Developments in Heat Transfer

# Modelling and Simulation of Turbulent Heat Transfer

Editors: B. Sundén & M. Faghri

WIT PRESS

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# Modelling and Simulation *of* Turbulent Heat Transfer

# International Series on Developments in Heat Transfer

## Objectives

The Developments in Heat Transfer book Series publishes state-of-the-art books and provides valuable contributions to the literature in the field of heat transfer. The overall aim of the Series is to bring to the attention of the international community recent advances in heat transfer by authors in academic research and the engineering industry.

Research and development in heat transfer is of significant importance to many branches of technology, not least in energy technology. Developments include new, efficient heat exchangers, novel heat transfer equipment as well as the introduction of systems of heat exchangers in industrial processes. Application areas include heat recovery in the chemical and process industries, and buildings and dwelling houses where heat transfer plays a major role. Heat exchange combined with heat storage is also a methodology for improving the energy efficiency in industry, while cooling in gas turbine systems and combustion engines is another important area of heat transfer research.

To progress developments within the field both basic and applied research is needed. Advances in numerical solution methods of partial differential equations, high-speed, efficient and cheap computers, advanced experimental methods using LDV (laser-doppler-velocimetry), PIV (particle-image-velocimetry) and image processing of thermal pictures of liquid crystals, have all led to dramatic advances during recent years in the solution and investigation of complex problems within the field.

The aims of the Series are achieved by contributions to the volumes from invited authors only. This is backed by an internationally recognised Editorial Board for the Series who represent much of the active research worldwide. Volumes planned for the series include the following topics: Compact Heat Exchangers, Engineering Heat Transfer Phenomena, Fins and Fin Systems, Condensation, Materials Processing, Gas Turbine Cooling, Electronics Cooling, Combustion-Related Heat Transfer, Heat Transfer in Gas-Solid Flows, Thermal Radiation, the Boundary Element Method in Heat Transfer, Phase Change Problems, Heat Transfer in Micro-Devices, Plate-and-Frame Heat Exchangers, Turbulent Convective Heat Transfer in Ducts, Enhancement of Heat Transfer and other selected topics.

# PREFACE

The book focuses on modeling and simulation of fluid flow and thermal transport phenomena in turbulent convective flows. The objective is to present the current state-of-the-art to predict turbulent heat transfer processes in fundamental and idealized flows as well as in engineering applications. The chapters cover a wide range of topics and are invited contributions from some of the most prominent scientists in this field.

The first chapter is introductory and gives an overview and classification of different turbulence models with focus on the essence of the approaches, their ability to predict correctly, and their turn-around time. It also provides a detailed overview on mathematical models including DNS, LES, RANS and hybrid methods that are currently being used in engineering design and analysis. Finally, it concludes with an appraisal of various models and addresses prediction of transition.

The second chapter presents a numerical algorithm for large eddy simulations (LES) of wall-bounded turbulent flows using unstructured computational grids. The focus is on predicting temperature and heat flux variation on walls and protrusions made of multiple materials with different properties in flows of industrial relevance such as cooling of electronics or of internal passages of gas-turbine blades. The approach adopted follows the Reynolds-averaged Navier–Stokes approach (RANS), with necessary modifications pertinent to the LES model.

Chapter three explores numerical simulation of turbulence–radiation interactions in reacting flows. Probability density function (PDF) methods have been found to be effective tools for the study of turbulence–radiation interactions. This chapter focuses on the introduction of PDF methods and their application to diffusion flames.

Chapter four examines the predictive capability of existing turbulence models for film-cooling flow applications and identifies their limitations. A new model has been proposed and the benefits of the model from robustness and accuracy perspectives have been identified.

Chapter five summarizes the current knowledge on the numerical prediction of turbulent impinging jet flows. The predictive capabilities of numerical models are evaluated by careful comparison with experimental data. Turbulent fluctuations in the velocity field are modeled using RANS methodology.

Chapter six describes recent advances and efforts to validate and apply RANS-based models for prediction of turbulent flow and heat transfer in ribbed ducts, relevant to gas turbine cooling and compact heat exchangers. The models are validated with available 2D and 3D experimental heat transfer and fluid flow data.

Prediction of transitional characteristics of flow and heat transfer in periodic fully developed ducts is presented in chapter seven. The prediction methodology is based on the low Reynolds number k–ε model coupled with the solution of the Navier–Stokes equations for the flow. The results are presented for the transitional characteristics of the fluid flow over an array of heated square blocks deployed along one wall of a parallel-plate duct and also for the fluid flow in corrugated ducts.

The last two chapters deal with simulation of turbulent flow and heat transfer for gas turbine applications. Turbulent heat transfer is of significant importance for the design of convectively cooled and film-cooled components in gas turbines. Chapter eight deals with turbulent and conjugate heat transfer simulation for gas turbine application and chapter nine focuses on simulation of turbulent flow in a duct with and without rotation, with application to cooling passages of gas turbine blades.

All of the chapters follow a unified outline and presentation to aid accessibility and the book provides invaluable information to both graduate researchers and R & D engineers in industry and consultancy.

We are grateful to the authors and reviewers for their contributions. We also appreciate the cooperation and patience provided by the staff of WIT Press and for their encouragement and assistance in producing this volume. The editors would also like to thank the Wenner-Gren Center Foundation in Sweden for the financial support.

Bengt Sunden and Mohammad Faghri
2005

WIT*PRESS*

## Condensation Heat Transfer Enhancement

***V.G. RIFERT**, Thermodistillation, Kiev, Ukraine and **H.F. SMIRNOV**, State Academy of Refrigeration, Odessa, Ukraine*

Professors V.G. Rifert and H.F. Smirnov have carried out research on heat transfer enhancement by condensation and boiling for over 30 years and have published more than 200 papers on the topic. In this book they provide research results from the former USSR to which there has previously been little access and also describe different theoretical models of the condensation process.

**Partial Contents:** Theoretical Principles of Heat Transfer at Film Condensation; Condensation on Horizontal Low-Finned Tubes – Theoretical Models; Experimental Study of Condensation Heat Transfer on Finned Tubes; Condensation on Vertical Profiled Surfaces and Tubes; Heat Transfer Enhancement at Film Condensation Inside Tubes; Condensation in the Electric Field; Hydrodynamics and Heat Transfer at Film Condensation of Rotating Surfaces.

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## Heat and Fluid Flow in Microscale and Nanoscale Structures

*Editors: **M. FAGHRI**, University of Rhode Island, USA and **B. SUNDÉN**, Lund Institute of Technology, Sweden*

Presenting state-of-the-art knowledge in heat transfer and fluid flow in micro- and nanoscale structures, this book provides invaluable information for both graduate researchers and R&D engineers in industry and consultancy. All of the chapters are invited contributions from some of the most prominent scientists in this active area of interdisciplinary research and follow a unified outline and presentation to aid accessibility.

**Contents:** Miniature and Microscale Energy Systems; Nanostructures for Thermoelectric Energy; Heat Transport in Superlattices and Nanowires; Thermomechanical Formation and Thermal Detection of Polymer Nanostructures; Two-Phase Flow Microstructures in Thin Geometries – Multi-Field Modeling; Radiative Energy Transport at the Spatial and Temporal Micro/Nanoscales; Direct Simulation Monte Carlo of Gaseous Flow and Heat Transfer in a Microchannel; DSMC Modeling of Near-Interface Transport in Liquid-Vapor Phase-Change Processes with Multiple Microscale Effects; Molecular Dynamics Simulation of Nanoscale Heat and Fluid Flow.

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# CONTENTS

# Chapter 1

# An overview of turbulence modeling

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## Abstract

Despite its great importance and the tremendous efforts that have been made to understand it, turbulence remains a thorny problem. Though great strides have been made and a plethora of predictive turbulence models have been developed, there is only a modicum of guidance available on what is practical and what can be relied upon for design and analysis. This chapter seeks to provide an introduction to turbulence modeling and to make some sense of it. First, the physics of turbulence are described briefly. Then, different mathematical approaches used to predict turbulent flows are outlined, with focus on their essence, their ability to predict correctly, and their turn-around time. Next, widely used, single-point closure models for Reynolds-averaged Navier–Stokes equations are summarized, with some reference to the principles used to develop them. Finally, an appraisal is given of the current state-of-art models, in order to provide guidelines on their usefulness. The chapter concludes with comments on transition prediction.

## Nomenclature

| | |
|---|---|
| $b_{ij}$ | anisotropy tensor |
| $C_p$ | constant pressure specific heat |
| $d$ | shortest distance to the wall |
| $k$ | turbulent kinetic energy or thermal conductivity |
| $P$ | rate of turbulent kinetic energy production |

| | |
|---|---|
| $Pr_T$ | turbulent Prandtl number |
| $R_T$ | turbulent Reynolds number: $R_T = k^2/\varepsilon\nu$ |
| $S_{ij}$ | mean rate of strain tensor: $S_{ij} = \frac{1}{2}\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right)$ |
| $t$ | time |
| $T$ | turbulent time scale or mean temperature |
| $U_i$ | mean velocity component in i-direction: $U_i = \overline{\overline{u}_i + u_i} = \overline{u}_i$ |
| $U_\tau$ | friction velocity: $U_\tau = \sqrt{\tau_w / \rho}$ |
| $u_i$ | fluctuating component of the velocity in i-direction |
| $x_i$ | spatial coordinate in i-direction |
| $y$ | coordinate normal to the wall |
| $y^+$ | normalized distance from wall: $y^+ = \rho U_\tau y / \mu$ |

**Greek**

| | |
|---|---|
| $\alpha$ | thermal diffusivity: $\alpha = k / \rho C_p = \nu / Pr_T$ |
| $\alpha_T$ | turbulent thermal diffusivity |
| $\varepsilon$ | dissipation rate of turbulent kinetic energy |
| $\kappa$ | von Karman constant |
| $\theta$ | fluctuating temperature |
| $\mu$, $\nu$ | dynamic, kinematic viscosity |
| $\mu_T$, $\nu_T$ | turbulent dynamic, kinematic viscosity |
| $\rho$ | density |
| $\tau_w$ | wall shear stress |
| $\omega$ | dissipation rate per unit k |
| $\Omega$ | vorticity |

# 1 Introduction

Most flows of engineering interest are turbulent. Turbulent flows are characterized by unsteadiness, three-dimensionality, and highly convoluted flow structures that span a wide range of length and time scales [1–5]. Although features of a turbulent flow can be immensely complicated at any instant of time, their ensemble-averaged mean might not be. For example, the mean turbulent flow can be steady or unsteady as well as zero, one, two or three-dimensional, with simple, smooth structures, dominated by one or two length and time scales.

For most engineering applications, interest is only in the mean flow field. The goal in predicting turbulent flows for design and analysis is to account for the relevant physics by using the simplest and the most economical mathematical model possible. Economics is as important as accuracy because predicting turbulent flows can be highly intensive computationally. In engineering applications, a prediction must be not only meaningful, but also obtained in a reasonable amount of time, in order to have a chance to impact design.

The objective of this introductory chapter is four-fold. The first is to give a