Progress Report

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LAGRANGIAN ANALYSIS OF CONTAMINANT DISPERSAL IN BOUNDED
TURBULENT SHEAR FLOWS

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Completed Work: Experimental & Numerical Results

Contaminant Dispersion.

Laboratory experiments and direct numerical simulations (DNS) of passive scalar contaminant dispersal in bounded shear flows have been carried out. The laboratory flow was a low speed turbulent boundary layer with a free stream velocity of 2 m/s. The lower wall of the 8 m long test section of the tunnel was investigated. At the end of this section, the turbulent boundary layer thickness was 14 cm and The momentum thickness Reynolds number was $R_\theta \approx 1,800$ ($R_\tau = u_\tau \delta / \nu \approx 830$). A Nichrome wire embedded in a 1/8 in. diameter ceramic sheath, 15 cm wide and flush mounted in the tunnel wall was used as heat source generator. The wire temperature was monitored with a K-type thermocouple, and the heat power input through a rheostat was 6.7 W/m. The temperature fluctuations downstream of the heat plume origin were recorded with a 2.5 μm tungsten cold wire probe heated slightly with a 1 mA current and operated by a constant current anemometer circuit. The free stream temperature was also monitored by a K-type thermocouple. Three vertical temperature profiles were taken at locations $x = 5, 10$ and 15 mm downstream of the source, corresponding to $x^+ = 27, 55$ and 82. During the entire experiment, the ambient temperature varied from about 24.5 to 25.0° C. The heating element was maintained 12.0° C above the ambient temperature.

The numerical approach used for comparison with the experimental measurements is the following. Two sets of velocity and scalar fields necessary for the Lagrangian analysis of turbulent scalar transport were obtained. In the first simulation, the complete velocity and scalar fields for 1000 consecutive time steps with a spacing of $\Delta t^+ = .05$ have been stored from a direct numerical simulation of a channel flow containing a spatially uniform source. In this simulation Neumann boundary conditions, i.e. zero wall diffusion, are

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applied, and $Pr = .71$ and $R_\tau = U_\tau h/\nu = 125$. A mesh with $64 \times 65 \times 64$ points and box size of $1250 \times 250 \times 625$ in the streamwise, wall-normal and spanwise directions, respectively, was used. In the second simulation, 780 consecutive fields covering a time $T^+ = 40$ was computed and stored for the case of channel flow with a line source at $y^+ = 15$ near one wall and at $y^+ = 25$ on the other. For this simulation $Pr = .71$ and $R_\tau = 145$, the mesh size is $96 \times 97 \times 96$ points and the box size is $1880 \times 290 \times 700$. The two simulations represent a total storage of approximately 100 gigabytes.

The averaged properties of the plumes developing downstream of line sources from these simulations have been used to study the accuracy of random flight and closure models in predicting one and two-dimensional mean scalar fields. The scalar fields derived from the direct numerical simulations are compared to the solutions to the equation for the mean scalar field given by

$$\frac{\partial \bar{C}}{\partial t} + \bar{U}_i \frac{\partial \bar{C}}{\partial x_i} = \frac{1}{Re Sc} \frac{\partial^2 \bar{C}}{\partial x_i^2} - \frac{\partial \overline{cu_i}}{\partial x_i} + Q \quad (1)$$

incorporating various modeling assumptions for the turbulent scalar flux $\overline{cu_i}$. Here $\bar{U}_i$ is the mean turbulent velocity field, c and u_i refer to fluctuating scalar and velocity components, Q is a source term, Sc is the Schmidt number and Re the Reynolds number. (Alternatively, $\bar{C}$ may be considered to be the temperature, in which case Sc is replaced by the Prandtl number, Pr). Among the models considered are the algebraic model proposed by Rogers, Mansour and Reynolds, the RNG model of Rubinstein and Barton, and the truncated transport closure predicted from the current Lagrangian theory. In addition, we consider the random flight model appropriate to shear flow proposed by Thomson.

This work has been presented at the Symposium on Non-Linear Problems in Energy Engineering, Argonne National Laboratory, 1992 and will also be presented at PACAM III this January in Sao Paulo Brazil and at the November, 1992 APS meeting in Tallahassee, Florida. A longer version is currently being written for submittal to *Physics of Fluids A* this fall. In the paper presented at the Argonne National Laboratory Symposium, the distributions of the mean temperature and of the rms and skewness factors of the temperature fluctuations measured at the x^+ locations are also compared to the DNS results. The agreement is reasonably good considering the difference in Reynolds number and the difference between channel and boundary layer flow. A copy of both the Argonne National Laboratory Symposium and PACAM III papers are attached to this report.

Research in Progress

Windtunnel Modifications for Flow Visualization

Between May and September 1992, we carried out several modifications to our laboratory windtunnel which will make possible laser sheet flow visualization along the whole

length of the 8 m test section. Moreover, the multi-sensor probe displacement mechanism has been replaced by a new traversing system which moves also in the streamwise direction. This is an essential feature for the phase of the project which involves simultaneous flow visualization and multi-sensor hot-wire anemometry at various cross-sections of the test section.

Backward Particle Paths for Scalar Transport Analysis

Backward particle paths needed to perform a Lagrangian analysis of scalar transport are in the process of being computed for each of the numerical data sets previously described. These consist of several thousand particle paths defined according to the planes on which they are found at the end of the simulation. Computation of such backward trajectories requires utilizing the stored velocity fields in reverse order. At the present time particle paths have been computed approximately half way through the first data set and a quarter of the way through the second. Once the complete set of paths are obtained, Lagrangian decomposition of the turbulent scalar transport correlation will be initiated. From this a physical interpretation of the transport correlation may be deduced.

Techniques for 3-D Visualization of Scalar Plumes

On the experimental side, we are implementing of a light sheet system capable of visualizing a 30cm x 30 cm x 5cm portion of the wall layer in order to extract quantitative information about the structure of the scalar plumes. The intent is to freeze this portion of the flow in 10 to 20 parallel slices. This will be achieved by traversing the 1mm thick light sheet at a rate of 1 to 10 KHz and synchronizing the slicing with a 16mm high-speed movie camera. At these slicing frequencies, we will need a powerful laser light source to get sufficient light energy on film. Two laser technologies are being evaluated: a continuous argon ion laser and a pulsed copper laser. Tests are being conducted on a round free jet at a Reynolds number based on the diameter of about 12,000. Three vendors have scheduled demonstrations of the laser equipment on our jet flow in October 1992. They are: Oxford lasers (pulsed copper laser), Spectra Physics and Coherent Lasers (argon ion laser). Based on this series of tests, we will choose the light source that is most suitable for this experimental 3-D visualization technique.

For the numerical simulations, techniques for three-dimensional visualization of scalar plumes have been developed. A black and white reproduction of a color image of a plume downstream of a point source is illustrated in the attached figure. In the future, these images will be combined with images of vortical structures (P. S. Bernard, J. M. Thomas and R. A. Handler, "Vortex Dynamics in Near Wall Turbulence", to appear in Proc. Int'l Conference on Near-Wall Turbulent Flows, Tempe, Arizona, March, 1993) to reveal the modes by which coherent quasi-streamwise vortices effect turbulent scalar transport. This physical view of transport complements the statistical results obtained by the backward particle path method.

LIST OF PUBLICATIONS

PAPERS

P. Vukoslavčević, J. M. Wallace, & J.-L. Balint, "The velocity and vorticity vector fields of a turbulent boundary layer. Part 1. Simultaneous measurement by hot-wire anemometry", *J. Fluid Mech.* **228**, pp. 25–51.

J.-L. Balint, J. M. Wallace, & P. Vukoslavčević, "The velocity and vorticity vector fields of a turbulent boundary layer. Part 2. Statistical properties", *J. Fluid Mech.* **228**, pp. 53–86.

J. M. Wallace, J.-L. Balint, & L. Ong, "An experimental study of helicity density in turbulent flows", *Phys. Fluids A* **4** (9), pp. 2013–2026, 1992.

R. A. Handler, P. S. Bernard, A. Rovelstad and J. Swearingen, "On the Role of Accelerating Particles in the Generation of Reynolds Stress", *Phys. Fluids A*, **4**, pp. 1317–1319, 1992.

A. L. Rovelstad, R. A. Handler and P. S. Bernard, "The Effect of Interpolation Errors on the Lagrangian Analysis of Simulated Turbulent Channel Flow", submitted to *J. Computational Physics*, 1992.

P. S. Bernard, A. Rovelstad and R. A. Handler, "Tests of Random Flight and Closure Models in Predicting Turbulent Scalar Transport", to be submitted to *Phys. Fluids A*, November, 1992.

P. S. Bernard, J. M. Thomas & R. A. Handler, "Vortex Dynamics and the Production of Reynolds Stress", submitted to *J. Fluid Mech.*, 1992.

P. Vukoslavčević, J.M. Wallace, J.-L. Balint, "Viscous Drag Reduction Using Streamwise-Aligned Riblets", *AIAA Jour.* **30**(4), pp. 1119–1122, 1992.

CONFERENCE PRESENTATIONS

J. M. Wallace, "Experimentally measured vorticity and helicity properties of turbulent flows", NATO advanced workshop on Topological Fluid Mechanics held at the University of California at Santa Barbara, Nov. 1991.

J.-L. Balint, L. Ong, J. M. Wallace, & F. Ladhari, "Characteristics of sublayer ejections in a turbulent boundary layer", 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

L. Ong, J. M. Wallace, & J.-L. Balint, "Joint probability analysis of measured velocity-vorticity components in a turbulent boundary layer", 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

P. Vukoslavčević, J.-L. Balint, & J. M. Wallace, "Statistical properties of a two-stream mixing layer, 44th annual meeting of the Div. of Fluid Dynamics of the American Physical Society, Nov. 1991.

P. S. Bernard, J. M. Thomas and R. A. Handler, "Vortex Dynamics in Near Wall Turbulence", to appear in Proc. Int'l Conf. on Near-Wall Turbulent Flows, Tempe, Arizona, March, 1993.

S.-R. Park & J.M. Wallace, "Flow Field Alteration and Viscous Drag Reduction by Riblets in a Turbulent Boundary Layer", to appear in Proc. Int'l Conf. on Near-Wall Turbulent Flows, Tempe, Arizona, March 1993.

R. A. Handler, A. L. Rovelstad and P. S. Bernard, "Tests of Random Flight and Closure Models in Predicting Turbulent Scalar Transport", to appear in Proc. PACAM III, Sao Paolo, Brazil, January, 1993.

A. L. Rovelstad, P. S. Bernard and R. A. Handler, "Implications of Lagrangian Transport Analysis for Large Eddy Simulations", presented at the Thirteenth Symposium on Turbulence, University of Missouri, Rolla, Missouri, September, 1992.

S.-R. Park & J.M. Wallace, "The Influence of Instantaneous Velocity Gradients on Turbulence Properties Measured with Multi-Sensor Hot-Wire Probes", presented at the Thirteenth Symposium on Turbulence, University of Missouri, Rolla, Missouri, September 1992 and submitted to Exp. in Fluids.

A. L. Rovelstad, R. A. Handler, P. S. Bernard and J. M. Thomas "Application of Lagrangian Transport Analysis to the Development of Large Eddy Simulation Subgrid-Scale Models", to be presented at ASME Fluid Engineering Conference.

P. S. Bernard, J. M. Wallace, A. L. Rovelstad, R. A. Handler, "On the Accuracy of Random Flight and Closure Models in Predicting Turbulent Scalar Transport", to be presented at the 45th Annual Meeting of the APS Division of Fluid Dynamics, Tallahassee, Florida, November, 1992.

J.M. Wallace, "Knowledge of the Vorticity Field in Turbulent Flows", presented at the Symposium on Turbulence on the occasion of Prof. S.J. Kline's retirement, Stanford University, August 1992.

INVITED SEMINARS

J. M. Wallace. "Properties of vorticity and helicity in turbulent flows", presented at Princeton, Rutgers, Pennsylvania State, Cornell and Stanford Universities.

P. S. Bernard. "Vortex Dynamics in Near Wall Turbulence", presented at Stanford University and University of California, Berkeley.

Conf. papers Cycled Separately

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