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WALL TURBULENCE

FINAL REPORT

TO

THE OFFICE OF NAVAL RESEARCH

ON

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Background: A program to study "Wall Turbulence" at the University of Illinois was initiated on April 1, 1988. This report covers work done under this grant until its completion on November 31, 1991.

Goals: This research was aimed at understanding turbulence generated at a wall. The goals were to investigate the structure of turbulence in the viscous wall region, to understand how production of turbulence is related to measured structural parameters, to develop models that will allow the computation of velocity and temperature fields, and to explore how the characteristics of wall turbulence are changed by external influences. The principal tools that were to be used are electrochemical techniques that measure turbulence characteristics in the immediate vicinity of a wall without interfering with the flow, the laser Doppler velocimeter, computer experiments, and pulsed-laser velocimetry. External influences to be studied are imposed flow oscillations, wavy walls and drag-reducing polymers.

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Two developments in our laboratory have had a strong impact on this research: A turbulence channel with a number of features that make it uniquely suitable for optical studies and for studies of flow over structured surfaces has been put into operation. A computer code has been developed that allows us to simulate three-dimensional turbulent flow in a channel at low-Reynolds numbers.

Accomplishments:

(a) Effects of imposed flow oscillations

Studies of the effect of imposed small amplitude flow oscillations have shown no effect on the time mean flow. Work was undertaken to see if imposed large amplitude oscillations can affect drag. The system used was water flow through a two inch pipe. The flow oscillations were introduced by a plunger pump whose motion is controlled by specially designed cams. The wall shear stress is measured by electrochemical methods. These are the first experiments of this type to show time-averaged drag-reduction. Reductions of the order of 10 per cent were observed with imposed sinusoidal oscillations that are large enough to cause flow reversal over part of the cycle. Reductions of the order of 10 per cent were also observed under certain conditions without flow reversal if non-sinusoidal imposed oscillations were used. This drag-reduction seems to be associated with the ability of the flow to adjust after a sudden change from an unfavorable pressure gradient to a favorable pressure gradient. A paper describing these results was presented at the Seventh International Conference on Turbulent Shear Flow in Munich and has been submitted for publication.

(b) Measurement of wall shear stress in reversing flows

A major accomplishment was the development of new possibilities in the measurement of local wall shear stress. One of the limitations in present methods is their inability to study a time-varying wall shear stress in the presence of a reversing flow (such as exists in separated regions). The proposed method involves measuring mass transfer (or heat) transfer to flush mounted probes. The work carried out with ONR support involved the use of two rectangular electrodes separated by a thin layer of insulation. These electrodes were operated under conditions that they are mass transfer controlled so that the electric currents flowing to the electrodes are proportional to the rates of mass transfer. The key feature of the technique is the development of algorithms that allow the solution of the inverse mass (or heat) transfer problem. Extensive laboratory tests were carried out to test the new method. The results of this work are described in three papers.

(c) Turbulence producing eddies

The identification of turbulence producing eddies is important not only from the viewpoint of developing a physical understanding of turbulence but also from the viewpoint of having theoretical background for controlling turbulence. We have made a new discovery in this area. This was accomplished with the direct numerical simulation of turbulent flow in a channel that was developed with support from ONR. We find that turbulence is produced by flow oriented eddies which start upstream from small vortices attached to the wall. These eddies grow in size downstream; they lift from the wall and continue to grow. Occasionally they turn into the z-plane to form a z-vortex. Most often they just dissipate as they move away from the wall. We have never been able to identify a horseshoe (or hairpin) vortex whose legs are the turbulence producing flow oriented eddies.

A challenging probiem which we started this past year was to discover how these vortices are born. This is a very painstaking task because we have to sort through many realizations of the full three-dimensional field to follow how these turbulence producing eddies change with time. (We actually could use some new innovative flow visualization methods). However, tentative results are very interesting. The vortices seem to start from a region with strong x-vorticity. This vorticity then gathers together to form an x-vortex (a streamwise vortex). This discovery is counter to the notion that a z-vortex is formed from z-vorticity close to the wall and that this z-vortex lifts from the wall and gets stretched into a horseshoe vortex.

(d) Development of a turbulence facility

In 1986 we undertook the design and construction of a facility in which to carry out optical studies of turbulent flow in enclosed rectangular ducts 2, 3 or 4 inches high. Its value is close to $500,000. The LDV studies by Niederschulte (described in previous reports) were done to document its performance. In the past two years we have carried out our first real research in the facility. This includes studies of flow over a wavy surface, studies of the structure of turbulence, and the initiation of studies of the effect of drag-reducing polymers.

(e) Flow over wavy surfaces

In previous work on flow over wavy walls we had measured streamwise velocity field, the wall shear stress and the wall pressure. From these results we inferred about the Reynolds stress. During the past year we completed a comprehensive set of direct measurements of the Reynolds stress. These include conditions of non-separated as well as separated flows. These measurements on this non-canonical (but well defined) field should supply a test for models of the Reynolds stress. It also could be important in understanding air-water interaction and wall drag.

We are particularly interested in connecting LDV measurements of Reynolds stress with structural information about the field. We completed a set of visual studies which show the philosophical limitations of present methods for modelling separated regions. At no time does the flow ever resemble what is indicated by the mean streamlines. Experiments are now being set up to make PIV measurements. This will enable us to define in a more quantitative way the structures indicated by visual studies.

(f) PIV studies of turbulent flow

Pulsed-image velocimetry opens the possibility of making simultaneous measurements of the velocity at multiple points in a flow field. During the past two years we have exploited this technique to study turbulent flow in a channel. Our initial experiments were done at a Reynolds number (based on the half channel width of 2800. Simultaneous measurements of two components of the velocity were made at 12,000 points. Two scales seem to dominate the flow. One of these is the large scale motions which involve large streaming flows extending almost over the whole channel cross section. The other is a smaller scale closed vortex with a dimension of about 100 wall units.

During the past year we completed studies at several larger Reynolds numbers. A surprising aspect of this work is that dramatic changes are observed when the Reynolds number changes from 2800 to 6000. The large scale motions appear the same, but a much larger population of smaller scale vortices are observed.

Two possibilities of this work are exciting: (1) The log-layer has been described as a region where the length scale of the turbulence increases linearly with distance from the wall. We now have an opportunity to interpret this scaling in terms of eddy structure. (2) By using a low pass filter we can separate out the large scale motions which seem to be carrying most of the Reynolds stress. By subtracting this from the original measurements the small scale motion can be examined independently. This offers an opportunity to examine directly the unresolved turbulence in large eddy simulations and to test models for the unresolved stresses.

(g) Polymer Drag-Reduction

Under the support of the Petroleum Research Fund and ONR we have carried out a very successful study to see how polymer molecules configure themselves in a turbulent field. These experiments were done in our DNS of turbulent flow in a channel. We used our particle tracking algorithms to obtain typical changes (with time) of the rate of strain tensor of a fluid particle. This was then used in a FENE bead and spring model of the polymer molecule.

The success of this work has prompted us to undertake companion laboratory studies to see how the presence polymer changes the turbulence. During the past year we have put in a large amount of time designing this experiment. The technique to be used is the PIV method. We have designed and installed an injection slot after doing several preliminary studies in a pipeline. Thermal wall shear stress probes have also been installed in our channel so that we will have a measurement of the wall drag at the instant the PIV picture is taken.

(h) Couette flow

During the past year we developed a DNS of Couette flow. This is simpler than turbulent flow in a channel in that the shear stress does not vary with distance from the wall. It also has some interesting features in that significant turbulence production can occur in the central region of the channel in addition to the wall region.

PUBLICATIONS

(1) Kuzan, J.B., Hanratty, T. J. & R. J. Adrian, Turbulent flows with incipient separation over solid walls, *Experiments in Fluids*, 7, 88-98 (1989).

(2) Lyons, S. L., Hanratty, T. J. & J. B. McLaughlin, Turbulence-producing eddies in the viscous wall region, *AIChE Journal*, 35, 1963-1974 (1989).

(3) Niederschulte, M. A., Adrian, R. J. & T. J. Hanratty, Measurements of turbulent flow in a channel at low Reynolds numbers, *Experiments in Fluids*, 9, 222-230 (1990).

(4) Hanratty, T. J., Lyons, S. L. & J. McLaughlin, Interpretation of polymer drag reduction in terms of turbulence producing eddies close to the wall, In *Structure of Turbulence and Drag Reduction* (ed. A. Gyr) p. 409, Springer-Verlag, Berlin Heidelberg (1990).

(5) Mao, Z. & T. J. Hanratty, Application of an inverse mass transfer method to the measurement of turbulent fluctuations in the velocity gradient at the wall, *Experiments in Fluids*, 11, 65-73 (1991).

(6) Mao, Z. & T. J. Hanratty, Analysis of wall shear stress probes in large amplitude unsteady flows, *Int. J. Heat Mass Transfer*, 34, 281-290 (1991).

(7) Liu, Z. C., Landreth, C. C., Adrian, R. J. & T. J. Hanratty, High resolution measurement of turbulence structure in a channel with particle image velocimetry, *Experiments in Fluids*, 10, 301-312 (1991).

(8) Hanratty, T. J. Effect of gas flow on physical absorption, In *Air-Water Mass Transfer*, Second International Symposium, U.S. Army Waterways Exp. Station/ASCE, Minneapolis, MN (1990).

(9) Lyons, S. L., Hanratty, T. J. & J. B. McLaughlin, Direct numerical simulation of passive heat transfer in a turbulent channel flow, *Int. J. Heat Mass Transfer*, 34, 1149-1161 (1991).

(10) Lyons, S. L., Hanratty, T. J. & J. B. McLaughlin, Large-scale computer simulation of fully-developed turbulent channel flow with heat transfer, *Int. Journal for Numerical Methods in Physics*, 13, 998-1028 (1991).

(11) Hanratty, T. J. Use of the polarographic method to measure wall shear stress, *J. Applied Electrochemistry*, 21, 1038-1046 (1991).

(12) Kontomaris, K., Hanratty, T. J. & J. B. McLaughlin, An algorithm for tracking fluid particles in a spectral simulation of turbulent channel flow, *J. Computational Physics*, to be published (1992).

(13) Mao, Z. & T. J. Hanratty, Measurement of wall shear rate in large amplitude unsteady reversing flows, *Experiments in Fluids*, to be published (1992).

(14) Kontomaris, K., Effect of molecular diffusivity on turbulent diffusion in isotropic turbulence, *Int. J. Heat Mass Transfer*, to be published.

ARTICLES UNDER REVIEW

(1) Mao, Z. & T. J. Hanratty, Influence of large amplitude sinusoidal and non-sinusoidal oscillations on drag.

(2) Massah, H., Kontomaris, K., Schowalter, W. R. & T. J. Hanratty, The configuration of

a FENE bead-spring chain for turbulent flow in a channel.

THESES

(1) Kontomaris, Konstantinos, Point Source Dispersion in a Direct Numerical Simulation of Turbulent Channel Flow, Ph.D. thesis, University of Illinois, Urbana, 1991.

(2) Poirier, Michael Robert, Mass Transfer in Turbulent Pulsatory Flows, Ph.D. thesis, University of Illinois, Urbana, 1989.

(3) Brooke, John William, A Study of Coherent Eddy Structure in Turbulent Channel Flow, M.S. thesis, University of Illinois, Urbana, 1991.

(4) Courtemanche, David James, Pressure Variation Over a Solid Wave Surface, M.S. thesis, University of Illinois, Urbana, 1989.

(5) Hudson, John Dale, The Prediction and Measurement of Reynolds Stress Over a Small Amplitude Wave, M.S. thesis, University of Illinois, Urbana, 1991.