Turbulence

(January to June 1999)

Report from the Organisers: GF Hewitt (Imperial); PA Monkewitz (EPFL); ND Sandham (Southampton); JC Vassilicos (DAMTP, Cambridge)

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Background and Objectives

Turbulence has long been acknowledged as one of the great unsolved scientific and even conceptual problems of our time. Turbulence occurs in industrial processes, in the oceans, in the atmosphere of the Earth and other planets and in many other astrophysical contexts. Turbulence occurs also in biological contexts, *eg* in humans, animals and even some plants. Engineers need to understand turbulent flows in order to control them, design for their adverse effects or utilise them to best effect (as in mixing processes). In all cases, prediction is a necessary element in engineering design calculations.

The development over the past 10-20 years of useable Computational Fluid Dynamics (CFD) codes has produced a sea change in the design and development approach, allowing products to be brought to the market much more rapidly and economically. However, CFD codes are necessarily based on turbulence models whose parameters have to be deduced from measurements. The generality of these parameters is questionable and the mathematical aspects of the models have been inadequately explored.

Turbulence and turbulent-like phenomena are of great interest as problems in mathematics and theoretical physics; some of the mathematical and physical concepts that have been developed in these studies are being applied in other areas of mathematical sciences, especially in the study of processes involving a combination of ordered and disordered phenomena stemming from the intertwining of random and deterministic dynamics.

The importance of turbulence in engineering led the Royal Academy of Engineering to prepare, after a number of internal discussions, a proposal for a Research Programme on Turbulence at the Isaac Newton Institute. This proposal was ultimately accepted by the Institute and the Research Programme took place from 6 January to 2 July 1999.

The programme had the following broad objectives:

Universality. Turbulence is often treated as if it were a universal phenomenon; a major aim of the programme was to assess the limitations of this approach.

Turbulence Structure and Vortex Dynamics. The central question here was to address mathematical aspects of the vortex dynamics including interactions between vortices and turbulence and connections to statistical modelling of turbulence.

Intermittency. Turbulence is often intermittent. The objective was to study the kinematics and dynamics of intermittency as a property of the Navier-Stokes equations in particular and of non-linear PDEs in general.

Transition and Control. In many industrial systems, maintenance of laminar flow can lead to great economies in design and operation. An objective of the programme was to establish whether the application of modern nonlinear dynamical system methods would yield new insights into this area.

Analysis and Numerical Simulation. A large amount of attention has been focused in recent years on direct numerical simulation (DNS) and large eddy simulation (LES) for the simulation of turbulent systems. An aim of the programme was to establish the potential of these approaches in tackling both fundamental and applied problems.

Closure Strategies. Numerical solution of the averaged Navier-Stokes equations (the Reynolds equations) is often straightforward, provided that a suitable closure model can be used to determine turbulent stresses and scalar fluxes. An important objective of the Research Programme was to establish the range of validity of such modelling strategies.

Applications. Since the programme resulted from an initiative at the Royal Academy of Engineering, a major objective was to assess the current status of turbulent flow prediction in the context of the many applications found in engineering. There was also a focus on applications in other areas such as meteorology.

As will be seen from what follows, significant progress was made with respect to all of these objectives

Organisation

The Isaac Newton Institute appointed four Organisers (see above).

JC Vassilicos and ND Sandham were in residence throughout the Research Programme. In the planning process for the Programme, very important input was provided by the **Scientific Advisory Committee** whose composition was as follows:

JCR Hunt (DAMTP, Cambridge): Chairman; BE Launder (UMIST): Co-Chairman; M Germano (Politecnico di Torino); JD Gibbon (Imperial College); S Kida (University of Nagoya); L Kleiser (ETH, Zurich); CE Leith (LLNL); M Lesieur (IMG, Grenoble); A Majda (Courant Institute); P Moin (Stanford University); D Thomson (Met Office)

Through the Royal Academy of Engineering, financial support was provided for the Programme by "core" contributors (each contributing £20k to the Programme) and "associate" contributors (each contributing £3k to the Programme). The original core contributors were Nuclear Electric, Rolls Royce, BG Technology, British Aerospace, DERA and the Meteorological Office. Associate contributors were

JRC Ispra, Ove Arup and Schlumberger. The core contributors formed an **Industrial Working Group** (under the *aegis* of the *Royal Academy of Engineering*) which had the following membership:

MW Reeks (Nuclear Electric): Chairman; J Coupland (Rolls-Royce); RP Cleaver (BG Technology); DP Hills (British Aerospace); AG Hutton (DERA); JR Noyce (Nuclear Electric); MJ Rabbitt (Nuclear Electric); DJ Thomson (Met Office). The Organisers also attended the meetings of this Committee.

During the preparation of the programme, Nuclear Electric was split into British Energy and Magnox Electric, and Magnox Electric was merged with BNFL.

An **Organising Committee** consisting of the Chairmen and Co-Chairmen of the Scientific Advisory Committee and the Industrial Working Group, plus the Organisers was set up as follows:

GF Hewitt (Imperial College) Chairman; JCR Hunt; BE Launder (UMIST); PA Monkewitz; MW Reeks (Nuclear Electric); ND Sandham; JC Vassilicos

Regular meetings were held of the Organisers, of the Organising Committee and of the Industrial Working Group. These meetings began during the planning period for the Research Programme and continued throughout the programme. The Scientific Advisory Committee operated on a consultative basis and did not meet formally.

Meetings and Workshops

The following major meetings were organised:

Symposium on Turbulent Systems: Problems and Opportunities (January 11th-12th, 1999). This Symposium was the opening one in the Research Programme and the objective was to set the scene for subsequent work in the Programme. Leading industrial practitioners and leading specialists in turbulence came together to outline the needs of industry for predictive methods for turbulent systems and to agree on ways forward in addressing these needs. An overview was provided in a plenary presentation by JCR Hunt and the areas covered in presentations by the industrial participants were as follows:

> *External Aerodynamic Flows* (Speakers: DP Hills and ARB Gould, British Aerospace; AG Hutton, DERA).
>
> *Internal Aerodynamic Flows* (Speakers: P Stow and J Coupland, Rolls-Royce).
>
> *Internal Flows with Heat Transfer* (Speakers:
> MJ Rabbitt, S Hickmott and RM Smith, British Energy).
>
> *Flows with Heat and Mass Transfer* (Speakers:
> RP Cleaver and PS Cumber, BG Technology).
>
> *Atmospheric/Environmental Flows* (Speakers:
> JCR Hunt; DJ Thomson and S Derbyshire, Meteorological Office).

Caucus discussions groups were held in each of the major areas and guidelines produced on industrial requirements in the area.

Symposium on Turbulence Structure (11-19 March 1999. In association with ERCOFTAC). This symposium addressed the mathematical aspects of vortex dynamics including interactions between vortices and turbulence, representations of complex internal structure and connections due to statistics and statistical modelling of turbulence. Developments in the study of universality of small scale turbulence were emphasised. The invited lecturers included:

CF Barenghi (Newcastle), JG Brasseur (Penn State), JCR Hunt, C Cambon (ECL), Y Couder (ENS, Paris), J Gibbon (Imperial College), F Hussain (Houston), RM Kerr (NCAR), S Le Dizes (Marseille), A Leonard (Caltech), M Lesieur (Grenoble), WD McComb (Edinburgh), HK Moffatt, JF Morrison (Imperial College), E Novikov (UCSD), K Ohkitani (Kyoto), AE Perry (Melbourne), A Tsinober (Tel Aviv), KR Sreenivasan (Yale), JC Vassilicos, Z Warhaft (Cornell), CHK Williamson (Cornell).

Instructional Conference on Closure Strategies for Modelling Turbulent and Transitional Flows (April 6th-17th, 1999). This Instructional Conference provided an opportunity for young researchers to interact with invited members of the INI Programme via a co-ordinated series of advanced lectures and informal discussions. The lecturers included:

S Banerjee (UCSB), JC Bonnet (Poitiers), C Cambon (ECL, France), TJ Craft (UMIST), T Gatski (NASA, Langley), K Hanjalic (Delft), B Ilyushin (Novosibirsk), WP Jones (Imperial College), BE Launder (UMIST), D Laurence (EDF), P Monkewitz, Y Nagano (Nagoya), W Rodi (Karlsruhe), D Roekaerts (Delft), ND Sandham, AM Savill (Cambridge).

Workshop on Direct and Large Eddy Simulation

(12-14 May 1999. Organised jointly with ERCOFTAC). The objective of this Workshop was to consider recent advances in DNS and LES and to provide a forum for discussion of future development directions. Invited speakers included:

M Germano (Turin), BJ Geurts (Twente), J Jimenez (Madrid), RM Kerr (NCAR), A Leonard (CalTech), S Sarkar (UCSD).

Symposium on Intermittency in Turbulent Flows and other Dynamic Systems (21-24 June 1999). This Symposium considered the mathematical properties of intermittency as a function of the Navier-Stokes equations and other non-linear dynamical systems. Invited lecturers included:

A Arneodo (Bordeaux), JG Brasseur (Penn State), FH Busse (Bayreuth), S Cilberto (Lyon), P Constantin (Chicago), CR Doering (Ann Arbor), G Eyink (Arizona), G Falkovich (Weizmann), M Farge (ENS), U Frisch (Nice), A Jensen (Niels Bohr), J Jiménez (Madrid), S Kida (Toki), JL Lumley (Cornell), T Mullin (Manchester), K Ohkitani (Kyoto), A Pumir (CRYRS, France), A Shraiman (Bell Labs), KR Sreenivasan (Yale), P Tabeling (ENS), A Tsinober (Tel Aviv), JC Vassilicos (Cambridge), A Vulpiani (Rome), W van de Water (Eindhoven).

Symposium on Future Strategies Towards Understanding and Prediction of Turbulent Systems

(29-30 June 1999). This Symposium was the closing event of the Research Programme and aimed to define future strategies for ongoing work in the field. The Symposium began with a series of presentations relating to the various technical areas. In this part of the Symposium, the speakers were:

MW Reeks (JRC, Ispra), JCR Hunt, GF Hewitt, JC Vassilicos, ND Sandham, BE Launder, JL Lumley (Cornell), FT Nieuwstadt (Delft), P Moin (Stanford) and N Peters (RWTH, Aachen).

There then followed presentations on the impact on application areas with summaries and presentations by DP Hills, British Aerospace (*External Aerodynamic Flows*), J Coupland, Rolls-Royce (*Internal Aerodynamic Flows*), MJ Rabbitt, British Energy (*Internal Flows with Heat Transfer*), RP Cleaver, BG Technology (*Internal Flows with Heat and Mass Transfer*) and DJ Thomson, Meteorological Office (*Atmospheric and Environmental Flows*). Each of these presentations was followed by a discussion and, to close the Symposium, an overview lecture was given by JCR Hunt.

In addition to the above Workshops and Symposia, a series of small-scale Workshops was held, involving mainly the residential participants at the Institute, but with some with some external invitees. These were as follows:

Perspectives in the Understanding of Turbulent Systems (January 13th-22nd, 1999)

Breakdown to Turbulence and its Control (March 22nd-31st, 1999)

Mathematics of Closure (April 19th-30th, 1999)

In addition to the above meetings, several of the industrial sponsors held one-day meetings to discuss their problems with residential and other participants. These were very successful in focusing the Programme onto these industrial problems.

Scientific Programme

Turbulence Structure and Vortex Dynamics

The programme, and the Symposium on Turbulence Structure in particular, succeeded in bringing together physicists, engineers, mathematicians and experimentalists working in the closely related fields of vortex dynamics and turbulence structure. The issues addressed fell under the following categories:

- Experiments of grid and shear turbulence revealing non-universality, departures from small-scale isotropy and strong Reynolds number dependencies of scalings (Sreenivasan, Warhaft).
- Fundamentals of vorticity and strain field dynamics and statistics in turbulence (Novikov, Ohkitani, Tsinober).
- Finite-time singularities (Moffatt, Kerr). Gibbon’s lecture at the Symposium on Turbulence Structure provided the link between finite-time singularities and alignments between vorticity and strain.
- Near-singularities, their dynamics and scalings (Leonard, Vassilicos).
- Vortex instabilities and cascades (Cambon, Hussain, Le Dizes, Williamson).
- Vortex structure and turbulent boundary layers (Hunt, Morrison, Perry).

Particular highlights of the Symposium on Turbulence Structure were the studies of the turbulent boundary layer in terms of distributions of different eddies of different sizes (Perry, Hunt); a new length-scale derived by Novikov which characterises vortex structure in turbulent flows; a conditional average approach by Novikov which provides the shape of "typical" vortex structure around a point with a given velocity, and it was of some interest that this vortex structure is of a helical-spiral type; Tsinober’s observation that most enstrophy and strain production is associated with large strain, alignment of vorticity with the largest eigenstrain and finite curvature of vortex lines; Barenghi’s exposition of the surprisingly many similarities between classical and superfluid turbulence; Hussain’s lecture on the core dynamics of a vortex in shear and the ensuing cascade scenario; Williamson’s beautiful experiments on wing-trailing vortices with proper measurements and account of velocity distribution and core radius permitting correct calculations of the growth rate of the Crow instability.

Finally, many contributed presentations concerned experimental investigations of spiral and stretched vortices. Tabeling’s group in Paris has developed very interesting and novel experiments where a strong stretched vortex is generated in isolation with access to its structure, dynamics and instability properties. One of these experiments is made in a small hydrodynamical channel and leads to a vortex with a spiral structure. Another is based on a "double rotating suction" system and reveals a clear breakdown sequence. Baudet from the Ecole Normale Superieure de Lyon reported on a detection technique of coherent vorticity using time-scale resolved acoustic spectroscopy, and may have detected something very similar to Lundgren’s spiral vortex in jet turbulence. This experimental work was flanked at the Symposium by numerical studies of the structure of small-scale vortex tubes in various turbulent flows (Brasseur, Flohr, Tanahashi).

Breakdown to Turbulence (Transition)

Although the principal theme of the programme was the understanding and modelling of fully turbulent flows, it was recognised that the mechanisms by which flows become turbulent, in particular the intermediate "pre-turbulent" flow states, may shed light on the physics of turbulence. The workshop focused on transition of wall-bounded shear flows (boundary layers) which are of the greatest practical importance. In a nutshell the problem faced by the aeronautical and flow machinery industry is the prediction of the transition location in a complex, generally three-dimensional flow, *eg* a swept wing including its root region or a three-dimensional compressor blade. The state of the art in industry was reviewed by Chris Atkin (DERA) who showed that industrial predictions are still mostly based on N-factors and that only the sophistication with which they are computed has evolved since their invention by AMO Smith. Hence, one of the principal problems of transition prediction remains the integration of receptivity to "free stream disturbances" into the transition prediction methodology which could finally lead to realistic disturbance-dependent predictions.

The different methods of computing disturbance amplification were presented by P Lucchini and J Healey. A lively discussion with S Cowley in particular of the application of parabolised stability equations (PSE) in non-parallel flows clearly revealed its weaknesses relative to the multiple scale method and to "proper" asymptotics based on triple deck theory, which is at the base of J Healey proposal for a non-linear, non-parallel e^N method. Another serious problem when computing N-factors in three-dimensional flows is the choice of trajectory along which amplification is to be computed. (In the context of PSE, this question is related to the direction in which the equations are to be parabolised). R Lingwood presents a proposal by Brevdo to take a trajectory parallel to the local group velocity vector. It is clear that such computations become very extensive if the maximum N-factor with respect to all the possible instability modes is sought and a superposition of wave packets in the spirit of Huygens may be worth pursuing. This latter point of discussion is related to the possible role of absolute instability in transition prediction. Starting from the unusually good correspondence between the radius of convective-absolute transition and transition to turbulence in the rotating disc boundary layer, R Lingwood further developed the ideas for the swept wing boundary layer where no true absolute instability (defined by the asymptotic behaviour of the impulse response) has been found. Beyond some chordwise station however, modes with zero group velocity in the chordwise direction exist and lead there to a wave packet edge parallel to the leading edge of the swept wing possibly corresponding to the transition line. While transition predictions based on absolute instability (or "chordwise absolute instability") are in principle independent of the exact nature and magnitude of the initial perturbation, provided there is any, it is still an open question whether this concept alone is sufficient for the swept wing in particular where minute roughness elements on the leading edge create in practice turbulent wedges and a "jagged" transition line. This issue is somewhat related to the non linear development of localised global modes arising from an absolute instability region in a non-parallel flow which has been discussed by S LeDizes.

On the difficult issue of receptivity, X Wu showed how the interaction of convecting gusts with sound can effectively generate Tollmien-Schlichting waves. P Lucchini, on the other hand, discussed the "receptivity" of the boundary layer to low-frequency, spanwise periodic disturbances (streamwise streaks and vortices) and made the connection to the Libby & Fox and Stewartson modes. This direction of research, in which the optimal initial perturbation for maximum amplification over a given streamwise interval is determined by upstream integration of the adjoint stability problem, is attractive as it limits the number of modes that need to be considered in a standard

N-factor computation and coupled to free stream disturbances. For high levels of external perturbations, such as provided by passing wakes in multi-stage rotating machinery, H Hodson and W Rodi showed evidence that the standard growth stage of a few instability modes is bypassed and turbulent spots can be formed immediately. An inviscid model for the latter was discussed by F Smith, the internal structure of spots were illustrated by the outstanding experiments of A Perry and the relevance of "shear sheltering" to this transition scenario with strong forcing was discussed by J Hunt.

Advancing further towards turbulence, the secondary instability of streaks and streamwise vortices and their interplay was the subject of talks by F Hussain, N Sandham and D Martinand. From these presentations it is becoming increasingly evident that the near-wall dynamics involving non-linear interactions between streamwise streaks, near-streamwise vortices and wave-like secondary instabilities of these structures defines the advancement of transition: after a regime in which these structures appear intermittently, transition is complete when the cycle linking these modes becomes self-sustained, thus constituting the "motor" of turbulence in wall-bounded flows. A transition criterion based on these concepts appears attractive, as the receptivity of the flow must be known for only a few low-frequency modes and, based on 4-mode analytical Waleffe-type models for Couette flow, there is hope that only a rough knowledge of the initial conditions within the basin of attraction of the self-sustained cycle may be necessary. A continuing effort combining DNS simulations, experiments and modelling will be required to assess the potential of these concepts for transition prediction in complex situations, notably strong pressure gradients, three-dimensionality, *etc*.

Finally, issues relating to the control of boundary layers for the purpose of drag reduction or separation avoidance, for instance, have been discussed by B Geurts, P Carpenter and J Morrison. The relationship between optimal control approaches, which generally require very large arrays of sensors and actuators plus considerable real-time computing power, and more practical "*ad hoc*" approaches could be an important area of study in the future.

For the future, the workshop has clearly brought out some of the key problems that need to be addressed in order to arrive at better, more rational transition predictions. Probably the most pressing problem is to quantify the receptivity of a flow to "external" or free stream disturbances with, in practice, a *minimum* knowledge about the nature of the forcing. While the current knowledge base consists mostly of sophisticated analyses of "simple" cases, it may be necessary to explore more probabilistic approaches. Another important problem is the evaluation of disturbance amplification including non-parallel effects, three-dimensionality and nonlinearity, once external perturbations have been converted to modal or non-modal boundary layer structures, and the related definition of more rational transition criteria. It is felt that the workshop has perhaps most contributed in this area through the vigorous exchanges between representatives of different "schools" and the confrontation with the industrial state of the art.

Scientific Programme: Modelling and Simulation

Even though a rigorous theory of turbulence is missing, even for the simplest flows, there is a continuing need to predict properties of turbulent flow for use in the industrial design process. It has long been recognised that the turbulence model is one of the most critical items in the application of computational fluid dynamics (CFD) software packages within industry. Examples of applications where turbulence has a critical influence were presented by industrial participants in the programme. These include prediction of the drag on an aircraft wing, design of a combustion chamber in a jet engine, safety engineering in nuclear reactors’ cooling vessels, turbulent combustion and atmospheric dispersion of pollutants.

Over the last century engineers have developed an array of methods to deal with turbulent flow based on experiments and some limited insight into supposedly universal aspects of turbulent flow, an example of which is the semi-logarithmic law of the wall which approximates the mean flow near a solid surface. Over the last 30 years these semi-empirical methods have been increasingly supplemented with calculations of the time averaged field equations of fluid flow. Due to the averaging, these equations contain more variables than equations and the problem of turbulence closure in this sense is to devise additional model equations that represent the turbulence to some desired level of accuracy.

By far the most popular closures used in CFD codes are the so-called two-equation methods where the required eddy viscosity is represented by two further quantities, for example (in the k-e model) the turbulence kinetic energy and dissipation rate, for which additional transport equations are formed. These methods are numerically robust and have constants that are tuned to predict certain canonical flows. Insight into the applicability of such methods has come from second moment closures where transport equations are written for all the Reynolds stresses. As an example these equations contain pressure-strain rate terms which amongst other effects need to model the inherent non locality of turbulence. Near a wall these terms contribute a pressure reflection effect. Recent modelling has included the elliptic relaxation method which is one of the first models to include some limited non-locality, and has also been applied in a reduced three-equation model. An alternative simplification of the full second moment closure can be made when the diffusive terms cancel equivalent terms in the turbulence kinetic energy equation. This leads to non linear algebraic equations for the Reynolds stresses, which contain much of the modelling capability of the second moment closure. In devising models, some use may be made of a concept of realisability, which ensures that models may not predict certain kinds of unphysical results, such as negative energy. It is generally accepted that for some problems, such as buoyancy-driven flows, the full second moment treatment is required, whereas for some weakly distorted boundary-layer problems the simpler two-equation models are adequate. Practical experience for model problems is being gathered from collaborative testing programmes. What is not at all clear is how to specify from first principles when a certain model may be expected to work, and when not. This difficulty is being addressed by the development of a guideline document (see *Conclusion* below).

There was lively debate during the programme on the future role of large-eddy simulations (LES) for practical calculations of turbulent flow. Simulations of turbulence are made possible by advances in computer performance. In direct numerical simulations (DNS) all spatial and temporal scales of turbulence are computed and the databases from such simulations effectively provide solutions of the governing equations for use in understanding turbulence and validating models. Model validation proceeds either *a priori*, by testing each term in the model equation against its exact counterpart, or else *a posteriori*, by comparing simulation results with model predictions. The restriction on DNS is that the cost increases dramatically with Reynolds number, putting most practical applications beyond reach for foreseeable developments in computer hardware. LES combines a numerical simulation of the large scales of turbulence with a model for the small scales, a simple rationale being that the small scales may be more universal, and hence possible to model more generally, whereas the large scales will always be problem dependent. If one tries to simulate, rather than model, the small scales of turbulence near a wall, the LES method is also limited by Reynolds number. Nevertheless simulations of flow around bluff bodies at Reynolds numbers comparable to traditional laboratory studies have demonstrated the feasibility of the methods, and there are programmes under way to compute, for example, the complete flow in a gas turbine combustor using LES. Such progress has led to a view from some quarters that in the not too distant future all predictions of turbulence will be made using LES, whilst others have pointed out that the invention of the car hasn't made the bicycle obsolete, and that traditional methods will continue to have their niche. The feasibility of practical LES calculations has led to detailed study in recent years of the various options for modelling. Most practitioners have by now moved from simple eddy viscosity models to dynamic procedures involving filtering operations on the computed flowfield. A new approach is almost entirely algorithmic, where the simulated scales are extrapolated to provide the prediction of the small scales to be modelled. Various mixed models, combining these approaches are also proposed. The whole area of small-scale modelling in LES is one in which the partial theories of turbulence, developed over the past thirty years may be profitably applied.

Intermittency

The issues addressed at the Symposium on Intermittency In Turbulent Flows and Other Dynamical Systems were a good reflection of the concerns and discussions at the INI before and after the Symposium. Intermittency in some form or another is a feature of non-linear ODEs and PDEs. ODEs were effectively the common focus of the studies by Lumley and Mullin. Lumley discussed the intermittent production of turbulence in the turbulent boundary layer's wall region which is dominated by a few large-scale coherent structures that break down intermittently. A Proper Orthogonal Decomposition of the Navier-Stokes equation leads to a system of coupled nonlinear ODEs which can be used to predict breakdown of structures and thereby act to reduce drag on the wall. Mullin's intervention concerned low-dimensional chaos and temporal intermittency found in Taylor-Couette and various other flows and claimed that it is not possible to reduce completely these dynamics to a low-order set of ODEs. The rest of the Symposium was on internal intermittency in PDEs and turbulence experiments.

The main questions asked were:

- How can we relate scaling exponents of structure functions to near-singular flow structure (*eg* vortex tubes but also other straining structures)?
- Is the near-singular flow structure an imprint of finite-time singularities of the Euler equations assuming they exist? If they exist, are they stable (Constantin)?

Ohkitani proved the existence of finite-time singularities in the inviscid Burgers equation without use of the Hopf-Cole solution and applied his method to the Euler equations with a Taylor-Green vortex initial condition to show that if a finite-time singularity exists it cannot be too weak. A condition for the non-existence of finite-time singularities of the Navier-Stokes equation was derived by Doering and Gibbon at the INI during the programme. Other PDEs that have been discussed for their intermittency properties during this Symposium are the advection-diffusion equation for scalar fields (Gawedski, Vassilicos) and the advection-stretching-diffusion equation for magnetic fields (Falkovich). Frisch showed that the probability distribution functions of velocity gradients generated by the Burgers equation has very broad skirts which obey an asymptotic -7/2 power law.

Experiments by Ciliberto, Sreenivasan, Tsinober and Vassilicos generated doubts on whether structure functions have well-defined power-law scalings even using very high Reynolds number experiments in the atmosphere. Mean shear seems to influence structure functions, and measurements of structure functions conditionally on high values of turbulent velocity fluctuations revealed a significant correlation between small and large scales. It may be that longitudinal structure functions, which have focused research interest since the seminal works of Kolmogorov, are not the most appropriate tools to study intermittency and scalings. In particular they are not very instructive as to the spatio-temporal flow structure of the turbulence. It is for this reason that an entire battery of new ideas, concepts and methods were presented and discussed at this Symposium. The oldest of these new approaches are not more than 20 years old, and the most recent date from the second half of the 1990s: they include wavelets, extended self-similarity, numerical vortex tube visualisation techniques, transversal and inverted structure functions, multipoint correlators and geometrical statistics (Constantin, Tsinober).

Arneodo showed how wavelets naturally generalise velocity increments, and by applying his wavelet method to turbulence one-point measurements he was able to conclude that if the turbulence is a multiplicative cascading process (which it may well not be) then this process is not self-similar. The wavelet transform was also applied to energy transfer and spectral properties of the Burgers equation by Brasseur. Van der Water's experimental evidence showed that power-law scalings are better defined for transverse than they are for longitudinal structure functions, and that transverse scaling exponents are smaller than the Kolmogorov predictions. Vulpiani introduced the study of the statistics of separations across which the velocity difference has a certain value. These statistics are called inverted structure functions, and they give improved results for Richardson's turbulent diffusion law. Finally, Pumir and Shraiman studied multipoint correlators and tetrad dynamics: moving from two-point to multi-point statistics seems to be a good way to probe more of the turbulence spatial flow structure.

Output and Achievements

The Research Programme was greatly beneficial to the participants, both those in residence and those who attended the seminars, symposia and workshops. People were given an opportunity of working closely with each other through the medium of the Research Programme and many future collaborations were initiated as a result of this process. Although it is always difficult to identify specific scientific and technical achievements, it is important to try to do so in order that the more detailed benefits of the Research Programme can be assessed. Such specific examples of achievements are as follows:

S Tanveer reported that Kolmogorov's celebrated -4/5 law can be obtained without Kolmogorov's assumption of local isotropy. In fact, it is important to note that a significant shift from studies of homogeneous isotropic turbulence to studies of non-homogeneous and/or non-isotropic turbulence by theoreticians and mathematicians was evidenced during the Programme.

During the programme, K Ohkitani and J Gibbon carried out pseudo-spectral computations of an Euler flow starting from a simple smooth initial condition and leading to what may be a breakdown in finite time. Moreover, they found that this apparent singularity persists in the Navier-Stokes case.

In response to discussions during the programme D McComb modified his Renormalization Group Theory approach to drop the assumption that probability density functions of velocity differences have a symmetric shape about their mean.

A Tsinober produced a significant advance in the relationship between statistics and structure in turbulence.

A number of interesting developments in large-eddy simulation were considered by participants in the programme. S Sarkar provided a rationale for mixed models that have been found previously to give good performance in several practical calculations. D McComb worked on an operational method for controlling the behaviour of high-wavenumbers in numerical simulation. B Geurts and A Leonard wrote a paper on the issue of whether LES was ready for practical calculations yet. The paper debates many of the issues discussed during the programme, including filtering, commutation errors, de-convolution methods and mixed models, and concludes with a set of guidelines for use of current methods. These recognise the fundamental limitations of current techniques and should provide a useful validation strategy for users of the methods. D Thomson and R Kerr provided a cross reference between engineering applications of LES and meteorological applications.

C Doering and J Gibbon collaborated in identifying a condition for the non-existence of finite-time singularities of the Navier-Stokes equations.

G Eyink produced a new analysis of the relationship between singularities and the -5/3 spectrum.

C Thompson and G Eyink wrote a joint paper on late-stage turbulence decay.

T Lundgren found a new asymptotic solution to the Navier-Stokes equation which has a -5/3 energy spectrum without time averaging.

As a direct result of interactions in the Research Programme, one of the companies made major changes in its strategy for the prediction of natural convection systems.

Useful progress was being made on mathematical analysis of turbulence models, and analysis leading to new models. R Maneau presented new work carried out with P Durbin's idea of elliptic relaxation. B Launder and T Craft showed practical benefits of introducing concepts based on realisability into second-moment closures by ensuring that a two-component limit of turbulence anisotropy was satisfied.

T Gatski showed the way models could be more rigorously constructed by starting with homogeneous turbulence and adding complexity, with continuous validation against DNS and experiment.

J Ferguson of Schlumberger made a presentation on what is believed to be the first applications of LES to two-phase dispersed flows.

The lagrangian view of turbulence was studied by A Pumir using a new method of tetrad dynamics. Collections of four points are followed in time and a tensor of velocity differences is formed. Preliminary results show some departures from expected scalings.

C Barenghi had useful interactions with B Geurts on the knottiness of the vortex tangle in superfluid turbulence. It appears that previous work on polymers can be carried over to this problem.

D McComb and M Oberlack began a collaboration to write a paper on the application of Galilean invariance principles in turbulence.

Core dynamics, an instability of vortex tubes that can lead to transition in the mixing layer without vortex pairing, was put forward as a cascade mechanism by F Hussain. S Le Dizes demonstrated that core dynamics could be considered as one example of a wider range of problems of elliptic instability and C Cambon noted the connections with rapid distortion theory of homogeneous turbulence. CHK Williamson was able to illustrate the phenomena with beautiful photographs from experiments (see opposite).

Vortex structure identification remains a complex issue but progress towards a common definition is being made using analysis based on the pressure Hessian. F Hussain proposed a threshold amplitude of the second eigenvalue of an approximation to the pressure Hessian, including only the strain and rotation rate tensors. S Kida prefers a method with no arbitrary choice of threshold, based on choosing a plane perpendicular to the axis of a vortex and then checking a discriminant in that plane. The resulting vortex 'skeleton' can then be analysed.

The problem of mean velocity profile near a solid wall has certainly not been solved to any general satisfaction but an achievement of the programme has been to bring the different approaches to a much wider audience, with the ideas subjected to extensive discussion. W George presented similarity approaches which give a semi-logarithmic law for boundary layers and an algebraic law for boundary layers.

K Sreenivasan investigated multiple layers, leading to two semi-logarithmic laws with the possibility of a critical layer in-between. M Oberlack showed how the possible forms of mean profile are related to the successive breaking of symmetries in near-wall turbulence. S Nazarenko worked on a new derivation of the semi-logarithmic law based on a feedback loop using rapid distortion theory.

There was some detailed work on turbulence mechanisms near a solid boundary. D Martinand and P Monkewitz presented a new dynamical system model of near-wall turbulence that provided a realistic model of the interplay between streaks, rolls, instability and mean flow modification. N Sandham verified streak stability calculations with F Hussain and J Jimenez, and in a new collaboration with F Hussain developed a streak-eduction algorithm to determine typical streak amplitudes from numerical simulation. A new collaboration between N Sandham and A Tsinober was begun to analyse enstrophy and strain rate budgets.

A new view on the structure of turbulent boundary layer at high Reynolds number was developed during the programme by J Hunt and J Morrison. They consider the dynamics to be controlled by outer-layer motions impinging on the wall. By contrast J Jimenez presented work in which all outer-layer motions had been filtered out by means of numerical experiments, yet the inner-layer still exhibited turbulent behaviour. Whether the two mechanisms can exist side by side at high Reynolds number is a question for future research.

Flow control applications of research on structures were stressed by F Hussain and J Morrison. The utility of minimal channel simulations to test control theories is now in some doubt after simulation results presented by J Lumley. As the number of active modes increased the flow became less amenable to control.

There was much support during the programme for new experiments, especially to clarify turbulence behaviour at high Reynolds number. A Tsinober presented new results from measurements of the atmospheric boundary layer using advanced instrumentation whereas P Tabeling was using a stirred tank of liquid helium to study scalings over a wide range of Reynolds number. A Perry described the features of boundary-layer turbulence that were Reynolds number dependent and how wall structural similarity methods could be applied. F Nieuwstadt presented plans for a new pressurised facility to study high Reynolds number boundary layers and address some of the issues. Given the increasing capabilities of numerical simulation at lower Reynolds numbers, it was agreed in discussion that the most useful experiments in the future would be those that could address the largest ranges of Reynolds numbers, and similarly for other non-dimensional parameters.

Outcome in Books and Documents

It is important, of course, to maintain records of the outcome and achievements of the Research Programme. The following books are being published, based on the various Workshops and Symposia:

Turbulence Structure and Vortex Dynamics (Edited by JCR Hunt and JC Vassilicos). Being published by Cambridge University Press in the Autumn of 1999.

Closure Strategies (Edited by BE Launder and ND Sandham). Being published by Cambridge University Press in early 2000.

Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) (Edited by P Voke, L Kleiser and ND Sandham). Being published by Kluwer in late 1999.

Intermittency (Edited by JC Vassilicos). Being published by Cambridge University Press in early 2000.

In addition to these more formal publications, it is noted that:

- Regular seminars and discussion sessions were held throughout the duration of the Research Programme. Copies of the transparencies etc produced for these presentations have been deposited in the Isaac Newton Institute Library.
- The material presented at the Workshop on Future Strategies (29th-30th June 1999) contains a wealth of information about the latest status in various areas and about industrial requirements. Copies of the presentations at this Workshop have been produced in bound form by the Institute and distributed to all participants. They are also available for reference in the INI Library.

Conclusion

The Research Programme on Turbulence provided a unique opportunity to review and examine this field. A wealth of new information was presented and discussed. Future strategies for development in the area were reviewed and agreed and two major reports are being prepared as follows:

- A paper for the Journal of Fluid Mechanics co-authored by the Chairman of the Scientific Advisory Committee and the Organisers where a broad review on current turbulence research is given on the basis of the six-month programme.
- A guidance document on closure models is being prepared by JCR Hunt which will provide a "road map" for users of such closure models. The choice of an appropriate closure model is strongly connected to the particular application. There are no universal models!
- A report is in preparation which will deal with the main areas of industrial and environmental applications, digesting all the material arising from the Research Programme, giving a state of the art description and recommendations based on current knowledge. Gaps will be identified and strategies for addressing them discussed. This report will be financed from the funding from the industrial participants and it will be completed by around the end of 1999.

All in all, it can be claimed that the Research Programme on Turbulence allowed a realistic view to be taken on the current state of the field. Central to many of the developments is the critical assessment of universality; quantitative aspects of scalings appear non-universal and other qualitative aspects relating to flow structure and geometrical statistics may well be universal. Much effort is focused on the relation between spatio-temporal flow structure and turbulence statistics and on new kinematics for the description of turbulent flows. Although DNS is making important contributions to fundamental understanding, it seems very likely that it will be many years yet before even LES can be realistically applied to the high Reynolds number, complex geometry situations found in industry. Thus, there is a need to use and develop new modelling approaches and also perhaps new closures which necessarily have to be based on new experiments. The need for good and innovative experiments motivated by existing and new turbulence concepts and theory, and the need for new modelling approaches taking full account of new findings from experiments and from numerical simulations (DNS and LES) are still paramount for the immediate future.

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