Q	flow per unit depth (source or sink)	m^2/s
$\dot{Q}$	quantity of heat	kJ
$\dot{Q}$	heat flow rate	W
q	heat per mass	J/kg
R	radius	m
R	characteristic gas constant	kJ/kg K
Re	Reynolds number $\rho u L / \mu$	
R_h	hydraulic radius (A/P)	m
r	coordinate	m
r	radius	m
$\vec{r}$	radius (vector)	m
$\bar{S}$	entropy	kJ/K
S_o	slope of channel bed	
S_w	slope of liquid surface	
S	slope of energy line	
S	control surface	
s	specific entropy	kJ/kg K
T	thermodynamic temperature	K
T	torque	N m
T	thrust	N
t	time	s
U	free stream velocity	m/s
$\underline{U}$	body velocity (vector)	m/s
$\underline{u}$	fluid velocity (vector)	m/s
$\bar{u}$	mean fluid velocity	m/s
u	a fluid velocity	m/s
u	fluid velocity component (x-direction)	m/s

u_a	axial component of velocity	m/s
u_R	relative velocity	m/s
u_r	radial component of velocity	m/s
u_S	fluid velocity relative to control surface	m/s
u_θ	tangential component of velocity	m/s
u_V	fluid velocity relative to control volume	m/s
u_w	whirl component of velocity	m/s
V	a volume	m^3
$\dot{V}$	control volume	
$\dot{V}$	volumetric flow rate	m^3/s
v	fluid velocity component (y-direction)	m/s
v	specific volume	m^3/kg
W	work	J
We	Weber number $u\sqrt{(\rho L/\gamma)}$	
W_x	shaft or electrical work	J
w	work per mass	J/kg
w	fluid velocity component (z-direction)	m/s
x	coordinate	m
y	depth of liquid (channel flow)	m
y	coordinate	m
z	height above arbitrary datum	m
z	coordinate	m

Greek symbols

α (alpha)	angle	
α	kinetic energy correction factor	
β (beta)	isobaric expansivity (thermal coefficient of cubical expansion)	K^{-1}
β	momentum correction factor	
Γ (gamma)	circulation	m^2/s
γ	ratio of specific heats or bulk moduli ($c_p/c_v = K_S/K_T$)	
γ	surface tension	N/m
Δ (delta)	difference in value	
δ	a very small increase of	
δ	thickness of boundary layer	m
δ^*	displacement thickness of boundary layer	m
ϵ (epsilon)	kinematic eddy viscosity	m^2/s
ζ (zeta)	vorticity	s^{-1}
η (eta)	efficiency	
η_H	hydraulic efficiency	
η_O	overall efficiency	
θ (theta)	an angle	
θ	temperature on arbitrary scale	$^{\circ}C$
λ (lambda)	temperature lapse rate ($-dT/dz$)	K/m
λ	friction factor = $4f$	

μ (mu)	dynamic viscosity	$\text{Pa s} \equiv (\text{N s/m}^2)$
ν (nu)	kinematic viscosity (μ/ρ)	m^2/s
Π (pi)	dimensionless parameter	
π	3.14159 ...	
ρ (rho)	mass density	kg/m^3
Σ (sigma)	summation	
σ	normal stress	Pa
τ (tau)	shear stress	Pa
τ_o	shear stress at boundary	Pa
ϕ (phi)	a function of	
ϕ	velocity potential function	m^2/s
ψ (psi)	stream function	m^2/s
ω (omega)	angular velocity	rad/s

Suffixes

c	critical
d	delivery
R	relative to
s	suction
S	relative to control surface
V	relative to control volume
x, y, z	component of vector quantity in x, y, z directions
o	stagnation conditions
1, 2	at inlet or outlet of control volume or machine rotor
∞	at a large distance upstream from body