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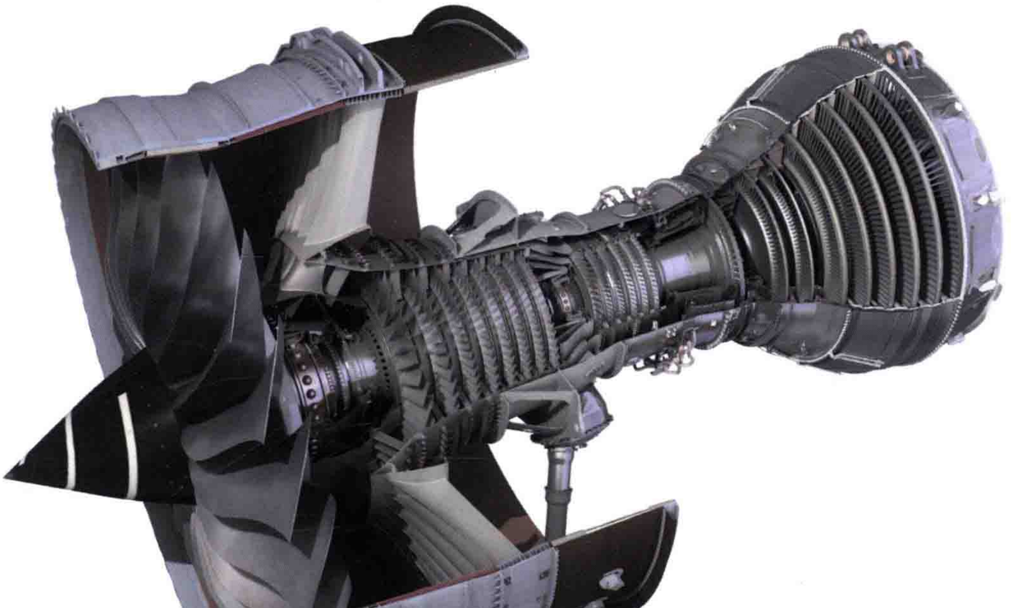
INTRODUCTION TO
ENGINEERING FLUID MECHANICS



MARCEL ESCUDIER

We inhabit a world of fluids, including air (a gas), water (a liquid), steam (vapour), and the numerous natural and synthetic fluids which are essential to modern-day life. Fluid mechanics concerns the way fluids flow in response to imposed stresses. The subject plays a central role in the education of students of mechanical engineering, as well as chemical engineers, aeronautical and aerospace engineers, and civil engineers. This textbook includes numerous examples of practical applications of the theoretical ideas presented, such as calculating the thrust of a jet engine, the shock- and expansion-wave patterns for supersonic flow over a diamond-shaped aerofoil, the forces created by liquid flow through a pipe bend and/or junction, and the power output of a gas turbine.

The first ten chapters of the book are suitable for first-year undergraduates. The latter half of the book covers material suitable for fluid mechanics courses for upper-level students. Although knowledge of calculus is essential, this text focuses on the underlying physics. The book emphasises the role of dimensions and dimensional analysis, and includes more material on the flow of non-Newtonian liquids than is usual in a general book on fluid mechanics—a reminder that the majority of synthetic liquids are non-Newtonian in character.

MARCEL ESCUDIER is Emeritus Harrison Professor of Mechanical Engineering at the University of Liverpool.

This book offers a fresh look into the teaching of fluid mechanics for engineering students starting on the subject. The underlying philosophy is that of maximising insight and understanding the physics of fluid mechanics, while still providing the rigorous tools needed for effective problem solving. This is a blend that only an author with substantial experience in the practice of engineering in industry and academia can provide. This book is comprehensive, including flows of compressible fluids, flows through some turbomachine bladings, internal and boundary layer flows, the differential forms of the governing equations, and applications to flows of generalised Newtonian fluids and turbulence. Mathematics is kept at the simplest level required for the purpose, but not more. The book clearly stands out from existing textbooks, and certainly will be useful to those concerned with learning and teaching successful introductory courses on fluid mechanics in engineering, in particular in mechanical, aeronautical and chemical engineering.

Fernando Tavares de Pinho, Faculty of Engineering, University of Porto, Portugal

This is a comprehensive yet readable undergraduate textbook on fluid mechanics. The first half of the book introduces the core material for engineering students, while the second half discusses more specialised subjects, such as compressible flows and turbulent flows. The latter can be used not only as supplementary material for 1st and 2nd year students, but also as a textbook for higher-level undergraduates and MSc students.

Kwing-So Choi, Faculty of Engineering, University of Nottingham, UK

Cover image: The cover design is based upon a cutaway view of the Rolls-Royce Trent XWB engine which powers the Airbus A350 XWB family of widebody aircraft. The XWB is a three-spool, high bypass, turbofan engine with a 3 m diameter fan and take-off thrust in the range 330-430 kN. Image reproduced courtesy of Rolls-Royce plc; (Background) ©iStock.com/ildogesto

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Introduction to Engineering Fluid Mechanics

To my wife Agnes, our son Stephen, and the memory of my Mother and Grandmother

Preface

A fluid is a material substance in the form of a liquid, a gas, or a vapour. The most common examples, to be found in both everyday life and in engineering applications, are water, air, and steam, the latter being the vapour form of water. The flow (i.e. motion) of fluids is essential to the functioning of a wide range of machinery, including the internal-combustion engine, the gas turbine (which includes the turbojet, turbofan, turboshaft, and turboprop engines), wind and hydraulic turbines, pumps, compressors, rapidly rotating discs (as in computer drives), aircraft, spacecraft, road vehicles, and marine craft. This book is concerned primarily with Newtonian fluids, such as water and air, for which the viscosity is independent of the flow. The quantitative understanding of fluid flow, termed fluid dynamics, is based upon the application of Newton's laws of motion together with the law of mass conservation. To analyse the flow of a gas or a vapour, for which the density changes in response to pressure changes (known as compressible fluids), it is also necessary to take into account the laws of thermodynamics, particularly the first law in the form of the steady-flow energy equation. The subject of fluid mechanics encompasses both fluid statics and fluid dynamics. Fluid statics concerns the variation of pressure in a fluid at rest (as will be seen in Chapter 4, this limitation needs to be stated more precisely), and is the basis for a simple model of the earth's atmosphere.

This text is aimed primarily at students studying for a degree in mechanical engineering or any other branch of engineering where fluid mechanics is a core subject. Aeronautical (or aerospace), chemical, and civil engineering are all disciplines where fluid mechanics plays an essential rôle. That is not to say that fluid flow is of no significance in other areas, such as biomedical engineering. The human body involves the flow of several different fluids, some quite ordinary such as air in the respiratory system and water-like urine in the renal system. Other fluids, like blood in the circulatory system, and synovial fluid, which lubricates the joints, have complex non-Newtonian properties, as do many synthetic liquids such as paint, slurries, and pastes. A brief introduction to the rheology and flow characteristics of non-Newtonian liquids is given in Chapters 2, 15, and 16.

As indicated in the title, this text is intended to introduce the student to the subject of fluid mechanics. It covers those topics normally encountered in a three-year mechanical-engineering-degree course or the first and second years of a four-year mechanical-engineering-degree course, as well as some topics covered in greater detail in the final years. The first ten chapters cover material suitable for a first-year course or module in fluid mechanics. Compressible flow, flow through axial-flow turbomachinery blading, internal viscous fluid flow, laminar boundary layers, and turbulent flow are covered in the remaining eight chapters. There are many other textbooks which cover a similar range of material as this text but often from a much more mathematical point of view. Mathematics is essential to the analysis of fluid flow but can be kept to a level within the capability of the majority of students, as is the intention here where the emphasis is on understanding the basic physics. The analysis of many flow situations rests upon a small number of basic equations which encapsulate the underlying physics. Between these fundamental equations and the final results, which can be applied directly to the solution of engineering problems, can be quite extensive mathematical manipulation and it is all too easy to lose sight of the final aim. A basic understanding of vectors is required but not of vector analysis. Tensor notation and analysis is also not required and the use of calculus is kept to a minimum.

The approach to certain topics may be unfamiliar to some lecturers. A prime example is dimensional analysis, which we suggest is approached using the mathematically simple method of sequential elimination of dimensions (Ipsen's method). The author believes that this technique has clear pedagogical advantages over the more widely used Rayleigh's exponent method, which can easily leave the student with the mistaken (and potentially dangerous) idea that any physical process can be represented by a simple power-law formula. The importance of dimensions and dimensional analysis is stressed throughout the book. The author has also found that the development of the linear momentum equation described in Chapter 9 is more straightforward to present to students than it is via Reynolds transport theorem. The approach adopted here shows very clearly the relationship with the familiar $F = ma$ form of Newton's second law of motion and avoids the need to introduce an entirely new concept which is ultimately only a stepping stone to the end result. The treatment of compressible flow is also subtly different from most texts in that, for the most part, equations are developed in integral rather than differential form. The analysis of turbomachinery is limited to flow through the blading of axial-flow machines and relies heavily on Chapters 3, 10, and 11.

'Why do we need a fluid mechanics textbook containing lots of equations and algebra, given that computer software packages, such as FLUENT and PHOENICS, are now available which can perform very accurate calculations for a wide range of flow situations?' To answer this question we need first to consider what is meant by accurate in this context. The description of any physical process or situation has to be in terms of equations. In the case of fluid mechanics, the full set of governing equations is extremely complex (non-linear, partial differential equations called the Navier-Stokes equations) and to solve practical problems we deal either with simplified, or approximate, equations. Typical assumptions are that all fluid properties remain constant, that viscosity (the essential property which identifies any material as being a fluid) plays no role, that the flow is steady (i.e. there are no changes with time at any given location within the fluid), or that fluid and flow properties vary only in the direction of flow (so-called one-dimensional flow). The derivation of the Navier-Stokes equations, and the accompanying continuity equation, is the subject of Chapter 15. Exact analytical solution of these equations is possible only for a handful of highly simplified, idealised situations, often far removed from the real world of engineering. Although these solutions are certainly mathematically accurate, due to the simplifications on which the equations are based they cannot be said to be an accurate representation of physical reality. Even numerical solutions, however numerically accurate, are often based upon simplified versions of the Navier-Stokes equations. In the case of turbulent flow, the topic of Chapter 18, calculations of practical interest are based upon approximate equations which attempt to model the correlations which arise when the Navier-Stokes equations are time averaged. It is remarkable that valuable information about practical engineering problems can be obtained from considerations of simplified equations, such as the one-dimensional equations, at minimal cost in terms of both time and money. What is essential, however, is a good physical understanding of basic fluid mechanics and a knowledge of what any computer software should be based upon. It is the aim of this text to provide just that.

Already in this brief **Preface** the names Navier, Newton, Rayleigh, Reynolds, and Stokes have appeared. In Appendix 1 we provide basic biographical information about each of the scientists and engineers whose names appear in this book and indicate their contributions to fluid mechanics.

Acknowledgements

The author gratefully acknowledges the influence of several outstanding teachers, both as a student at Imperial College London and subsequently as a Research Associate at the Massachusetts Institute of Technology. My interest in, and enjoyment of, fluid mechanics was sparked when I was an undergraduate by the inspiring teaching of Robert Taylor. Brian Spalding, my PhD supervisor, and Brian Launder are not only internationally recognised for their research contributions but were also excellent communicators and teachers from whom I benefitted as a postgraduate student. As a research associate at MIT I attended lectures and seminars by Ascher H. Shapiro, James A. Fay, Ronald F. Probstein, and Erik Mollo-Christensen, all inspiring teachers. Finally, my friend Fernando Tavares de Pinho has given freely of his time to answer with insight many questions which have arisen in the course of writing this book.

Marcel Escudier
Cheshire, August 2016

Notation

Each Roman, Greek, and mathematical symbol is followed by its meaning, its SI unit, and its dimension(s).

Lower-case Roman symbols

a	acceleration	$\mathrm{m/s^2}$	$\mathrm{L/T^2}$
c	blade chord length	m	L
c	concentration	$\mathrm{kg/m^3}$	$\mathrm{M/L^3}$
c	soundspeed	m/s	L/T
c	wetted perimeter	m	L
c_f	skin-friction coefficient	–	–
c_0	speed of light in vacuum	m/s	L/T
d	diameter	m	L
e	energy	J	$\mathrm{ML^2/T^2}$
$\dot{e}_{xx}$	extensional strain rate in x-direction	1/s	1/T
f	non-dimensional velocity	–	–
f_x	body force per unit mass acting in the x-direction	$\mathrm{m/s^2}$	$\mathrm{L/T^2}$
f_D	Darcy friction factor	–	–
f_F	Fanning friction factor	–	–
$\overline{f_F}$	average Fanning friction factor	–	–
g	acceleration due to gravity	$\mathrm{m/s^2}$	$\mathrm{L/T^2}$
g_0	acceleration due to gravity at sea level ($z = z' = 0$)	$\mathrm{m/s^2}$	$\mathrm{L/T^2}$
h	height	m	L
h	spacing of parallel plates	m	L
h	specific enthalpy	kJ/kg	$\mathrm{L^2/T^2}$
h_0	specific stagnation enthalpy	kJ/kg	$\mathrm{L^2/T^2}$
$h_{0,REL}$	relative stagnation enthalpy	kJ/kg	$\mathrm{L^2/T^2}$
i	angle of incidence	° or rad	–
j	number of independent dimensions	–	–
k	number of non-dimensional groups	–	–
k	radius of gyration	m	L
k	specific turbulent kinetic energy	$\mathrm{m^2/s^2}$	$\mathrm{L^2/T^2}$
$\overline{k}$	time-averaged specific turbulent kinetic energy	$\mathrm{m^2/s^2}$	$\mathrm{L^2/T^2}$
k_B	Boltzmann constant	J/K	$\mathrm{ML^2/T^2K}$
l	length	m	L
l_K	Kolmogorov length scale	m	L
l_M	mixing length	m	L

m	mass	kg	M
m	wedge-flow exponent	–	–
m_A	added mass	kg	M
$\dot{m}$	mass flowrate	kg/s	M/T
n	amount of substance	kmol	M
n	number of physical quantities	–	–
n	power-law exponent in power-law viscosity model	–	–
p	static pressure	Pa	$\mathrm{M/LT^2}$
p_G	gauge pressure	Pa	$\mathrm{M/LT^2}$
p_H	hydrostatic pressure	Pa	$\mathrm{M/LT^2}$
p_{REF}	reference pressure	Pa	$\mathrm{M/LT^2}$
p_T	total pressure	Pa	$\mathrm{M/LT^2}$
p_V	vapour pressure	Pa	$\mathrm{M/LT^2}$
p_0	stagnation pressure	Pa	$\mathrm{M/LT^2}$
$p_{0,REL}$	relative stagnation pressure	Pa	$\mathrm{M/LT^2}$
$\overline{p}$	average static pressure	Pa	$\mathrm{M/LT^2}$
p'	fluctuating component of static pressure	Pa	$\mathrm{M/LT^2}$
p'	intermediate static pressure	Pa	$\mathrm{M/LT^2}$
p^*	non-dimensional static pressure	–	–
$\dot{q}$	heat transfer rate	W	$\mathrm{ML^2/T^3}$
$\dot{q}'$	heat transfer rate per unit length	W/L	$\mathrm{ML/T^3}$
r	radial distance	m	L
s	arc length	m	L
s	cascade-blade spacing (or pitch)	m	L
s	distance along a streamline	m	L
s	specific entropy	$\mathrm{m^2/s^2 \cdot K}$	$\mathrm{L^2/T^2\theta}$
s_0	specific stagnation entropy	$\mathrm{m^2/s^2 \cdot K}$	$\mathrm{L^2/T^2\theta}$
t	elapsed time	s	T
t	temperature	°C	θ
$\tilde{t}$	non-dimensional time	–	–
t^*	non-dimensional time	–	–
u	specific internal energy	kJ/kg	$\mathrm{L^2/T^2}$
u	velocity component in x-direction	m/s	L/T
$\overline{u}$	time-averaged value of velocity component u	m/s	L/T
u'	fluctuating component of velocity component u	m/s	L/T
u^*	non-dimensional value of velocity component u	–	–
u^+	velocity component u normalised by u_τ	–	–
u_P	velocity of plastic plug	m/s	L/T
u_0	centreline velocity	m/s	L/T
u_τ	friction velocity	m/s	L/T
v	specific volume	$\mathrm{m^3/kg}$	$\mathrm{L^3/M}$
v	velocity component in y- or r-direction	m/s	L/T
$\overline{v}$	time-averaged value of velocity component v	m/s	L/T