Encyclopedia of Fluid Mechanics

VOLUME 8

Aerodynamics and Compressible Flows

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CONTRIBUTORS TO THIS VOLUME

A. L. Addy, Dept. of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

M. J. Andrews, Dept. of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey, USA.

K. A. Ansari, Dept. of Mechanical Engineering, Gonzaga University, Spokane, Washington, USA.

P. S. Ayyaswamy, Dept. of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, Pennsylvania, USA.

N. C. Baines, Dept. of Mechanical Engineering, Imperial College, London, United Kingdom.

F. V. Bracco, Dept. of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey, USA.

N. P. Cheremisinoff, Exxon Chemical Co., Linden, New Jersey, USA.

R. Chevray, Dept. of Mechanical Engineering, Columbia University, New York, New York, USA.

H. W. Coleman, Dept. of Mechanical and Nuclear Engineering, Mississippi State University, Mississippi State, Mississippi, USA.

E. Dick, Dept. of Machinery, State University of Ghent, Sint Peitersnieuwstraat, Ghent, Belgium.

J. C. Dutton, Dept. of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA.

A. Ecer, Purdue University, Indianapolis, Indiana, USA.

P. Freymuth, Dept. of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, USA.

W. Genxing, Nanjing Aeronautical Institute, Nanjing, China.

K. N. Ghia, University of Cincinnati, Cincinnati, Ohio, USA.

U. Ghia, University of Cincinnati, Cincinnati, Ohio, USA.

A. A. M. Halim, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio USA.

H. Hayami, Kyushu University, Kasuga, Fukuoka, Japan.

M. Hayashi, Dept. of Aeronautical Engineering, Kyushu University, Fukuoka, Japan.

B. K. Hodge, Dept. of Mechanical and Nuclear Engineering, Mississippi State University, Mississippi State, Mississippi, USA.

N. E. Huang, Laboratory for Oceans, Goddard Space Flight Center, Greenbelt, Maryland, USA.

S.-I. Iida, Dept. of Mechanical Engineering, Hokkaido University, Sapporo, Japan.

Y. Joshi, Dept. of Mechanical Engineering, Naval Postgraduate School, Monterey, California, USA.

K. Kamijo, National Aerospace Laboratory, Kakuda, Miyagi, Japan.

Z. Kazimierski, Technical University of Lodz, Lodz, Poland.

J. A. Liburdy, Dept. of Mechanical Engineering, Clemson University, Clemson, South Carolina, USA.

P. M. Ligrani, Dept. of Mechanial Engineering, Naval Postgraduate School, Monterey, California, USA.

K. A. Mansour, Dept. of Chemical Engineering, University of Illinois, Chicago, Illinois, USA.

M. Moheban, Dept. of Mechanical Engineering, Imperial College, London, United Kingdom.

M. J. Morris, Dept. of Mechanical and Industrial Engineering, University of Illinois, Urbana, Illinois, USA.

S. Murad, Dept. of Chemical Engineering, University of Illinois, Chicago, Illinois, USA.

Y. Ohya, Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan.

A. Okajima, Dept. of Mechanical Engineering, Kanazawa University, Kanazawa, Japan.

S. Okamoto, Dept. of Mechanical Engineering, Snibaura Institute of Technology, Tokyo, Japan.

R. Ruderich, MTU Motoren-und Tubinen-Union, Munchen, Federal Republic of Germany.

M. Salikuddin, Lockheed-Georgia Co., Marietta, Georgia, USA.

T. Sattelmayer, Brown Boveri Research Centre, Baden, Switzerland.

B. L. Sawford, CSIRO Division of Atmospheric Research, Mordialloc, Australia.

Y. Senoo, Miura Co., Matsuyama, Japan.

C. K. W. Tam, Dept. of Mathematics, Florida State University, Tallahassee, Florida, USA.

R. P. Taylor, Dept. of Mechanical and Nuclear Engineering, Mississippi State University, Mississippi State, Mississippi, USA.

D. Vandenberghe, Dept. of Machinery, State University of Ghent, Ghent, Belgium.

S. Wittig, Institute for Thermal Turbomachinery, University of Karlsruhe, Federal Republic of Germany.

W. Wysocki, Technical University of Lodz, Lodz, Poland.

M. Xiao, Nanjing Aeronautical Institute, Nanjing, China.

ABOUT THE EDITOR

Nicholas P. Cheremisinoff, Ph.D., heads the product development group of the Elastomers Division of Exxon Chemical Co., Linden, N.J. He has extensive experience in analyzing multiphase flows and in designing reactor operations for manufacturing specialty chemicals and synthetic fuels production. Dr. Cheremisinoff received his B.S., M.S., and Ph.D. degrees in chemical engineering from Clarkson College of Technology. He is the author, co-author, and editor of more than forty volumes, including Gulf Publishing Company's multivolume *Handbook of Heat and Mass Transfer*, and the *International Journal of Engineering Fluid Mechanics*.

PREFACE

This volume covers compressible flow dynamics and aerodynamic principles important to discrete type flow phenomena and process apparatus design. It is not intended as a basic overview of classical compressible flow dynamics, but rather a treatise on advanced techniques for analyzing such flows. Volumes 1 and 2 of the *Encyclopedia of Fluid Mechanics* contain more fundamental discussions of compressible flow dynamics and applications to conventional unit operations such as gas transportation and compression/blower dynamics. Many discussions in this volume employ numerical techniques. (See Section III of Volume 6 to obtain a working knowledge of numerical methods as applied to flow dynamic analyses.)

This eighth volume of the *Encyclopedia* is divided into two sections. Section I, "Turbulence Phenomena and Modeling," comprises seventeen chapters. The first two chapters provide orientation in terms of property differences between compressible and incompressible fluids. Chapters 3 through 14 describe numerical and experimental analyses of the structure of compressible flows. Considerable discussion of wake formation and vortex shedding about obstacles is included. Chapters 13, 15, and 16 are designed to provide a theoretical understanding of the subjects of turbulence and heat transfer, with Chapter 16 emphasizing the aerodynamics and heat transfer mechanisms involved in non-reacting two-phase systems. Chapter 17 provides further discussions on two-phase systems by treatment of wind-generated wave phenomena.

Section II, "Selected Engineering Problems," is designed to provide detailed analyses of several problems of industrial importance. This section covers transitory flow in diffusers, transonic flows through turbine cascades, centrifugal and axial blower analyses, compressible flow in valves, cryogenic pumps, and numerical treatment of atomized flows. The last two chapters in the volume address the use and dynamics of wind machines.

The time and efforts of forty-four specialists were enlisted in the production of this volume. Their efforts in producing this work are to be commended. In addition, special thanks is extended to Gulf Publishing Company and its editorial staff for the fine production of this volume.

Nicholas P. Cheremisinoff

ENCYCLOPEDIA OF FLUID MECHANICS

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Turbulence Phenomena and Modeling
Selected Engineering Problems

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N. P. Cheremisinoff, Editor

in collaboration with—

A. L. Addy
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W. Wysocki
M. Xiao

CHAPTER 1

VISCOSITY OF FLUIDS

S. Murad and K. A. Mansour

Chemical Engineering Department
University of Illinois at Chicago
Chicago, Illinois, USA

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INTRODUCTION

Viscosity is the most important of the physical properties of fluids, traditionally classified as transport properties. It plays an important role in the design and operation of chemical processes because of the importance of fluid flow in the chemical industry. Viscosity is a dynamic property (i.e., for a fluid at rest it has no significance), and in general is only state dependent, except for certain fluids classified as thixotropic or rheopectic. In engineering, viscosity always refers to what would be more correctly shear viscosity. Another viscosity coefficient, usually referred to as the coefficient of dilational viscosity or bulk viscosity, is a measure of the rate of transfer of energy from the translational to the internal degrees of freedom [1]. For most engineering problems it is probably not of any great significance [2]. In addition, viscosity can be independent of shear rate, as mandated by Newton's Law of viscosity, or dependent on it. Fluids that fall within the former category are termed Newtonian, and include *all* gases, and homogeneous nonpolymeric liquids. Fluids in the latter category are called non-Newtonian and include many industrially important fluids such as slurries, suspensions, polymeric liquids, etc. In this report we will confine ourselves to the shear viscosity of Newtonian fluids. The fluids of interest will include dilute gases, dense gases, and liquids. Both pure fluids, and mixtures (including aqueous solutions) will be discussed. For non-Newtonian fluids the reader is referred to several recent reviews [3–5], while for bulk viscosity, which is known for very few fluids, a useful source is reference [6].

Viscosity is a measure of the internal fluid friction which opposes dynamic changes in the fluid. The viscosity coefficient thus defines the momentum flux resulting in the fluid because of a velocity gradient. For one-dimensional flow, the governing equation is:

$$\tau_{yx} = -\eta \frac{dV_x}{dy} \tag{1}$$

where V_x is the velocity in the direction of flow, and τ_{yx} is the shear stress in the direction of flow, on a fluid surface of constant y (i.e., a surface of constant velocity), by a fluid in the region of lesser y [2]. For laminar flows, η is independent of the shear stress or shear rate for Newtonian fluids, but dependent for non-Newtonian fluids. Finally, if the flow is turbulent, the viscosity also becomes strongly dependent on position (that is, it will vary from point to point in the fluid) and is usually referred to as eddy viscosity or turbulent coefficient of viscosity [7].

Theories for momentum transfer and viscosity can be divided into three broad categories: those based on rigorous statistical mechanical principles, such as computer simulation, Enskog theory, etc; those based on semi-theoretical principles, such as corresponding states, free volume theory, etc; and finally, those based on purely empirical insights. We will discuss in some detail methods that fall within the first category, since even though at present they cannot be used directly for estimating viscosity very efficiently, they provide considerable insight for developing more practical semi-theoretical methods. Purely empirical methods are of some utility in interpolating experimental data, but since they do not address the "cause and effect" issue, they cannot be used for any meaningful extrapolation.

THEORIES: DILUTE GASES

The estimation of viscosity from rigorous statistical mechanics is most tractable in the case of dilute monatomic molecules. The solution for such a case has been provided by Chapman and Enskog (CE) [8]. The error usually incurred in using the CE theory for densities up to one-fifth the critical density is about 5 percent [9]. In addition, the assumption of monatomicity is also not as restrictive as it may appear on first sight. CE theory is known to work well for polyatomic molecules [10], and can also be moderately useful for polar molecules, although an extension is available for including polar molecules in the CE framework [11, 12]. The final result from the CE theory for viscosity is:

$$\eta = \frac{5}{16} \frac{(\pi m k T)^{1/2}}{\pi \sigma^2 \Omega^{(2,2)*}} \tag{2}$$

where m = the molecular mass,
σ = size parameter (defined so that the intermolecular interaction is zero at σ separations)
k = the Boltzmann constant
T = absolute temperature
and $\Omega^{(2,2)*}$ = the reduced collision integral.

The latter is a function of temperature, and the intermolecular interaction between the molecules. The molecular interaction can be approximated by various potential models. For viscosity the most useful are the Lennard-Jones potential, and the m − 6 − 8 potential, defined as:

$$\phi_{LJ} = 4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right] \tag{3}$$

$$\phi_{m,6,8} = \frac{\varepsilon}{m-6}[6+2\gamma]\left(\frac{r_m}{r}\right)^{m} - \frac{\varepsilon}{m-6}[m-\gamma(m-8)]\left(\frac{r_m}{r}\right)^{6} - \gamma\varepsilon\left(\frac{r_m}{r}\right)^{8} \tag{4}$$

In Equation 3, σ and ε are the Lennard-Jones size and energy parameters, while in Equation 4 there are four independent parameters, m, γ, ε, and r_m. The collision integrals for the Lennard-Jones potential have been tabulated and fitted to an empirical expression by Neufeld et al., which for the viscosity are [13]:

$$\Omega = 1.16145/(T^*)^{0.14874} + 0.52487 \exp(-0.77320T^*) + 2.15178 \exp(-2.43787T^*) \quad (5)$$

where $T^* = kT/\varepsilon$ is the reduced temperature. The Lennard-Jones parameters are given in several texts and handbooks, e.g. [1, 9, 12]. The collision integrals for the m − 6 − 8 potential have been tabulated in reference [14], along with parameters for some molecules. In general, however, m − 6 − 8 potential parameters are not as widely available as Lennard-Jones parameters, even though it is generally considered a more realistic representation of intermolecular forces in simple systems.

For polar molecules, two approaches can generally be used. One can include electrostatic forces in Equations 3 or 4, or define an angle averaged potential, in which one attempts to incorporate electrostatic forces in the nonpolar part of the potential. Electrostatic forces can be included in an intermolecular potential, by either directly including the effect of the charge distribution (generally discretized), in the potential model, or by expanding the charge distribution in a multipolar expansion. In the multipolar expansion it is generally sufficient to include multipoles till the quadrupole moment in the expansion. In addition, multi-body effects such as induction forces are also usually much more important in polar systems. Finally, the intermolecular potential in polar molecules is also dependent on the orientation of the molecules, which complicates theoretical calculations considerably [9]. Mason and Monchick [11] have included dipolar interactions as a first approximation for the effect of polar forces. In addition to assuming that electrostatic multipole moments beyond the dipole can be ignored for viscosity estimations, Mason and Monchick also assumed that the relative orientation of the molecules remains constant during the collision. The collision integral was then calculated for several possible sets of relative orientations, and an unweighted average was used to obtain the final results. The collision integrals for such an intermolecular potential, and the parameters for several small polar molecules have been tabulated by them. Bae and Reed [15] have used the latter route, i.e., averaged dipolar interactions. It has been only moderately successful, since it requires the nonpolar parameters of the intermolecular potential to be temperature dependent, which further complicates the estimation technique.

For mixtures of dilute gases, the Chapman-Enskog theory leads to the following approximate equation:

$$\eta = \frac{\sum_{i=1}^{n} y_i \eta_i}{\sum_{j=1}^{n} y_j \phi_{ij}} \quad (6)$$

where ϕ_{ij} is a binary adjustable parameter. It is best estimated from binary experimental data ($\phi_{ii} = 1$), but several approximate correlations have been suggested in the past few decades [12]. For mixtures of simple nonpolar molecules only, mixing rules based on Enskog dense gas theory have been developed [16], which are also valid for dilute gases.

THEORIES: DENSE FLUIDS

Unlike dilute gases, the kinetic theory for dense gases has not been sufficiently developed to enable reasonable estimates to be made for viscosity using rigorous statistical mechanical theories. Consequently, many approximate semi-theoretical techniques have been developed in the past few decades. The most significant recent development in the theory for viscosity has been the development of the molecular dynamics technique for investigating viscosity in the dense fluid region.