Preface

The present book was originally developed for a postgraduate course on Modeling and Simulation of Turbulent Flows taught by the author at Aix-Marseille University for a number of years. A first edition in French appeared in 1993 at Hermes publishers, with new expanded editions in 1998 and 2006. This last French edition was the basis for the present English edition.

Although there exists extensive scientific literature that deals with turbulent flows and their numerical modeling, the information is generally disseminated among numerous papers in specialized international publications. The aim of the present book is to give an introductory, synthetic presentation of numerical modeling and simulation methods for turbulent flows from its basic foundations. It is primarily intended for potential users of numerical models, postgraduate students at university, as well as researchers and practicing engineers interested in the practical calculation of turbulent flows. Some technical details have been marked by a vertical line in the left margin. These may be of interest to some readers but can be skipped if desired. The book gives the physical foundations of the modeling methods and leads the reader to a point where he can implement and make use of the model equations in practical applications with a clear knowledge of the underlying physics and then go deeper into more advanced techniques. Having in mind the actual numerical solution on the computer, some recapitulative tables on numerical methods are grouped together in the last chapter. We shall not claim to or aim at exhaustiveness by any means, considering the numerous works that have been achieved in the field of turbulence modeling, but rather we shall try to follow a rational pathway through the multiform landscape of turbulence modeling, with an emphasis laid upon basic concepts and methods of approach.

In spite of the great variety of experimental studies on the structure of turbulent flows, the fundamental mechanisms in turbulence phenomena still remain incompletely elucidated and even nowadays many problems remain open, sometimes enigmatic.

However, most fluid flows encountered in the domain of industrial practice are likely to be turbulent and many phenomena, such as heat or mass transfer, are so intimately linked to the fluid motion that their study requires prior calculation of the turbulent flow. Thus, the numerical prediction of turbulent flows is of primary importance for numerous practical applications (industrial, environment, etc.).

The proposed presentation relies on several traditional basic concepts for fluid turbulence phenomenology, and in particular the Kolmogorov theory. The methodology of one point closures is developed all the way to its application to second order moment transport models. Lower order models will then be presented as simplified approaches deduced from second order closures, even if the historical order is the reverse. The impact of spectral theories is also essential, in particular on the notions of spectral equilibrium or on linear and non-linear interactions. These spectral theories, although mainly representative of homogenous turbulence, allow a more refined description of turbulence interaction mechanisms.

Among existing theories and models, preference is given to methods that lead to actual numerical predictions of turbulent flows. In this way, and besides one point and two point statistical closures, the book also addresses large eddy simulation methods that have been developed and increasingly used since the advent of supercomputers. This standpoint has led us to discard detailed presentation of analytical theories and every purely theoretical approach not leading to practical prediction methods.

Compared to the deductive reasoning prevailing in exact sciences, the method of approach used in turbulence modeling may be surprising because of its empiricism. However, the modeling approach is not specific to turbulence, it is also used in many domains in physics. According to M. Dode[1] there are two ways to study natural phenomena: the method of exact science and the model method. The method of exact science such as in thermodynamics, mechanics, optics, electromagnetism, is based on very few fundamental principles, the value of which is considered absolute in the field of the science under consideration. These fundamental principles or postulates have an experimental origin and have been discovered by induction. All scientific laws are then deduced from these first premises by applying mathematics and the rigor of these laws is absolute within the domain in which the postulates are assumed.

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1 Translated from M. DODE, *Le deuxième principe*, Sédes Ed., Paris, 1965.

On the other hand, the model method tries to interpret the phenomena and to represent their mechanisms through a picture. This is the case for the atomic theory which proposed a mechanical model for the structure of an atom. In the model method, we try to imagine a mechanism whose details remain hidden and that would be capable of giving an interpretation of observed facts. Once this mechanism is defined, we try to draw all the possible conclusions from it. The general character of the proposed model is then recognized according to the value of the predictions it allows, predictions that exact sciences are not able to provide. The method of exact science and the model method are not conflictive, they are complementary. The further our knowledge advances, the further the physical models move away from direct experimentation and become more and more abstract until they become pure "model equations".

According to this line of thought, a turbulence model is thus composed of "model equations". They describe a phenomenon, which is not actual turbulence but which is sufficiently close to it for representing a useful simplified picture. The accuracy of the model and its ability to represent the properties of a turbulent flow, are directly dependent on our knowledge of the physics of the phenomena that it has been possible to build in the equations.

The model is an almost quantified summary of our present knowledge on fluid turbulence. According to this point of view, mathematical models are perfectible and indeed are improving everyday, enriched by new concepts inspired by experimental results or numerical simulations or progress achieved in theoretical approaches.

The present book gives a prominent position to formalism and equations, thus allowing a rational approach to models in connection with underlying physical concepts and intuition. Beyond the description of existing models, the aim is to show how to develop mathematical models and their elaboration process. In this prospect, equations, which are the very language of science, allow us both to condense the physical concepts into a mathematical scheme and to provide a predictive tool. They call to mind this "bijection" between the physical world and mathematical formalism toward which theories and models are tending.

Recent years have seen remarkable developments in turbulence modeling towards more and more advanced formulae that are the fruit of much research carried on in this domain by various research teams around the world. Effort has been concentrated in particular on the realizability properties allowing us to deal with "extreme" states of the turbulence field (high anisotropies and also compressibility effects, reorganization by rotation, etc.) and also on a more refined description of the underlying physics aiming at a wider universality of description. These efforts towards model development, along with the emergence of new concepts, are currently ongoing, largely boosted by the quick expansion of new measurement techniques such as lazer velocimetry and especially by the generalized use of direct numerical turbulence simulations that provide numerical databases for calibrating and testing turbulence models. Direct numerical simulations, in spite of their limitations in Reynolds number, allow us not only to consider types of flows or physical parameter values that are impossible to obtain experimentally but also to test the closure hypotheses directly. Thus, the different turbulent phenomena being more easily differentiated and studied separately, this results in a more detailed physical description that goes beyond a mere mimicry of the observed behavior of a turbulent flow. We can say that the development of new techniques of approach including direct numerical simulations of turbulence, far from substituting for modeling, have been on the contrary a catalyst for progression. We can then observe, not only an improvement of turbulence models but also a larger variety of model types (non-linear models, transport equations for new quantities, etc.) arising. Second order closures remain however a preferred reference level of closure allowing both extended potentials in physical description and an efficient numerical solution of the equations. From the user point of view, the methods of approach of turbulent flows are very varied, ranging from one point closure models with a limited number of equations up to advanced transport modeling and large eddy simulations that can be considered as hybrid methods between modeling and simulation. All these methods must be considered as more complementary than competitive and the choice of a particular method will be mainly guided by the type of problem to be solved and by the type of answers that are expected.