Turbulence in Fluids

Stochastic and Numerical Modelling

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by

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Second revised edition

:ADEMIC PUBLISHERS
'STON / LONDON

Library of Congress Cataloging in Publication Data

Lesieur, Marcel.
Turbulence in fluids : Stochastic and numerical modelling / Marcel Lesieur. -- 2nd rev. ed.
p. cm. -- (Fluid mechanics and its applications ; v. 1)
Includes bibliographical references.
Includes index.
ISBN 0-7923-0645-7 (alk. paper)
1. Fluid mechanics. 2. Turbulence. 3. Transport theory.
I. Title. II. Series.
QC145.2.L47 1991
532'.0527--dc20 90-46046

ISBN 0-7923-0645-7

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

Kluwer Academic Publishers incorporates
the publishing programmes of
D. Reidel, Martinus Nijhoff, Dr W. Junk and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

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

Printed on acid-free paper

Printed in the Netherlands

FLUID MECHANICS AND ITS APPLICATIONS

Volume 1

Series Editor: R. MOREAU
MADYLAM
Ecole Nationale Supérieure d'Hydraulique de Grenoble
Boîte Postale 95
38402 Saint Martin d'Hères Cedex, France

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 particulary 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.

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 to the first edition

Turbulence is a dangerous topic which is often at the origin of serious fights in the scientific meetings devoted to it since it represents extremely different points of view, all of which have in common their complexity, as well as an inability to solve the problem. It is even difficult to agree on what exactly is the problem to be solved.

Extremely schematically, two opposing points of view have been advocated during these last ten years: the first one is "statistical", and tries to model the evolution of averaged quantities of the flow. This community, which has followed the glorious trail of Taylor and Kolmogorov, believes in the phenomenology of cascades, and strongly disputes the possibility of any coherence or order associated to turbulence.

On the other bank of the river stands the "coherence among chaos" community, which considers turbulence from a purely deterministic point of view, by studying either the behaviour of dynamical systems, or the stability of flows in various situations. To this community are also associated the experimentalists who seek to identify coherent structures in shear flows.

My personal experience in turbulence was acquired in the first group since I spent several years studying the stochastic models of turbulence, applied to various situations such as helical or two-dimensional turbulence and turbulent diffusion. These techniques were certainly not the ultimate solution to the problem, but they allowed me to get acquainted with various disciplines such as astrophysics, meteorology, oceanography and aeronautics, which were all, for different reasons, interested in turbulence. It is certainly true that I discovered the fascination of Fluid Dynamics through the somewhat abstract studies of turbulence.

This monograph is then an attempt to reconcile the statistical point of view and the basic concepts of fluid mechanics which determine the evolution of flows arising in the various fields envisaged above. It is true that these basic principles, accompanied by the predictions of the instability theory, give valuable information on the behaviour of turbulence and of the structures which compose it. But a statistical analysis of these structures can, at the same time, supply information about strong non-linear energy transfers within the flow.

I have tried to present here a synthesis between two graduate courses given in Grenoble during these last few years, namely a "Turbulence" course and a "Geophysical Fluid Dynamics" course. I would like to thank my colleagues of the Ecole Nationale d'Hydraulique et Mécanique and Université Scientifique et Médicale de Grenoble, who offered me the opportunity of giving these two courses. The students who attended these classes were, through their questions and remarks, of great help. I took advantage of a sabbatical year spent at the Department of Aerospace Engineering of the University of Southern California to write the first draft of this monograph: this was rendered possible by the generous hospitality of John Laufer and his collaborators. Finally, I am grateful to numerous friends around the world who encouraged me to undertake this work.

I am greatly indebted to Frances Métais who corrected the English style of the manuscript. I am uniquely responsible for the remaining mistakes, due to last minute modifications. I ask for the indulgence of the English speaking reader, thinking that he might not have been delighted by a text written in perfect French. I hope also that this monograph will help the diffusion of some French contributions to turbulence research.

Ms Van Thai was of great help for the drawings. I am also extremely grateful to Jean-Pierre Chollet, Yves Gagne and Olivier Métais for their contribution to the contents of the book and their help during its achievement, and to Sherwin Maslowe who edited several Chapters.

This book was written using the TEX system. This would not have been possible without the constant help of Evelyne Tournier, of Grenoble Applied Mathematics Institute, and of Claude Goutorbe, of the University computing center.

Finally I thank Martinus Nijhoff Publishers for offering me the possibility of presenting these ideas.

Grenoble, October 1986 — Marcel Lesieur

Foreword to the second edition

Four years seems to be a good period of time to assess one's old points of view in such rapidly evolving field as Turbulence and Fluid Mechanics. The new possibilities offered by direct-numerical simulations have provided a lot of information on vortex dynamics, coherent structures and transition, compressible or rotating flows. The third chapter now gives a basic presentation of the linear-instability theory applied to shear or thermally unstable flows. A substantial part of the phenomenology in Chapter VI is devoted to mixing-length theory applied to turbulent shear flows. Concerning the stochastic models, it seemed necessary to include more information on the D.I.A. and R.N.G. theories. New calculations and experiments on stratified or shear flows have been incorporated, with emphasis put on the three-dimensional structures topology. Recent results on the intermittency of isotropic turbulence, and on passive scalar diffusion are also included. Finally, I rewrote Chapter XII on large-eddy simulation in order to make it more general and accessible to graduate students. This is the general point of view which has been my guideline during the write up for this second edition.

All this makes for a much more substantial book. I hope the original spirit of the first edition has not been lost, but I think it has resisted well to my attacks. Particular thanks are extended to Pierre Comte and the graduate students of our group for their important visual contribution which illustrates so well coherent structures and transition. Many thanks also to Olivier Métais who contributed greatly to certain of the new numerical results shown here, and for his permanent and total support and interest. Jim Riley was unlucky enough to spend his sabbatical with us in Grenoble during these last few months, and influenced many of my conclusions, while pretending to correct the language of a few chapters. Finally, I am indebted to all the sponsoring agencies and companies who showed a continuous interest during all these years in the development of fundamental and numerical research on Turbulence in Grenoble.

Grenoble, June 1990 Marcel Lesieur

Contents

Chapter I

INTRODUCTION TO TURBULENCE IN FLUID MECHANICS

1 - Is it possible to define turbulence?

Everyday life gives us an intuitive knowledge of turbulence in fluids: the smoke of a cigarette or over a fire exhibits a disordered behaviour characteristic of the motion of the air which transports it. The wind is subject to abrupt changes in direction and velocity, which may have dramatic consequences for the seafarer or the hang-glider. During air travel, one often hears the word turbulence generally associated with the fastening of seat-belts. Turbulence is also mentioned to describe the flow of a stream, and in a river it has important consequences concerning the sediment transport and the motion of the bed. The rapid flow of any fluid passing an obstacle or an airfoil creates turbulence in the boundary layers and develops a turbulent wake which will generally increase the drag exerted by the flow on the obstacle (and measured by the famous C_x coefficient): so turbulence has to be avoided in order to obtain better aerodynamic performance for cars or planes. The majority of atmospheric or oceanic currents cannot be predicted accurately and fall into the category of turbulent flows, even in the large planetary scales. Small-scale turbulence in the atmosphere can be an obstacle towards the accuracy of astronomic observations, and observatory locations have to be chosen in consequence. The atmospheres of planets such as Jupiter and Saturn, the solar atmosphere or the Earth's outer core are turbulent. Galaxies look strikingly like the eddies which are observed in turbulent flows such as the mixing layer between two flows of different velocity, and are, in a manner of speaking, the eddies of a turbulent universe. Turbulence is also produced in the Earth's outer magnetosphere, due to the development of instabilities caused by the interaction of the solar wind with the magnetosphere. Numerous other examples of turbulent flows arise in aeronautics, hydraulics, nuclear and chemical engineering, oceanography, meteorology, astrophysics and internal geophysics.

It can be said that a turbulent flow is a flow which is disordered in time and space. But this, of course, is not a precise mathematical definition. The flows one calls "turbulent" may possess fairly different dynamics, may be three-dimensional or sometimes quasi-two-dimensional, may exhibit well organized structures or otherwise. A common property which is required of them is that they should be able to mix transported quantities much more rapidly than if only molecular diffusion processes were involved. It is this latter property which is certainly the more important for people interested in turbulence because of its practical applications: the engineer, for instance, is mainly concerned with the knowledge of turbulent heat diffusion coefficients, or the turbulent drag (depending on turbulent momentum diffusion in the flow). The following definition of turbulence can thus be tentatively proposed and may contribute to avoiding the somewhat semantic discussions on this matter:

- a) Firstly, a turbulent flow must be unpredictable, in the sense that a small uncertainty as to its knowledge at a given initial time will amplify so as to render impossible a precise deterministic prediction of its evolution.

- b) Secondly, it has to satisfy the increased mixing property defined above.

- c) Thirdly, it must involve a wide range of spatial wave lengths.

Such a definition allows in particular an application of the term "turbulent" to some two-dimensional flows. It also implies that certain non dimensional parameters characteristic of the flow should be much greater than one: indeed, let l be a characteristic length associated to the large energetic eddies of turbulence, and v a characteristic fluctuating velocity; a very rough analogy between the mixing processes due to turbulence and the incoherent random walk allows one to define a turbulent diffusion coefficient proportional to $l\,v$. As will be seen later on, l is also called the integral scale. Thus, if ν and κ are respectively the molecular diffusion coefficients[1] of momentum (called below the kinematic molecular viscosity) and heat (the molecular conductivity), the increased mixing property for these two transported quantities implies that the two dimensionless parameters $R_l = lv/\nu$ and lv/κ should be much greater than one. The first of these parameters is called the Reynolds number, and the second one the Peclet number. Notice finally that the existence of a large Reynolds number implies, from the phenomenology developed in Chapter VI, that the ratio of the largest to the smallest scale may be

[1] These coefficients will be accurately defined in Chapter II.

of the order of $R_l^{3/4}$. In this respect, the property b) stressed above implies c).

A turbulent flow is by nature unstable: a small perturbation will generally, due to the nonlinearities of the equations of motion, amplify. The contrary occurs in a "laminar" flow, as can be seen on Figure I-1, where the streamlines, perturbed by the small obstacle, reform downstream. The Reynolds number of this flow, defined as

$$Re = [\text{fluid velocity}] \times [\text{size of the obstacle }]/\nu$$

is in this experiment equal to 2.26 10^{-2}. This Reynolds number is different from the turbulent Reynolds number introduced above, but it will be shown in chapter III that they both characterize the relative importance of inertial forces over viscous forces in the flow. Here the viscous forces are preponderant and will damp any perturbation, preventing a turbulent wake from developing.

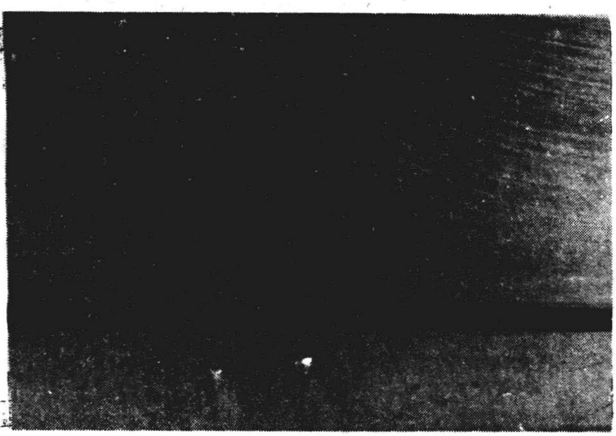

Figure I-1: Stokes flow of glycerin past a triangular obstacle (picture by S.Taneda, Kyushu University; from Lesieur (1982), courtesy S. Taneda and "La Recherche")

There is a lot of experimental or numerical evidence showing that turbulent flows are rotational, that is, their vorticity $\vec{\omega} = \vec{\nabla} \times \vec{u}$ is non zero, at least in certain regions of space. Therefore, it is interesting to ask oneself how turbulence does in fact arise in a flow which is irrotational upstream[2]. It is obviously due to the viscosity, since an immediate consequence of Kelvin's theorem, demonstrated in Chapter II, is that zero-vorticity

[2] for instance, a uniform flow

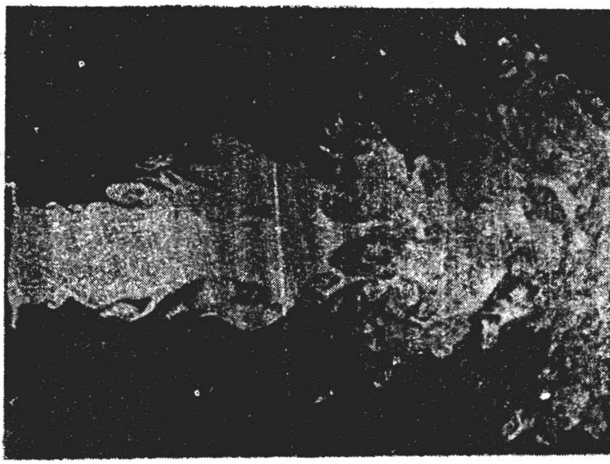

Figure I-2: turbulent jet (picture by J.L. Balint, M. Ayrault and J.P. Schon, Ecole Centrale de Lyon; from Lesieur (1982), courtesy J.P. Schon and "La Recherche")

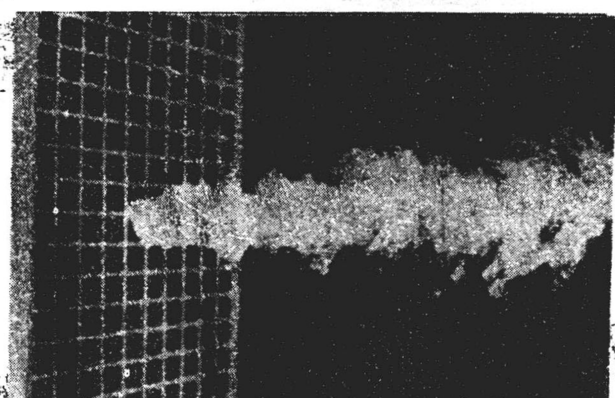

Figure I-3: turbulence created in a wind tunnel behind a grid. Here turbulence fills the whole apparatus, and a localized source of smoke has been placed on the grid to visualize the development of turbulence (picture by J.L. Balint, M. Ayrault and J.P. Schon, Ecole Centrale de Lyon; from Lesieur (1982), courtesy "La Recherche")

is conserved following the motion in a perfect fluid[3]: the presence of

[3] The perfect fluid is an approximation of the flow where molecular

Figure I-4: turbulence in a mixing layer (Brown and Roshko, 1974). In I-4a, the Reynolds number (based on the velocity difference and the width of the layer at a given downstream position) is twice Figure I-4b's (courtesy A.Roshko and J. Fluid Mech.)

boundaries or obstacles imposes a zero-velocity condition which produces vorticity. Production of vorticity will then be increased, due to the vortex filaments stretching mechanism to be described later, to such a point that the flow will generally become turbulent in the rotational regions. In what is called grid turbulence for instance, which is produced in the laboratory by letting a flow go through a fixed grid, the rotational "vortex streets" behind the grid rods interact together and degenerate into turbulence. Notice that the same effect would be obtained by pulling a grid through a fluid initially at rest. In some situations, the vorticity is created in the interior of the flow itself through some external forcing or rotational initial conditions (as in the example of the temporal mixing layer presented later on).

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viscous effects are ignored.