Turbulent Shear Flows

I

Selected Papers from the First International Symposium on Turbulent Shear Flows

Editors:
F. Durst B. E. Launder F. W. Schmidt
J. H. Whitelaw

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Selected Papers from the First International Symposium on Turbulent Shear Flows, The Pennsylvania State University, University Park, Pennsylvania, USA, April 18–20, 1977

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With 256 Figures

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Franz Durst

Sonderforschungsbereich 80 der Universität Karlsruhe, Kaiserstrasse 12,
D-7500 Karlsruhe 1, Fed. Rep. of Germany

Brian E. Launder

Department of Mechanical Engineering, University of California,
Davis, CA 95616, USA

Frank W. Schmidt

Mechanical Engineering Department, The Pennsylvania State University,
University Park, PA 16802, USA

James H. Whitelaw

Department of Mechanical Engineering, Imperial College of Science and Technology,
Exhibition Road, London SW7 2BX, England

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Preface

The present book contains papers that have been selected from contributions to the *First International Symposium on Turbulent Shear Flows* which was held from the 18th to 20th April 1977 at The Pennsylvania State University, University Park, Pennsylvania, USA. Attendees from close to 20 countries presented over 100 contributions at this meeting in which many aspects of the current activities in turbulence research were covered. Five topics received particular attention at the Symposium:

Free Flows
Wall Flows
Recirculating Flows
Developments in Reynolds Stress Closures
New Directions in Modeling

This is also reflected in the five chapters of this book with contributions from research workers from different countries. Each chapter covers the most valuable contributions of the conference to the particular chapter topic. Of course, there were many additional good contributions to each subject at the meeting but the limitation imposed on the length of this volume required that a selection be made.

The realization of the *First International Symposium on Turbulent Shear Flows* was possible by the general support of:

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The editors would like to express their thanks to the numerous people who helped to make the *First International Symposium on Turbulent Shear Flows* so successful. Particular thanks are due to those authors who contributed to this book. Their close cooperation with the editors and Springer-Verlag was very much appreciated.

Karlsruhe, October 1978 *The Editors*

Springer Series in Computational Physics

Editors: W. Beiglböck, H. Cabannes, S. Orszag

F. Bauer, O. Betancourt, P. Garabedian

A Computational Method in Plasma Physics

1978. 22 figures. VIII, 144 pages
ISBN 3-540-08833-4

Contents: Introduction. – The Variational Principle. – The Discrete Equations. – Description of the Computer Code. – Applications. – References. – Listing of the Code with Comment Cards. – Index.

This book presents a numerical method for computation and analysis of the equilibrium and stability of a plasma in three dimensions with toroidal geometry but no symmetry. The method has been used for the design of experiments at the Los Alamos Scientific Laboratory and the Max Planck Institute for Plasma Physics in Garching. A computer code that implements the method is described in detail and a Fortran listing is included. Examples are presented that compare numerical results with both exact theoretical solutions and experimental data. The material is relevant to high beta stellarator and Tokamak devices now in operation in connection with the magnetic fusion energy research program.

M. Holt

Numerical Methods in Fluid Dynamics

1977. 107 figures, 2 tables. VIII, 253 pages
ISBN 3-540-07907-6

Contents: General Introduction. Brief Review of Concepts of Numerical Analysis. – The Godunov Schemes. – The BVLR Method. – The Method of Characteristics for Three Dimensional Problems in Gas Dynamics. – The Method of Integral Relations. – Telenin's Method and the Method of Lines.

The first part of this monograph is concerned with numerical problems in gas dynamies. The discussion of finite difference methods is concentrated on hyperbolic systems. The author describes the present status of two approaches developed in the USSR, both based on the method of characteristics: the method of Godunov and the BVLR method due to Rusanov and coworkers. Other techniques treated in this volume are due to Butler and Sauer. In later chapters the author describes the methods of integral relations introduced by Dorodnitsyn, Telenin's method and the method of Lines – techniques based on polynomial or series representation to the unknowns – all applied to problems in fluid dynamics. The presentation is made for graduate students in mechanical engineering and applied mathematics with basic knowledge of fluid mechanics. Many applications and samples of numerical solutions of model problems are presented.

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Turbulence

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2nd corrected and updated edition. 1978. 47 figures, 4 tables. XI, 339 pages
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Contents:

P. Bradshaw: Introduction. *H.-H. Fernholz:* External Flows. *J. P. Johnston:* Internal Flows. *P. Bradshaw, J. D. Woods:* Geophysical Turbulence and Buoyant Flows. *W. C. Reynolds, T. Cebeci:* Calculation of Turbulent Flows. *B. E. Launder:* Heat and Mass Transport. *J. L. Lumley:* Two-Phase and Non-Newtonian Flows.

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Volume 41

Progress in Numerical Fluid Dynamics

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Editor: H. J. Wirz
1975. 146 figures, 6 tables.
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ISBN 3-540-07408-2

Contents:

F. R. Bailey: On the Computation of Two- and Three-Dimensional Steady Transonic Flows by Relaxation Methods. – *S.-I. Cheng:* A Critical Review of Numerical Solution of Navier-Stokes Equations. *B. Fraejis de Veubeke:* Variational Principles in Fluid Mechanics and Finite Element Applications. *E. Krause:* Recent developments of Finite-Difference Approximations for Boundary Layer Equations. *P. Kutler:* Computation of Three-Dimensional, Inviscid Supersonic Flows. *T. J. Mueller:* Numerical and Physical Experiments in Viscous Separated Flows. *J. Smoldern:* Stability of Explicit Time Dependent Treatment of Hyperbolic Boundary Problems. *G. C. Vansteenkiste:* Improving of the Numerical Solutions by using Analogue Subroutines. *H. J. Wirz:* Computation of Unsteady Boundary Layers.

Volume 72

Les Instabilités Hydrodynamiques en Convection Libre, Forcée et Mixte

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1978. 71 illustrations, 15 tables
IX, 202 pages (52 pages en Anglais)
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Contents:

A. Effets prétransitionnels et étude du point critique. *Avec contribution des J. P. Boon, L. Brenig, W. Horsthemke, M. Malek-Mansour, P. M. Bisch, P. Manneville, J. J. Bernard, J. P. Caltagirone, A. Azouni, J. C. Legros, J. K. Platten.* – B. Etude de la convection – liquides newtoniens. *Avec contribution des B. Dulieu, M. G. Velarde, P. H. Roberts, P. M. Bisch, A. Sanfeld, P. Joos, Y. Verburgh, P. Atten, J. C. Lacroix, P. Berge, M. Dubois, J. C. Legros, J. K. Platten, Y. Poneau.* – C. Liquides non newtoniens. *Avec contribution des E. Dubois-Violette, E. Guyon, P. Pieranski, H. N. W. Lekerkerker, G. Vanderborck, J. K. Platten*

Volume 75

Structure and Mechanisms of Turbulence I

Proceedings of the Symposium on Turbulence Held in Berlin August 1–5, 1977
Editor: H. Fiedler
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Volume 76

Structure and Mechanisms of Turbulence II

Proceedings of the Symposium on Turbulence Held in Berlin, August 1–5, 1977
Editor: H. Fiedler
1978. 209 figures, 3 tables.
XX, 406 pages
ISBN 3-540-08767-2

The volumes contain lectures held at the Symposium on Turbulence held in Berlin in 1977. They cover essentially all the problems (experimental, numerical, theoretical) and trends of present day turbulence research. The talks given mainly cover the following subjects: structure of free and wall-bounded shear flows, scalar transport and noise.

Contents

Part I Free Flows

Part II Wall Flows

Part III Recirculating Flows

Part IV Developments in Reynolds Stress Closures

Part V New Directions in Modeling

Part I

Free Flows

Introductory Remarks

J. H. Whitelaw

Department of Mechanics and Engineering, Imperial College of Science and Technology, Exhibition Road, London SW7 2BX, Great Britain

The five papers of this chapter are concerned with subsonic jet and wake flows but are otherwise different and together represent a wide spectrum of research activity. The first paper, that of *Dopazo* and *O'Brien*, addresses the problem of intermittency and its representation within conservation equations. The three following papers describe the application of three different experimental techniques, namely laser-Doppler anemometry, hot-wire anemometry and a four-wire arrangement for the measurement of velocity and temperature and their correlations; two of these contributions relate to jets and one to a plane wake. The last paper presents a method for the calculation of square jets issuing into still surroundings and makes use of a two-equation turbulence model and steady, three-dimensional, boundary-layer equations.

Rodi's [1] recent review of experimental data of uniform-density, free turbulent boundary layers provides a useful background of information against which to examine the two papers concerned with jets, and *Launder*'s [2] contribution to the modeling of passive scalars is relevant to the heated-wake measurements of *Fabris*. In addition, the present remarks and their relationship to the two calculation-type papers are made with the paper of *Launder* and *Morse* [3] in mind. This is particularly relevant since a major purpose of the Symposium from which the present papers stem, was to aid an appraisal and improvement of available methods for calculating turbulent shear flows. It also provides an important reference state from which to judge improvements since [3] provides evidence of present inability to represent mean flow features of a round jet, a plane jet and a mixing layer by the same turbulence model.

Examination of the magnitude of the discrepancies between calculation and measurement of simple plane and round jet properties provides a salutory starting point for this overview of free turbulent flows. Table 2 of [3] indicates discrepancies of 12% and 55% in the calculated values of growth rate, and the blame is attributed to the modeling of the pressure-strain process and to the source terms in the dissipation equation. As a consequence, *Rodi*'s [1] plea for measurements to test specific modeling assumptions is especially appropriate although, in view of the capabilities of presently available measurements techniques, very difficulty to satisfy.

The measurements of *Reed*, *Spiegel*, and *Hartland* were obtained in the fully developed region of an axisymmetric free jet and provide detailed correlation data which can be related to length scales and, therefore, to dissipation. The working fluid was water and with laser-Doppler anemometry allowed precise measurements with frequency response limited by the dimensions of the control volume but satisfactory for all except the smallest turbulent scales. The correlation measurements are not presented in the form of length scale distributions but, even if they were, the link between measurements and the length scale appearing in the dissipation term of the turbulence energy equation of a two-equation model cannot be explicitly defined. Similarly, in the Reynolds stress model of [3], where a relationship between the measurements and dissipation is desirable, this can only be provided if local isotropy is assumed and, once again, the consequent length scale is ill defined. These comments indicate a difficulty in fulfilling *Rodi*'s request for direct tests of assumptions. The value of the measurements remains and lies mainly in their contribution to increased physical understanding of free turbulent jet flows.

The far-wake experiments of *Fabris* also relate to a simple flow configuration and increase our physical understanding of turbulent flow, this time with emphasis directed to turbulent heat flux rather than to momentum flux. The working fluid was air and a new four-wire probe allowed a detailed investigation of conventional and conditioned averages of velocity, temperature, and their correlations. The measurements can be related directly to equations for the mean square of the temperature fluctuations and for turbulent heat flux. The conditioned averages indicate values of second- and third-order correlations within heated fluid which arise intermittently due to the turbulent motion and which can be directly linked to the intermittency discussion of *Dopazo* and *O'Brien*. The results make it very clear that even though an effective viscosity/effective "Prandtl" number approach can provide an approximate representation of the time-averaged properties, it is inappropriate to the conditionally sampled results. This very important conclusion implies that the simple effective Prandtl number approach, currently used for heat transfer and combustion calculations, for example *Hutchinson*, *Khalil* and *Whitelaw* [4], cannot be expected to result in more than an approximation for turbulent flows with temperature gradients. However, since the solution of time-averaged equations itself implies that any solution will be an approximate representation of the flow problem, the practical purpose is to ensure that the turbulent heat-flux approximation is as precise and economical of computer time as required.

Dopazo and *O'Brien* are particularly concerned with the intermittency of free turbulent flows and, recognizing the difference between conventional and conditional averages such as those of *Fabris*, developed equations to represent the conditionally averaged properties. The approach is promising although it is more likely to provide guidance for the modeling of more conventional equations than to form a basis for a generally applicable calculation procedure of its own. This probability is emphasized by the limited influence of intermittency in free flows and its much lesser relevance to confined flows. Conditional averages are useful in flows without free-flow-type intermittency, and the use of conditionally averaged equations is likely to have a wider application than that of the flow configuration of *Fabris*. It remains to be seen whether this conditioned approach may be overtaken by the subgrid scale modeling of Chap. 5, which can more directly represent identifiable structures.

A different form of identifiable structure exists in the jet flow of *Bremhorst* and *Harch* and has relevance to dispersion and noise problems. In this case, an axisymmetric free jet was pulsed at frequencies of 10 and 25 Hz with an upstream valve and hot-wire anemometry used to determine the resulting axial velocity and its moments. The mean velocity characteristics, in nondimensional form, were similar to those for the unpulsed flow but with increased entrainment due to the translation of the virtual origin. The rms of velocity fluctuations was increased by the imposed fluctuations, and the increased magnitude was sustained to 18 diameters, the furthest downstream measurement station. The turbulent fluctuations appear to be influenced by the imposed fluctuations only in the upstream region, but it is clear that an approach similar to that of *Dopazo* and *O'Brien* or the solution of time-dependent equations with subgrid scale modeling would be necessary to represent the flow. The measurements of spectra indicate the presence of a wide range of higher harmonics of the imposed-fluctuation frequency and suggest the additional possibility of a turbulence model involving wave number space.

McGuirk and *Rodi* describe calculated results obtained from the solution of three-dimensional, boundary-layer-type equations with a two-equation model modified empirically to represent round and plane jets. The modification involves one of the "constants" of the dissipation equation and replaces it by a linear function of a retardation parameter. This functional relationship has not been tested in any direct sense but is justified by calculations of round and plane jets, with the modification accepted as part of the model. These calculations result in values of mean velocity parameters in reasonable accord with measurement. The resulting calculations of three-dimensional jet flows, i.e., jets issuing from rectangular orifices, are shown to represent corresponding measurements with precision which is adequate for most engineering applications. Detailed examination of the results indicate discrepancies which, in part, stem from the initial conditions. Profiles of initial values of all dependent variables are required and can have a considerable influence on the downstream flow. For example, and particularly relevant to the calculations of *McGuirk* and *Rodi*, the initial transverse velocity components are unknown and can have a relatively large effect.

It should be clear from the above remarks that *Rodi*'s request for experimental data is being met, at least in part. Direct testing of assumptions inherent in presently formulated dissipation equations and the modeling of pressure correlations are beyond the capability of available instrumentation. The application of hot-wire and laser-Doppler anemometry is, however, resulting in a wider and increasingly more precise range of data against which models embodied in solution procedures can be tested. The relatively larger influence of small geometry variations and transverse velocity components, in some flows, will represent a likely limitation of calculation procedures with any model assumption. It should also be remembered that averaged models lead to approximate representations of a flow and that those of the form used by *McGuirk* and *Rodi* require considerable modification to represent flows with intermittency or imposed pulsations. In the medium term, it is likely that the time-average models will provide the basis for engineering-type calculations. In the longer term conditionally sampled equations or, more likely, the solution of time-dependent equations with subgrid scale modeling will probably be used.

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Intermittency in Free Turbulent Shear Flows

Cesar Dopazo

Department of Applied Science, Brookhaven National Laboratory
Upton, NY 11973, USA

Edward E. O'Brien

Department of Mechanical Engineering, State University of New York
Stony Brook, NY 11794, USA

Abstract

A formalism previously used in the context of deformable porous media and turbulent/nonturbulent intermittent flows is restated here. The behavior of the intermittency function derivatives at the interface gives rise to surface integrals over the latter. The conditioned equations of continuity, momentum, energy, vorticity, and conservation of a scalar are derived for the turbulent and irrotational zones. Surface integrals with a precise physical meaning enter the conditioned equations. They can be interpreted as entrainment of mass, momentum, energy and scalar, and as direct interactions between the turbulent and irrotational regions. Use is made of the experimental conditioned measurements for: (i) the plane wake behind a heated flat plate, and (ii) the heated turbulent round jet; the profiles of entrainment of mass and the combination of direct interactive force and entrainment of momentum are calculated. These derived profiles are compared with models proposed by previous investigators.

Nomenclature

C	Molecular flux of scalar through the interface, Eq. (41)
D	Orifice diameter for the jet
dS	Interface surface infinitesimal element
E	Entrainment of mass per unit mass, Eq. (17)
F	Mean force per unit mass of turbulent on irrotational zones
f_1, f_2, f_3, f_4	Self-preserving functions defined by Eqs. (51)–(64)
f_γ	Interface crossing rate
g, h^2	Self-preserving functions defined by Eqs. (54) and (63)
I	Intermittency function
K	Entrainment of total kinetic energy, Eq. (30)
$l(x)$	Half-width of the wake based on velocity defect
M	Average entrainment of momentum, Eq. (21)
n	Normal to the interface pointing towards the turbulent zone
P, Q	Any fluid mechanical variables
p	Pressure
q	Molecular scalar flux vector
r	Radial coordinate for the jet
$r_{1/2}$	Half-radius of the jet based on velocity
$S(x, t)$	Surface of the turbulent/nonturbulent interface

T	Scalar
T_m	Maximum value of T at a section of the jet
t	Time
U_J	Jet exit velocity
U_m	Maximum value of the mean velocity at a section of the jet
U_0	Free stream velocity for the wake
U_s	Velocity defect at the centerplane of the wake
$\boldsymbol{u}$	Velocity vector
$\boldsymbol{u}^s$	Interface velocity
u, v	x and y (or r) velocity components
V	Elementary control volume
v^e	Modulus of the velocity of advance of the interface relative to a fluid element at the same point
W	Mechanical work done by the turbulent fluid upon the irrotational fluid
w	Tangential velocity component for the jet
$\boldsymbol{x}$	Position vector
x, y	Streamwise and normal coordinates
γ	Intermittency factor
δ_m	Momentum thickness of the boundary layer at the trailing edge of the plate
δ_{ij}	Kronecker delta
η	Similarity variable
Θ	Mean entrainment of scalar T
μ	Viscosity of the fluid
ν	Kinematic viscosity of the fluid
ρ	Density of the fluid
σ_{ij}	Viscous stress tensor
ϕ	$\frac{\sigma_{ij}}{\rho}\frac{\partial u_i}{\partial x_j}$ in the kinetic energy equations
ω_i	Vorticity component

Subscripts

1, 0	Relative to turbulent and irrotational zone variables
i	Vector component
r	Axial component of a vector
x, y	Streamwise and normal components of a vector

Special Symbols

∇	Gradient operator
∇^2	Laplacian operator
Bold symbol	Vector
$-$	Average
$'$	Fluctuating variable or function derivative

Introduction

Since the discovery of intermittency in free turbulent shear flows by *Corrsin* [2] and its exploration in subsequent studies by *Townsend* [10] and *Corrsin* and *Kistler* [3], the concept of an intermittency function has been widely used in experimental investigations. The intermittency function allows one to identify separately the turbulent and nonturbulent regions coexisting in an intermittent flow. A more adequate description of velocity and scalar fields can then be provided. The conditional sampling technique [1, 6, 12, 13] multiplies the random variable to be averaged by a generated signal which is unity in the tur-