Preface

This book is primarily intended as a graduate text in Turbulent Flows for engineering students, but it may also be valuable to students in atmospheric sciences, applied mathematics and physics, as well as to researchers and practicing engineers.

The principal questions addressed are:

(i) How do turbulent flows behave?

(ii) How can they be described quantitatively?

(iii) What are the fundamental physical processes involved?

(iv) How can equations be constructed to simulate or model the behavior of turbulent flows?

In 1972 Tennekes and Lumley produced a textbook that admirably addresses the first three of these questions. In the intervening years, due in part to advances in computing, great strides have been made towards providing answers to the fourth question. Approaches such as Reynolds-stress modelling, PDF methods, and large-eddy simulation (LES) have been developed that, to an extent, provide quantitative models for turbulent flows. Accordingly, here (in Part II) an emphasis is placed on understanding how model equations can be constructed to describe turbulent flows; and this objective provides focus to the first three questions mentioned above (which are addressed in Part I). However, in contrast to the book by Wilcox (1993), this text is not intended to be a practical guide to turbulence modelling. Rather, it explains the concepts and develops the mathematical tools that underlie a broad range of approaches.

There is a vast literature on turbulence and turbulent flows, with many worthwhile questions addressed by many different approaches. In a one-semester course, or in a book of reasonable length, it is possible to cover only a fraction of the topics, and then with only a few of the possible approaches. The present selection of topics and approaches has evolved over the 20 years I have been teaching graduate courses on turbulence at MIT and Cornell. The emphasis on turbulent flows—rather than on the theory of homogeneous turbulence—is appropriate to applications in engineering, atmospheric sciences and elsewhere. The emphasis on quantitative theories and models is consistent with the scientific objective—of developing a tractable, quantitatively-accurate theory of the phenomenon—and is ideal for providing a solid understanding of computational approaches to turbulent flows, e.g., turbulence models and LES.

With the exceptions of LES and DNS (direct numerical simulation), the theories and models presented stem from the *statistical* approach, pioneered by Osborne Reynolds, G.I. Taylor, Prandtl, von Kármán and Kolmogorov. A sizeable fraction of the academic research work in the last 25 years has emphasized a more *deterministic* viewpoint: for example experiments on coherent structures, and models based on low-dimensional dynamical systems (e.g., Holmes et al. 1996). At this stage, this alternative approach has not led to a generally applicable quantitative model, nor—for better or for worse—has it had a major impact on the statistical approaches. Consequently, the deterministic viewpoint is not emphasized nor is it systematically presented.

The book consists of two Parts followed by a number of Appendices. Part I provides a general introduction to turbulent flows, including: the Navier-Stokes equations; the statistical representation of turbulent fields; mean-flow equations; the behavior of simple free-shear and wall-bounded flows; the energy cascade, turbulence spectra and the Kolmogorov hypotheses. In the first five chapters, the focus is first on the mean velocity fields, and how they are affected by the Reynolds stresses. The concept of "turbulent viscosity" is introduced with a thorough discussion of its deficiencies. The focus then shifts to the turbulence itself, in particular to the production and dissipation of turbulent kinetic energy. This sets the stage for a description (in Chapter 6) of the energy cascade and the Kolmogorov hypotheses. The spectral description of homogeneous turbulence in terms of Fourier modes in wavenumber space is developed in some detail. This provides an alternative perspective on the energy cascade; and it is also used in subsequent chapters in the descriptions of DNS, LES and rapid distortion theory (RDT).

Simple wall-bounded flows are described in Chapter 7, starting with the mean velocity fields and proceeding to the Reynolds stresses. The exact transport equations for the Reynolds stresses are introduced, and their balances in a turbulent boundary layers are examined.

The simulation and modelling approaches described in Part II are: DNS, turbulent viscosity models (e.g., the k-ε model), Reynolds-stress models, PDF methods and LES. It is natural to consider DNS first (in Chapter 9) since it is conceptually the most straightforward approach. But its restriction to simple, low-Reynolds-number flows motivates the consideration of other approaches. The most widely used turbulence models are the turbulent-viscosity models described in Chapter 10. Reynolds-stress models (Chapter 11) provide a more satisfactory connection to the physics of turbulence. The Reynolds-stress balance equations can be obtained from the Navier-Stokes equations, and the various contributions to this balance have been measured in experiments and simulations. Rapid distortion theory is introduced to shed light on the effects that mean velocity gradients have on the Reynolds stresses. In developing and presenting modelled Reynolds-stress equations, the emphasis is on the fundamental concepts and principles, rather than on the detailed forms of particular models.

Chapter 12 deals with PDF methods. The primary object of study is the (one-point, one-time, Eulerian) joint probability density function (PDF) of velocity. The first moments of this PDF are the mean velocities; the second moments are the Reynolds stresses. For several reasons it is both natural and advantageous to proceed from the Reynolds-stress to the PDF level of description: in the PDF equation, convection (by both mean and fluctuating velocity) appears in closed form, and hence does not have to be modelled; the effect of rapid distortions on turbulence can (in a limited sense) be treated exactly; and PDF methods are becoming widely used for turbulent reactive flows (e.g., turbulent combustion) because they are able to treat reaction exactly—without modelling assumptions.

Essential ingredients in PDF methods are stochastic Lagrangian models, such as the Langevin model for the velocity following a fluid particle. These models are also described in the context of turbulent dispersion (where they originated with G.I. Taylor's 1921 classic paper).

The final chapter describes large-eddy simulation (LES) in which the large-scale turbulent motions are directly represented, while the effects of the smaller, subgrid-scale motions are modelled. Many of the concepts and techniques developed in Chapters 9-12 find application in the modelling of the subgrid-scale processes.

I use this book in a one-semester course, taught to students who previously have taken one or more graduate courses in fluid mechanics and applied mathematics. For most students, there is a good deal of new material, but I find that they can successfully master it, provided that it is clearly and fully explained. Accordingly there are many appendices that provide the necessary development and explanation of mathematical techniques and results used in the text. In my experience, it is best not to rely upon the students' prior knowledge of probability theory, and consequently the necessary material is provided in the text (e.g., Sections 3.2–3.5).

For a less demanding pace, Parts I and II can be covered in two semesters—there is ample material. Alternatively, if a coverage of modelling is not required, Part I by itself provides a reasonably complete introduction to turbulent flows.

Many of the exercises ask the reader to "Show that ...", and thereby introduce additional results and observations. Consequently, it is recommended that all the exercises be read, even if they are not performed. The book is designed to be a self-contained text, but sufficient references are given to provide an entry into the research literature.

However much care is taken in the preparation of a book of this nature, it is inevitable that there are errors in the first printing. A list of know corrections is given at `http://mae.cornell.edu/~pope/TurbulentFlows`. The reader is asked to report any further corrections to the author at `pope@mae.cornell.edu`.

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