A. Pollard and S. Candel (Eds.)

IUTAM Symposium on
Turbulent Mixing and Combustion

IUTAM

IUTAM Symposium on
Turbulent Mixing and Combustion

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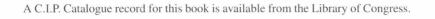*Kingston, Ontario, Canada*

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FLUID MECHANICS AND ITS APPLICATIONS
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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.

IUTAM Symposium on Turbulent Mixing and Combustion

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Acknowledgement

Dedication

The Scientific Committee was saddened to learn of the death of Professor Tony Perry in January 2001. This Symposium is dedicated to his memory.

Anthony Edward Perry

~ TONY ~
19.2.1937 to 3.1.2001

"...he was a most distinguished researcher. Townsend said, "the best in turbulence" "

\- Julian Hunt 2001

Professors Perry and Hunt are members of the Scientific Committee of the IUTAM Symposium on Turbulent Mixing and Combustion.

Preface

The goals of the Symposium were to draw together researchers in turbulence and combustion so as to highlight advances and challenge the boundaries to our understanding of turbulent mixing and combustion from both experimental and simulation perspectives; to facilitate cross-fertilization between leaders in these two fields. These goals were noted to be important given that turbulence itself is viewed as the last great problem in classical physics and the addition of chemical reaction amplifies the difficulties enormously.

The papers that have been included here reflect the richness of our subject. Turbulence is rich and complex in its own right. And, its inner structure, hidden in the morass of scales, large and small, can dominate transport. Earlier IUTAM Symposia have considered this field, Eddy Structure Identification in Free Turbulent Flows, Bonnet and Glauser (eds) 1992 and Simulation and Identification of Organized Structures in Flows, Sorensen, Hopfinger and Aubry (eds) 1997. The combustion community is well served by its specialized events, most notable is the bi-annual International Combustion Symposium, held under the auspices of the Combustion Institute. Mixing is often considered somewhere in between these two. This broad landscape was addressed in this Symposium in a somewhat temporal linear fashion of increasing complexity. The lectures considered the many challenges posed by adding one element to the base formed by others: turbulence and turbulent mixing in the absence of combustion through to turbulent mixing dominated by chemistry and combustion. The Symposium gathered experimental, theoretical and computational contributions, which were focused on either fundamental or more practical questions.

Direct numerical simulations were described in a number of papers in this Symposium. DNS have emerged as a preferred method to explore the details of turbulence and combustion. Another area of considerable interest for many practical applications is that of large eddy simulations (LES). Progress during the recent period has been made mainly for non-reactive flows. Much research is now focused on the development of large eddy simulations for combustion and particularly sub-grid scale models. This aspect was well covered by a group of papers in this Symposium. There are challenging problems in this field and many open questions; encouragingly, some clear demonstrations were presented of the potential of these novel computational approaches.

This Symposium benefited enormously from insights gained from those who work in physical experiments where initial and boundary conditions are often difficult to quantify and control and indeed, the exquisite at-

tention to detail and error analysis that is demanded by their craft. Much can be learnt from such detailed studies when they are focused on complex flow problems (mixing of supercritical fluids, synthetic jets, mixing in micro-combustors) or when they are specifically designed to provide data for the new modelling approaches and methods.

The invited speakers' lectures gave a remarkable introduction and overview of the many facets of turbulence, turbulent mixing and combustion and provided considerable insights on the future of this field of research. Villermaux began the Symposium by providing fresh new insights into mixing mechanisms. Dimotakis followed by adding the effects of combustion to mixing. Meneveau returned to mixing, but in the context of Large Eddy Simulation and scale separation. Vervisch considered LES of partially premixed combustion and thus provided the first complete foray into combustion. Moin, the penultimate invited speaker, considered the progress made in LES of a gas turbine combustor and control of mixing and last, but definitely not least, Janicka provided a perspective on the future of turbulent mixing and combustion.

The Symposium comprised 6 invited plenary and 50 papers presented either orally or as posters. The extensive discussions that followed each presentation are included here and they added a pedagogic flavour to the symposium. Each poster session was awarded a Best Poster Award. The winners were Helie and Trouve, Johnson and Kostiuk, and Juniper, Tripathi, Scouflaire, Robon and Candel. Papers were selected for inclusion in this volume based on their impact. The editors reviewed each paper. This volume contains 38 of the 56 papers presented and are presented here grouped broadly according to:

⇒ Turbulence and mixing (Invited - Villermaux)
⇒ Turbulent Mixing with Combustion (Invited - Dimotakis)
⇒ Modeling scalars (Invited - Meneveau)
⇒ DNS/LES of flames (Invited - Vervisch)
⇒ Control (Invited - Moin)
⇒ Perspectives for Turbulent Mixing and Combustion (Invited - Janicka)

The editors hope that this volume will stimulate further interaction between the turbulence, mixing and combustion communities.

Andrew Pollard and Sebastien Candel
Editors
Kingston and Paris, February 2002.

Opening Address

Turbulence and Combustion

Tomomasa TATSUMI
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It is my great honour and pleasure to give an Opening Address in this
IUTAM Symposium on "Turbulent Mixing and Combustion" on behalf
of the IUTAM.

1.   IUTAM

The present symposium is one of the IUTAM Symposia sponsored
by the IUTAM, or the International Union of Theoretical and Applied
Mechanics. Every two years, the IUTAM collects proposals for such sym-
posia from the scientists in the various fields of Theoretical and Applied
Mechanics all over the world and selects about eight to ten of them per
year as the IUTAM Symposia. The IUTAM Symposia are reserved to
invited participants and its refereed Proceedings are published in series
mostly by the Kluwer Academic Publishers. To our great pleasure, now
the IUTAM Symposia are generally considered as the top-level interna-
tional symposia in the respective research fields and their Proceedings
as the first-class literature on the subjects.

The IUTAM was founded in 1947 shortly after the end of the Sec-
ond World War. It has, however, an excellent prehistory as the ICAM,
or the International Congress of Applied Mechanics, whose beginning
dates back to 1922, when an International Conference on Hydro- and
Aerodynamics was held at Innsbruck, Austria, under the joint chair-
manship of two young scientists, Theodore von Kármán in Aachen and
Tullio Levi-Civita in Rome [1]. It was just after the First World War
and concurrent with the great revolutions in Physics such as Relativ-
ity Theory and Quantum Mechanics. Although less eminent than these
revolutions, there also existed novel developments in Hydro- and Aero-
dynamics such as Turbulence by Osborn Reynods, Shock Wave by G.I.
Taylor and Boundary Layer by Ludwig Prandtl. Thanks to the introduc-
tion of these novel concepts, all unphysical singularities existed in old
Hydrodynamics of an inviscid fluid have disappeared and given place
to the physical realities including Turbulence, Shock waves and Bound-

ary layers which can be described by the Navier-Stokes equations of the viscous fluid.

Von Kármán's idea was based on the recognition of a large discrepancy between such rapid developments in the new fields of Hydro- and Aerodynamics on one hand, and only a limited space devoted to such problems at scientific meetings on the other. He proposed to break the dependence of these new fields from their mother disciplines, Mathematics, Physics and Engineering. His proposal was strongly supported by Levi-Civita and they succeeded in organizing the above-mentioned International Conference.

This Conference, which was a highly successful one, was the begining of the ever-growing series of the ICAM which have been held almost regularly every four years at various cities in the world. After the interruption due to the Second World War, the ICAM was succeeded by the IUTAM as the ICTAM, or the International Congress of Theoretical and Applied Mechanics. It is well known that the 20th ICTAM was held in the year of 2000 at Chicago, USA.

2. Fluid Mechanics

About eighty years since the time of Innsbruck Conference, no one can deny that enormous developments have been achieved so far in various fields of Theoretical and Applied Mechanics, particularly in its core field, Fluid Mechanics.

As mentioned before, the big progress in Fluid Mechanics during the first half of the 20th century has been achieved by the introduction of new concepts such as turbulence, shock wave and boundary layer. In the later half of this century, the progress has been largely promoted by the employment of another series of novel concepts such as Local Equilibrium of Turbulence by A.N. Kolmogorov, Soliton by Norman Zabusky and M.D. Kruskal, Chaos by E.N. Lorenz and Fractals by Benoit Mandelbrot. The large contribution by the high-speed numerical computation is also to be noted.

Thus it seems to be well established that all fluid motions including highly complex flows at large Reynolds numbers can be described precisely and in detail as the solutions of the Navier-Stokes equations, either analytical or numerical, although it is still a matter to be proved mathematically. In this sense, von Kármán's idea of proposing Hydro- and Aerodynamics as an independent research sector from their mother disciplines seems to be well justified.

3.   Turbulence and Combustion

Now let us consider our central subject "Turbulent Mixing and Combustion". Although I am not very familiar with this subject it was fortunate for me to learn from an excellent lecture on "Turbulent Mixing" given by Prof. Paul Dimotakis at the 20th ICTAM [2].

To my understanding, "Turbulent Mixing" provides the initial and boundary conditions for "Combustion" and, on the other hand, it finds its simplified version in the diffusion in homogeneous turbulence. Thus it can be said that in order to understand "Combustion" properly we have to know about "Turbulent Mixing", and in order to understand "Turbulent Mixing" we have to know about "Homogeneous Turbulence". Then, how far do we know about "Homogeneous Turbulence"? Concerning this point, people's views are at variance, but I think that the theory of Homogeneous Turbulence must be made as simple and clear as possible in order that it can be applied to Non-Homogeneous Turbulence of more complex nature. In this sense, let me present here my simple but hopefully correct view of "Homogeneous Turbulence" on this occasion.

4.   Velocity Distributions of Turbulence

It is well known that the most complete statistical information of turbulence is provided by the probability distributions of its velocity $\mathbf{u}(\mathbf{x}, t)$ at all values of the coordinate $\mathbf{x}$ and the time t. The simplest of such distributions are the one- and two-point velocity distributions which are written for homogeneous turbulence as,

$$f(\mathbf{u}_1, t) = <\delta(\mathbf{u}(\mathbf{x}_1, t)|\mathbf{u}_1)> \qquad (0.1)$$

$$f^{(2)}(\mathbf{u}_1, \mathbf{u}_2; \mathbf{r}, t) = <\delta(\mathbf{u}(\mathbf{x}_1, t)|\mathbf{u}_1)\delta(\mathbf{u}(\mathbf{x}_2, t)|\mathbf{u}_2)>, \mathbf{r} = \mathbf{x}_2|\mathbf{x}_1 \quad (0.2)$$

where $< \cdot >$ denotes the mean value with respect to a certain initial distribution.

The equation governing the one-point distribution f is already given by Lundgren [3] and Monin [4] independently, but the equation is not closed since it includes the two-point distribution $f^{(2)}$ as another unknown. This unclosedness is not solved even if we proceed to the equation for $f^{(2)}$ since the latter includes another higher-order distribution $f^{(3)}$ an so on, and this is indeed nothing but the central difficulty of the turbulence problem. So far, a number of attempts have been made for solving this difficulty mostly in terms of the moment-expansion formalism, but the distributions f and $f^{(2)}$ themselves have not been dealt with except for numerical and phenomenological arguments.

In this context, let me propose a closure assumption for connecting f and $f^{(2)}$ [5]. First, introduce a couple of the cross-velocities, that is,

the velocity-sum $\mathbf{u}_+ = (\mathbf{u}_1 + \mathbf{u}_2)/2$ and the velocity-difference $\mathbf{u}_- = (\mathbf{u}_2 - \mathbf{u}_1)/2$ and express $f^{(2)}$ in term of these velocities as,

$$f^{(2)}(\mathbf{u}_1, \mathbf{u}_2; \mathbf{r}, t) = 2^{-3} g^{(2)}(\mathbf{u}_+, \mathbf{u}_-; \mathbf{r}, t) \tag{0.3}$$

and then factorize $g^{(2)}$ into the distributions of the velocity-sum g_+ and the velocity-difference g_- as,

$$g^{(2)}(\mathbf{u}_+, \mathbf{u}_-; \mathbf{r}, t) = g_+(\mathbf{u}_+, \mathbf{r}, t) g_-(\mathbf{u}_-, \mathbf{r}, t) \tag{0.4}$$

assuming the independence of g_+ and g_-.

Obviously, the cross-independence assumption (3) and (4) is equivalent to the notion of Kolmogorov's local equilibrium hypothesis which assumes the statistical independence of the small-scale components of turbulence from those of large-scale [6]. This relationship is also supported experimentally so far as the distance r is below the order of the inertial length [7].

Applying the assumption (3) and (4) to $f^{(2)}$ in the equation for f and doing some order-of-magnitude analysis, we obtain the following closed equation for f:

$$[\partial/\partial t + \alpha^2(t)\triangle] f(\mathbf{u}, t) = 0 \tag{0.5}$$

where $\triangle = |\partial/\partial \mathbf{u}|^2$ and $\alpha^2(t)$ is a function proportional to the energy dissipation rate,

$$\epsilon(t) = (\nu/2) q (\partial u_i/\partial x_j + \partial u_j/\partial x_i)^2 r \tag{0.6}$$

It should be noted that eq.(5) includes only a single parameter $\alpha^2(t) \propto \epsilon(t)$ but not the viscosity ν as an independent parameter. This means that the statistics governed by eq.(5) satisfies the inertial similarity which depends only upon $\epsilon(t)$, while Kolmogorov's local equilibrium similarity depends in general upon two independent parameters $\epsilon(t)$ and ν.

5.   Inertial Similarity

Equation (5) for f has the following self-similar solution in time:

$$f(\mathbf{u}, t) = (t/(4/3)\pi\epsilon_0)^{3/2} \exp[-|\mathbf{u}|^2 t/(4/3)\epsilon_0], \quad \epsilon(t) = \epsilon_0/t^2 \tag{0.7}$$

which represents an isotropic normal (Gaussian) distribution of the one-point velocity $\mathbf{u}$. As mentioned before, the distribution (7) depends only upon an inertial parameter ϵ_0, which does not vanish in the inviscid limit $\nu \to 0$. This makes a clear contrast of eq.(7) to the normal distribution of weak turbulence which includes ν as the reverse diffusion constant.

Reflecting the lack of the external excitation in eq.(5), the distribution (7) changes in time. At the initial instant $t = 0$, it represents a uniform

distribution with vanishing probability density. For $t > 0$, it grows up as the normal distribution with increasing height and decreasing variance in time, and eventually for $t \to \infty$ it tends to a delta distribution $\delta(\mathbf{u})$, representing the dead still state.

6.   Inertial Normality

The same argument can be applied to the equation for the two-point velocity distribution $f^{(2)}$ which includes the three-point distribution $f^{(3)}$, and thus $f^{(2)}$ is obtained as the solution of this closed equation. Since, however, $f^{(2)}$ is a function of two-vector variables, it can be expressed more conveniently in terms of its factors in (4), the distributions of the velocity-sum $g_+(\mathbf{u}_+, \mathbf{r}, t)$ and the velocity-difference $g_-(\mathbf{u}_-, \mathbf{r}, t)$. Actually, all existing measurements of the two-point velocity distributions, either experimental or numerical, are mostly presented in terms of g_+ and g_-.

It should be noted that there exist isotropic normal distributions for both g_+ and g_- expressed as

$$g_\pm(\mathbf{u}_\pm, \mathbf{r}, t) = (t/(2/3)\pi\epsilon_0)^{3/2} \exp[-|\mathbf{u}_\pm|^2 t/(2/3)\epsilon_0] \qquad (0.8)$$

Obviously, the normal distributions (8) is identical to the normal distribution (7) except that the variance of (8) is $1/2$ of that of (7). This implies that the distributions g_+ and g_- are nothing but the con- volutions of two independent velocity distributions f at the points $\mathbf{x}_1$ and $\mathbf{x}_2$. The independence of the two velocities for arbitrary distance $\mathbf{r}$ is guaranteed by the inertial similarity which makes all the correlation lengths of the order of the Kolmogorov length $\eta = (\nu^3/\epsilon)^{1/4}$ vanishingly small.

On the other hand, the inertial similarity causes a difficulty for the distribution (8) since it does not satisfy the coincidence conditions in the limit of $\mathbf{r} \to 0$,

$$g_-(\mathbf{u}_+, 0, t) = f(\mathbf{u}_1, t), \quad g_-(\mathbf{u}_-, 0, t) = \delta(\mathbf{u}_-) \qquad (0.9)$$

This discrepancy is, however, only apparent, and in reality there exists a dissipation region of finite length, and the distribution (8) changes rapidly but continuously to the limits (9) through this region. This process of transition of g_+ and g_- can be described in the framework of the present approximation (4) if we start from the equations for g_+ and g_-, but this problem will be dealt with in a separate work.

The above-mentioned relationship between the inertial normality and the dissipation region in the velocity distributions of turbulence has close resemblance with that for the inviscid outer flow and the boundary layer in the laminar problem. In either case, the inertial or inviscid regions

occupy the major physical space, but they essentially owe their physical reality to the dissipative or viscous regions limited to the infinitesimal space. The inertial normality of the velocity distributions prevailing the major physical space gives a good reason for the practical success of the so-called quasi-normal theories of turbulence. The secret is how to take into account the inertial dissipation ϵ into the approximation scheme and actually the success or not of the theories totally depends upon their degrees of incorporating this inertial effect.

The merit of the inertial normality largely depends upon its simplicity and clarity which provide us with strong power for expanding the research field from Homogeneous Turbulence to Non-Homogeneous Turbulence, including shear flows, thermal effects, electro-magnetic interactions, chemical reactions, and so on and, of course, our central subject "Turbulent Mixing and Combustion".

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