FLUID MECHANICS AND ITS APPLICATIONS

D. Drikakis and B.J. Geurts (Eds.)

# Turbulent Flow Computation

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# Turbulent Flow Computation

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KLUWER ACADEMIC PUBLISHERS
DORDRECHT / BOSTON / LONDON

A C.I.P. Catalogue record for this book is available from the Library of Congress.

Turblence

ISBN 1-4020-0523-7

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Sold and distributed in North, Central and South America
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

*Printed on acid-free paper*



Printed in the Netherlands.

# Mechanics

## *FLUID* MECHANICS AND ITS APPLICATIONS

*Series Editor*: R. Moreau

*Aims and Scope of the Series*

The purpose of this series is to focus on subjects in which fluid mechanics plays a fundamental role. As well as the more traditional applications of aeronautics, hydraulics, heat and mass transfer etc., books will be published dealing with topics which are currently in a state of rapid development, such as turbulence, suspensions and multiphase fluids, super and hypersonic flows and numerical modelling techniques. It is a widely held view that it is the interdisciplinary subjects that will receive intense scientific attention, bringing them to the forefront of technological advancement. Fluids have the ability to transport matter and its properties as well as transmit force, therefore fluid mechanics is a subject that is particularly open to cross fertilisation with other sciences and disciplines of engineering. The subject of fluid mechanics will be highly relevant in domains such as chemical, metallurgical, biological and ecological engineering. This series is particularly open to such new multidisciplinary domains.

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TURBULENT FLOW COMPUTATION

FLUID MECHANICS AND ITS APPLICATIONS
Volume 66

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*Aims and Scope of the Series*

The purpose of this series is to focus on subjects in which fluid mechanics plays a fundamental role.

As well as the more traditional applications of aeronautics, hydraulics, heat and mass transfer etc., books will be published dealing with topics which are currently in a state of rapid development, such as turbulence, suspensions and multiphase fluids, super and hypersonic flows and numerical modelling techniques.

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The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of a field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

*For a list of related mechanics titles, see final pages.*

# Preface

In various branches of fluid mechanics, our understanding is inhibited by the presence of turbulence. Although many experimental and theoretical studies have significantly helped to increase our physical understanding, a comprehensive and predictive theory of turbulent flows has not yet been established. Therefore, the prediction of turbulent flow relies heavily on simulation strategies. The development of reliable methods for turbulent flow computation will have a significant impact on a variety of technological advancements. These range from aircraft and car design, to turbomachinery, combustors, and process engineering. Moreover, simulation approaches are important in materials design, prediction of biologically relevant flows, and also significantly contribute to the understanding of environmental processes including weather and climate forecasting.

The material that is compiled in this book presents a coherent account of contemporary computational approaches for turbulent flows. It aims to provide the reader with information about the current state of the art as well as to stimulate directions for future research and development. The book puts particular emphasis on computational methods for incompressible and compressible turbulent flows as well as on methods for analysing and quantifying numerical errors in turbulent flow computations. In addition, it presents turbulence modelling approaches in the context of large eddy simulation, and unfolds the challenges in the field of simulations for multiphase flows and computational fluid dynamics (CFD) of engineering flows in complex geometries. Apart from reviewing main research developments, new material is also included in many of the chapters.

This book aims to appeal to a broad audience of applied scientists and engineers who are involved in the development and application of CFD methods for turbulent flows. The readership includes academic researchers as well as CFD practitioners in industry. The chapters were composed to constitute an advanced textbook for PhD candidates in the field of CFD and turbulence. The book can also be used as a complementary textbook at the level of MSc (or MEng) studies in engineering, applied mathematics and physics departments.

In the rest of this preface we will briefly outline the content of the contributing chapters.

The first chapter provides a review of spectral element methods on unstructured grids and focuses primarily on the numerical uncertainties in under-resolved simulations using spectral methods. The authors discuss the effect of under-resolved discretization of the advective (nonlinear) terms and dealiasing on non-uniform grids. They present several flow examples and diagnostic approaches that can be employed to detect erroneous predictions.

Chapter 2 outlines the basic structure of high resolution methods and proposes their use as an effective turbulence model in the context of large eddy simulation (LES). Theoretical arguments as well as computational evidence, based on comparisons of multimaterial mixing simulations and experiments, are provided. These concern the ability of high resolution methods for hyperbolic conservation laws to achieve many of the properties of subgrid scale models.

Issues related to symmetry-preserving discretization of the Navier-Stokes equations and their effects on turbulent flow simulations, are discussed in Chapter 3. The authors draw the attention of the reader to difference operators that have the same symmetry properties as the corresponding differential operators. These are illustrated for model equations such as the convection-diffusion equation, as well as for the full Navier-Stokes equations.

The fourth chapter presents methods for analysing and quantifying numerical errors in direct numerical simulations (DNS) and LES of turbulent flow. The author discusses all types of errors arising in these simulations, i.e., aliasing, truncation, time-stepping and commutation errors, and comments on their analysis.

Chapter 5 presents the design of adaptive low-dissipative high order schemes for turbulent flow computations. A summary of linear and nonlinear stability, and an outline of the rationale and criteria for designing such adaptive schemes, is presented. The control of adaptive numerical dissipation for high order schemes is also covered.

The sixth chapter discusses issues pertinent to the predictability and reliability of numerical simulations of multiscale complex nonlinear problems in computational fluid dynamics. The author outlines the sources of nonlinearities, the knowledge gained by studying the dynamics of numerics for nonlinear model problems, as well as specific approaches for ensuring confidence in the numerical simulations.

The Lagrangian-Averaged Navier-Stokes$-\alpha$ (LANS$-\alpha$) approach for modelling turbulence is presented in Chapter 7. This approach aims to eliminate some of the heuristic elements that would otherwise be involved in the modelling of subgrid scale stresses. The authors investigate the physical and numerical properties of the LANS$-\alpha$ subgrid parameterization through simulations of a turbulent mixing layer.

Developments and challenges in the computation of geophysical turbulence are discussed in Chapter 8. It is demonstrated that in the absence of an explicit subgrid-scale turbulence model, nonoscillatory forward-in-time (NFT) methods offer means of implicit subgrid-scale modelling. These methods can be quite effective in large-eddy simulations of high Reynolds number flows. Theoretical discussions are illustrated with examples of meteorological flows that address the range of applications from micro-turbulence to change in climate.

The ninth chapter discusses developments in the field of turbulent multiphase flows. A method based on solving the Navier-Stokes equations by a finite difference/front tracking technique is presented. The inclusion of fully deformable interfaces and surface tension, in addition to inertial and viscous effects, is described. The chapter also highlights new areas where computations are still in their infancy.

Chapter 10 demonstrates the applicability of modern computational methods and engineering turbulence models to a number of turbulent flows of engineering interest. The techniques discussed in this chapter include traditional turbulence closures as well as hybrid RANS/LES models for unsteady flows. The generation of high quality grids and the development of efficient methods for unsteady flows are identified as major challenges in future CFD research.

We would like to gratefully acknowledge the contributing authors for their substantial effort in preparing the chapters. We hope that the book will provide a good introduction to the various facets of computational fluid dynamics as well as stimulate further research in the fields of numerical methods and turbulence modelling, and their application in technology and natural sciences.

DIMITRIS DRIKAKIS, LONDON, UNITED KINGDOM.

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# Contributing Authors

**Paul Batten** obtained his Ph.D. in parallel computing at the University of Southampton, UK, in 1991. He subsequently held positions at the Manchester Metropolitan University and UMIST, Manchester, performing research into blast-wave simulation and turbulence modeling, respectively. Dr. Batten moved to California in January 1999 to work for Metacomp Technologies, Inc., where his current research activities include acoustics and turbulence modeling for unsteady flows. His research interests include computational methods, numerical algorithms and turbulence modeling.

**Bernard Bunner** is an engineer in the Microfluidics and Biotechnology group at Coventor, a MEMS consulting company. He obtained his PhD in Mechanical Engineering and an MSc in Electrical Engineering from the University of Michigan. His research interests include multiphase flows, microfluidics and numerical methods.

**Sukumar Chakravarty** is the founder and president of Metacomp Technologies, Inc., since 1994. From 1979 till then he was Manager of CFD at the Rockwell Science Center, earning the Rockwell Engineer of the Year award in 1989. He is an Adjunct Professor at UCLA, teaching numerical analysis and computational aerodynamics. He is a pioneer in numerical algorithms and several other computational areas. He was co-author of a paper that won NASA's H. Julian Allen Award for 1985.

**Dimitris Drikakis** is a Professor of Fluid Mechanics at Queen Mary, University of London (QMUL). Previous academic appointments include a visiting Professorship at the Laboratory of Aerodynamics and Biomechanics of the Universite de la Méditerranée, Marseille, France; a Readership in Computational Fluid Dynamics at QMUL; a Lectureship at the University of Manchester Institute of Science and Technology (UMIST); the posts of senior scientist and group leader at the Chair of Fluid Mechanics of the University of Erlangen-Nuremberg, Germany. His research interests include computational fluid dynamics, computational methods, turbulence, aerodynamics, biofluid mechanics, microflows, nano-engineering and scientific computing.

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**Bernard J. Geurts** teaches Computational Mathematical Physics at the University of Twente since 1991. He is a visiting professor at Queen Mary, University of London since 1999. He coordinates the special interest group of ERCOFTAC (European Research Council On Flow, Turbulence And Combustion) on computational fluid dynamics (LESig) and is author of the book *Elements of Direct and Large-Eddy Simulation.* His research interests center around flows with complex physics, e.g., turbulence, multiphase flows, polymer-physics, combustion and biology. Moreover, he works in nonlinear dynamics, numerical methods and simulation.

**Sandip Ghosal** is currently an Associate Professor of Mechanical Engineering at Northwestern University. He obtained a Ph.D. in Physics from Columbia University in the area of Astrophysical Fluid Dynamics and was employed as a researcher at Stanford University, Los Alamos National Laboratories and Sandia National Laboratories in the United States. He is most well known in the turbulence community through his contributions to LES, in particular in the mathematical development of the "dynamic model" and the systematic methods of error analysis that he introduced in LES. In addition to turbulence, his current research interests include combustion and the fluid mechanics of microfluidic systems.

**Uriel Goldberg** received his Ph.D.in physics of fluids from Case Institute of Technology, 1984, was Member of the Technical Staff, Rockwell Science Center, 1984-1995 and research associate, UMIST, Manchester, England, 1995-

1996. Dr. Goldberg joined Metacomp Technologies, Inc. as Senior Scientist in 1996. His activities include development of turbulence models for use in CFD.

**Darryl D. Holm** works in the Mathematical Modeling and Analysis Group in the Theoretical Division at Los Alamos National Laboratory. He is co-founder and past Acting Director of the Los Alamos Center for Nonlinear Studies and is now a Laboratory Fellow. He currently leads the Turbulence Working Group at Los Alamos. Holm's primary scientific interest is nonlinear science – ranging from integrable to chaotic behavior – especially nonlinear dynamics of optical pulses and fluids. In fluid dynamics, Holm is applying Lagrangian averaging, asymptotics and other dynamical systems methods to study the mean effects of subgrid scales on nonlinear wave structures and momentum transport as a basis for turbulence closure models.

**George Em Karniadakis** received his M.Sc. and Ph.D. from Massachusetts Institute of Technology in 1984 and 1987, respectively, both in Mechanical Engineering. He did his postdoc at Stanford University, and he previously taught at Princeton University. He is currently Professor of Applied Mathematics at Brown University. He has pioneered spectral methods on unstructured grids, parallel simulations of turbulence in complex geometries, and microfluidics simulations.

**Robert M. Kirby** received his B.Sc. in Applied Mathematics and Computer and Information Sciences from the Florida State University in 1997. He received his Sc.M. in Applied Mathematics from Brown University in 1999, and is currently working on a Sc.M. in Computer Science and Ph.D. in Applied Mathematics at Brown University. His research interests are in software design, parallel computing and direct numerical simulation of flow-structure interactions.

**Joseph M. Prusa** is a Collaborating Associate Professor at Iowa State University, Ames, IA. He has also been a visiting scientist at the National Center for Atmospheric Research, Boulder, CO. His research interests include atmospheric physics and the development of generalized coordinate models for analysis and computation of thermo-fluid dynamics problems.

**William Rider** is a Technical Staff Member in the Computer and Computational Science Division at Los Alamos National Laboratory. He has worked at Los Alamos since 1989. His principal research activities include the development of high resolution shock capturing methods, solution methods for multimaterial incompressible flows, numerical methods for mixing flow, Newton-