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TURBULENCE STRUCTURE OF MIXING SWIRLING FLOWS

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This study is an experimental investigation of a swirling inner flow which develops along a constant-diameter centerbody in the presence of an unconfined, axially-directed outer flow. The data which have been acquired include local mean velocity and static pressure profiles at six streamwise locations for different prescribed mass flow rate ratios. Local wall shear stress measurements were made at these six streamwise locations in order to investigate local law-of-the-wall behavior in the vicinity of the centerbody. Reynolds stress measurements were also made in order to quantify the local turbulence structure. This report describes the scope of these measurements and the physical characteristics of the flow which have been deduced from the data. The implications of the results from a turbulence modeling point of view is also discussed.

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Research Objectives

This project is an experimental study of co-annular jets which develop along an unconfined centerbody with swirl present in the inner stream. The purpose of this study is to gain a fundamental understanding of a flow situation similar to that which exists in a turbofan engine where a swirling inner flow mixes with an axially directed by-pass flow. The project was initiated under the direction of Professor Gordon C. Oates, whose untimely death in November 1986 led to the appointment of Professor Fred B. Gessner as Principal Investigator in March 1987. Mean flow and turbulence (Reynolds stress) data have now been acquired in sufficient detail so that the physics of the flow are well understood. The data are of sufficient quality to serve as a data base against which turbulence models can be tested. Inasmuch as the results of this work have been accepted for presentation at two national conferences, but have not yet been published, this report will focus on these results and the interpretation of these results as a means of turbulence model assessment.

Status of the Research

The basic flow facility is the same as that used by Mattingly (1982) in his experiments on co-annular jet mixing with swirl, except that the blow-down air supply system used in his study was replaced by a continuous flow, high pressure fan. This modification eliminated the high noise level, intermittent mode of operation associated with the blow-down system without sacrificing the ability to run at high Reynolds numbers. The inner and outer streams within this facility exit at atmospheric pressure from a dual concentric nozzle, with swirl present in the inner stream, as shown in Fig. 1. Swirl is imparted to the inner stream by means of twenty adjustable, equally-spaced airfoil shaped (NACA-0012) blades mounted on a stator upstream of the nozzle. The radial width of each stream is 25.4 mm (1-inch) at the nozzle exit and the inner stream is bounded by a 101.6-mm (4-inch) diameter centerbody beyond the nozzle exit. The data taken in the present study are all referred to a nominal axial bulk velocity of 11.7 mps (38.4 fps) for the inner stream at the nozzle exit. The velocity profile of the inner stream at this location is that of a partially developed turbulent boundary layer with a nominal swirl angle of 35° which is approximately constant across the width of the stream. The outer stream is nominally uniform across its width at the nozzle exit.

Initial mean-flow data were taken for three outer-to-inner mass flow rate ratios ($\dot{m}_o / \dot{m}_i$ = 0, 0.5 and 1.0) with the inner stream mass flow rate held constant. These results and their physical interpretation are discussed in our two previous annual technical reports (1 October 1986 to 30 September 1987 and 1 October 1987 to 30 September 1988). The present report focuses on subsequent mean flow and turbulence data which were taken for an operating mass flow rate ratio of unity. Initial data were taken at x/D = 0 (6 mm downstream of the nozzle exit; refer to Fig. 1). These data indicated that the centerbody boundary layer was fully turbulent and in local equilibrium at this location. Data at this station and at downstream stations were taken by means of both pressure probes and hot wire probes. Details of the experimental techniques and methods of data reduction are given by Frey and Gessner (1990).

Static pressure distributions measured at six streamwise locations downstream of the nozzle exit are shown in Fig. 2, where the local static pressure measured relative to atmospheric pressure ($P-P_a$) is normalized by the dynamic pressure associated with the axial bulk velocity of the inner flow ($U_{b,i}$). The static pressure was measured directly be means of a pitot-static tube aligned with the local mean-flow direction at each point in the flow (open symbols). The static pressure was also evaluated by radial integration of the r-direction momentum equation, starting the calculations at the centerbody surface (r/R = 1) with the measured wall static pressure (solid symbols). In the initial mixing region (x/D = 0 and 0.5) there is generally good agreement between corresponding values, noting that the local static pressure in the inner swirling stream is below atmospheric pressure by virtue of streamline curvature effects. Further downstream (e.g., at x/D = 4.5 and 6), pitot-static values are consistently negative, even in the outer region of the flow, whereas values based on integration from the wall approach the correct limiting value of zero. This behavior implies that pitot-static measurements in the outer region of the flow were influenced by relatively high turbulence levels in this region and that values based on integration from the wall (i.e., the solid symbols) depict more accurate behavior.

If the local static pressure is negative and underestimated when measured by means of a pitot-static tube, one would anticipate the local mean velocity values based on the difference between total pressure probe data (assumed correct) and pitot-static data would be overestimated. This behavior can be seen to some extent in Fig. 3a, specifically at x/D = 4.5 and 6, where axial mean velocity component values based on pressure probe measurements slightly exceed their counterparts measured by means of a hot-wire probe. At other streamwise locations (e.g., at x/D = 0, 0.5, 1.5 and 3), there is generally good agreement between axial mean velocity component values measured by means of both techniques. This is especially true at all streamwise locations for the tangential mean velocity component, where both techniques yield results that agree very well (refer to Fig. 3b).

Although the results shown in Figs. 2 and 3 are in accord with anticipated behavior, other mean-flow results appear to indicate the presence of large-scale structures within the flow. Figure 4 shows radial velocity component profiles measured at the six streamwise locations (upper portion) and the variation of local flow angle ($\beta = \tan^{-1} W/U$) with streamwise position measured on and near the centerbody surface (lower portion). From the figure it can be seen that the radial velocity component is negative at x/D = 1.5 and then becomes positive at x/D = 3 before becoming negative again at x/D = 4.5. This behavior is indicative of a streamline pattern which undulates around the centerbody as the flow proceeds downstream. Associated with this behavior are undulations in the local flow angle on and near the centerbody surface. These undulations appear to be the result of a centrifugal instability which is initiated in regions of the flow where the mean angular momentum is decreasing with increasing radius. Analysis of the data has shown that this condition is particularly severe in the initial mixing region. The implications of these observations are discussed in greater detail by Frey and Gessner (1990).

Reynolds normal stress distributions measured at the six streamwise locations are shown in Fig. 5. The distributions measured at each location are truncated at a radial position where the local streamwise turbulence intensity starts to exceed 60%. (Typical intensity levels in the outer region of the flow can approach 100%, a region where hot-wire probe techniques are no longer valid because of rectification errors induced by local flow reversal effects.) The distributions in Fig. 5 measured immediately downstream of the nozzle exit (at x/D = 0) indicate that the exiting swirling inner stream emanates from a well-developed turbulent boundary layer flow within the inner nozzle, whereas the relatively uniform flow emanating from the outer nozzle (refer to Fig. 3a) is at a low turbulence level. Figure 5 also shows that peak intensity levels exist in the shear layer region between the inner and outer streams (near r/R = 1.5) immediately downstream of the nozzle exit. This effect diminishes in the downstream direction as turbulent mixing occurs between the two streams. One interesting observation is that near-wall levels of $\overline{w^2}$ increase markedly in the downstream direction while $\overline{v^2}$ levels in this region remain relatively constant. (Compare the solid and dashed line distributions in Fig. 5c.) Also, $\overline{w^2}$ levels in the near-wall region tend to approach $\overline{u^2}$ levels well downstream of the nozzle exit (compare the distributions at $x/D = 6$ in Figs. 5a and 5c). This behavior is indicative of a change in the anisotropy among $\overline{u^2}$, $\overline{v^2}$ and $\overline{w^2}$ as the flow proceeds downstream, which implies that departures from local equilibrium have occurred.

The extent to which the flow is in non-equilibrium at the downstream stations can be seen more clearly by referring to the Reynolds shear stress distributions in Fig. 6. Figure 6a shows $\overline{uv}$ profiles measured at the six streamwise locations. The axial mean velocity component profile measured at $x/D = 3$ is shown superimposed on this figure (dashed-line distribution; arbitrary units). From the figure it can be seen that $\overline{uv} = 0$ at a radial position where $\partial U/\partial r$ is non-zero, and that $\overline{uv}$ undergoes a sign change in the presence of an axial mean velocity gradient which remains positive. At this same streamwise location ($x/D = 3$), Fig. 6c shows that $\overline{vw}$ remains positive throughout the region where $\partial W/\partial r$ changes sign. This behavior also exists at $x/D = 4.5$ and 6 and implies that eddy viscosity or length-scale type modeling will not be adequate for this flow. Inasmuch as the conventional form of the k-ε turbulence model employs an eddy viscosity defined as $\nu_t = c_\mu k^2/\varepsilon$, where ν_t is always positive, this model will also be inadequate for predicting the present flow. Thus, closure at the full Reynolds stress transport equation level will be required if the main features of this flow are to be predicted accurately.

The use of wall functions for predicting the present flow was also examined. Figure 7 shows resultant mean velocity profiles measured in the $x\theta$ plane at the six streamwise locations and plotted in terms of law-of-the-wall coordinates. In this figure U_s corresponds to the magnitude of the vector sum of U and W, U_τ is the resultant wall shear stress, and yU_τ/ν is terminated at a radial position where U is still less than its maximum value (e.g., at $r/R = 1.3$ for data taken at $x/D = 3$, 4.5 and 6; refer to Fig. 3a). Figure 7 appears to indicate that the near-wall flow is in local equilibrium at all six streamwise locations where data were taken. This behavior is not observed, however, if one examines near-wall distributions of k/U_τ^2, plotted as shown in Fig. 8, where k is the turbulence kinetic energy. In the initial mixing region ($0 \leq x/D \leq 1.5$), Fig. 8 shows that the conventional form of the wall function for k, namely $k/U_\tau^2 = 1/\sqrt{c_\mu}$ with $c_\mu = 0.09$, is well satisfied in the immediate vicinity of the centerbody surface. At the downstream stations, near-wall levels of k/U_τ^2 increase markedly as a result of a diminishing wall shear stress in the presence of turbulence kinetic energy levels which still equal or exceed upstream values. Thus, the wall function approach for modeling k is not valid for the present flow. This same conclusion applies to wall functions referred to the individual Reynolds stress components if closure at the full Reynolds stress transport equation level is adopted.

The afore-mentioned results are currently being analyzed from the point of view of compatibility with: (1) eddy viscosity component models; (2) gradient and flux Richardson number models; and (3) algebraic Reynolds stress models which have been proposed for swirling turbulent flows. The results of this effort will be presented in a paper now under preparation (Frey and Gessner, 1990). Perhaps the most interesting physical feature observed in the present study is the presence of an undulating streamline pattern around the centerbody, as noted earlier with reference to Fig. 4. These undulations are apparently caused by a centrifugal instability which arises in the outer portion of inner stream where the mean angular momentum is decreasing in the radial direction [$\partial(rW)/\partial r < 0$]. This condition is most severe in the initial mixing region (refer to Fig. 3a) and is probably responsible, in large part, for the departures from local equilibrium which have been observed downstream (as described earlier with reference to Figs. 5c, 6a, 6c and 8). This behavior was observed for an outer-to-inner stream mass flow rate ratio of unity which was held constant in the present series of experiments. The sensitivity of the results to different mass flow rate ratios (different simulated turbofan by-pass flow conditions) should be the subject of further study.

References

Mattingly, J.D. (1982), "Experimental Investigation of the Mixing of Highly Swirling Flows," MS Thesis, Department of Aeronautics and Astronautics, University of Washington.

Frey, M.O., and Gessner, F.B. (1990), "Experimental Investigation of Co-Annular Jet Flow with Swirl over a Centerbody," accepted for presentation at the AIAA 21st Fluid Dynamics, Plasma Dynamics and Lasers Conference to be held in Seattle, Washington, 18–20 June 1990 (to be submitted to the *AIAA Journal* for publication).

Professional Personnel Associated with the Research Effort

1 August 1985 — 9 March 1987

Professor Gordon C. Oates, Principal Investigator (deceased November 1986)

Professor Fred B. Gessner, Co-Principal Investigator

Dr. Roger K. Nicholson, Post-doctoral Research Associate

Mr. Philip M. Dang, Research Assistant (received MS degree Spring Quarter 1987)

10 March 1987 — 30 September 1989

Professor Fred B. Gessner, Principal Investigator

Professor Robert E. Breidenthal, Co-Principal Investigator

Dr. Roger K. Nicholson, Post-doctoral Research Associate (departed November 1987)

Mr. Mark O. Frey, Research Assistant (accepted position December 1987)

Publications

1. *Theses*

Dang, P.M., "A Mean Flow Field Study of Coaxial Jets with Swirl using Five-Hole Pressure Probe and Hot-Wire Anenometry," MS Thesis, Department of Aeronautics and Astronautics, University of Washington, March 1987.

Frey, M.O., "An Experimental Study of Co-Annular Jet Flow with Swirl over a Centerbody," MS Thesis, Department of Aeronautics and Astronautics, University of Washington (in preparation).

2. *Conference Papers*

Frey, M.O., and Gessner, F.B., "Mean Flow Field and Reynolds Stress Behavior in Co-Annular Jet Flow with Swirl over a Centerbody," accepted for presentation at *the forum on* Benchmark Test Cases for Computational Fluid Dynamics, ASME/FED Conference, Toronto, Canada, 3–9 June 1990.

Frey, M.O., and Gessner, F.B., "Experimental Investigation of Co-Annular Jet Flow with Swirl over a Centerbody," accepted for presentation at the AIAA 21st Fluid Dynamics, Plasma Dynamics and Lasers Conference to be held in Seattle, Washington, 18–20 June 1990 (to be submitted to the *AIAA Journal* for publication).

Interactions

This project was among several projects discussed by Professor Gessner in a presentation entitled: "Research on Complex Turbulent Flows at the University of Washington." The presentation was made to approximately 110 attendees from universities, industry and the NASA Research Centers at the First NASA CFD Validation Workshop held at NASA-Ames in July 1987. This project was also among several projects described in a seminar presentation at the Imperial College of Science and Technology, London, while Professor Gessner was on sabbatical leave (March-June 1988) working with Professor Peter Bradshaw and his students.

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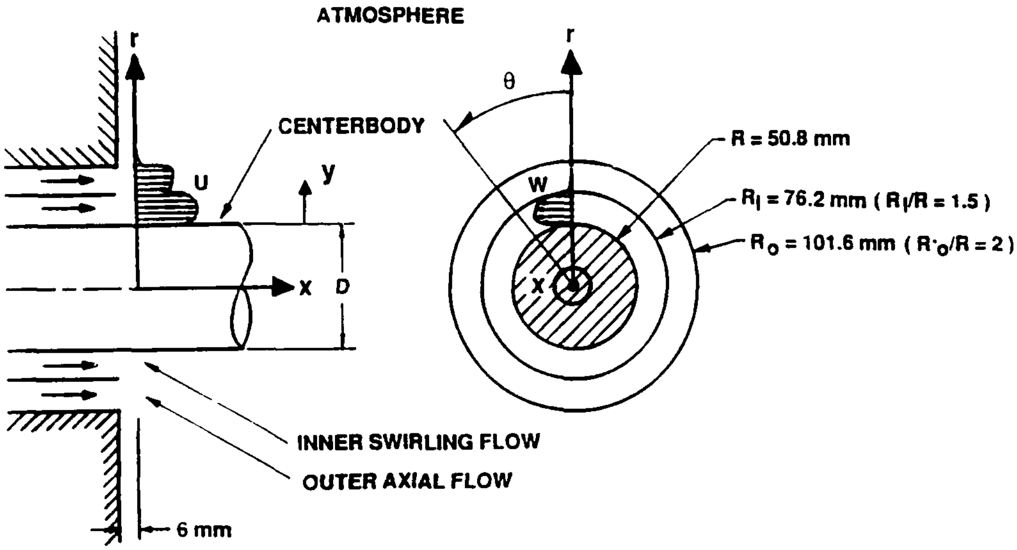


Fig. 1 Physical flow configuration and coordinate system.

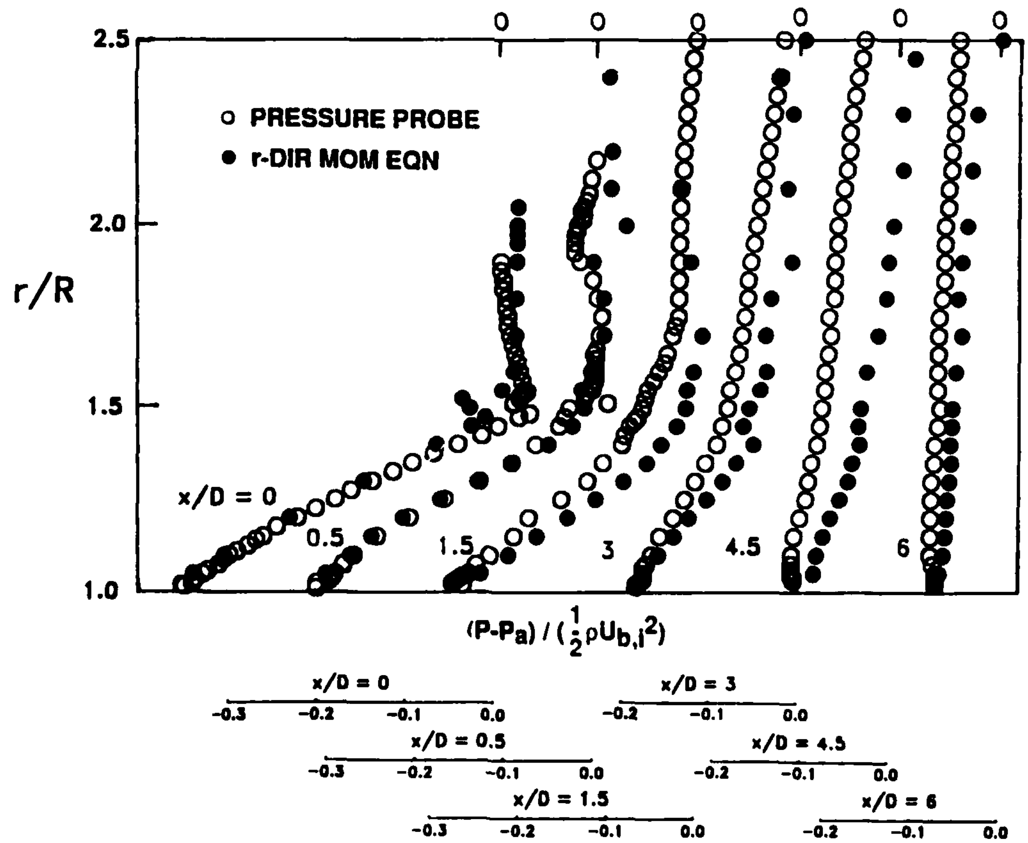
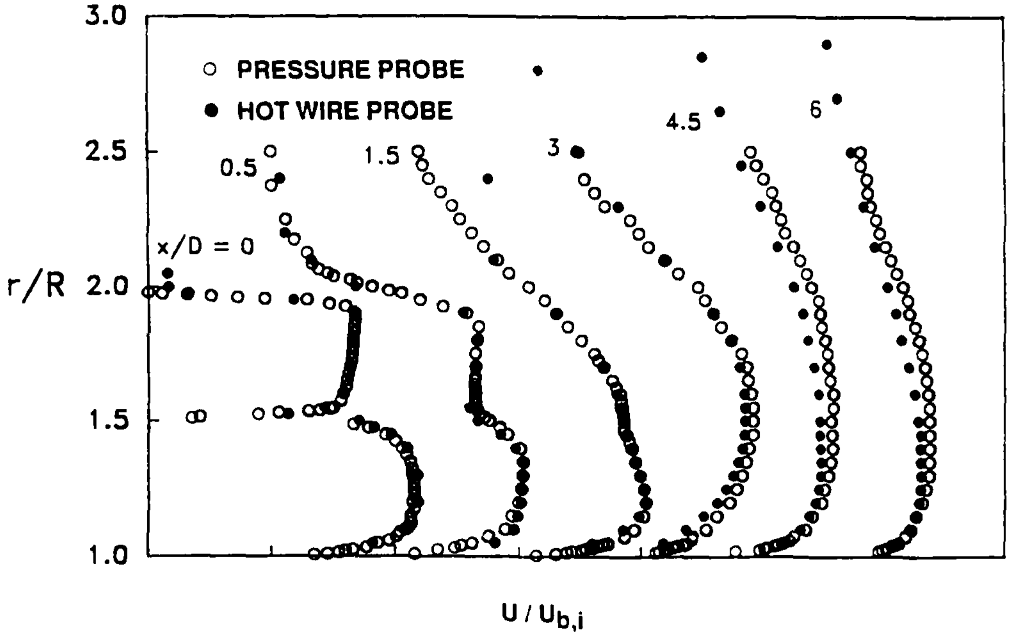
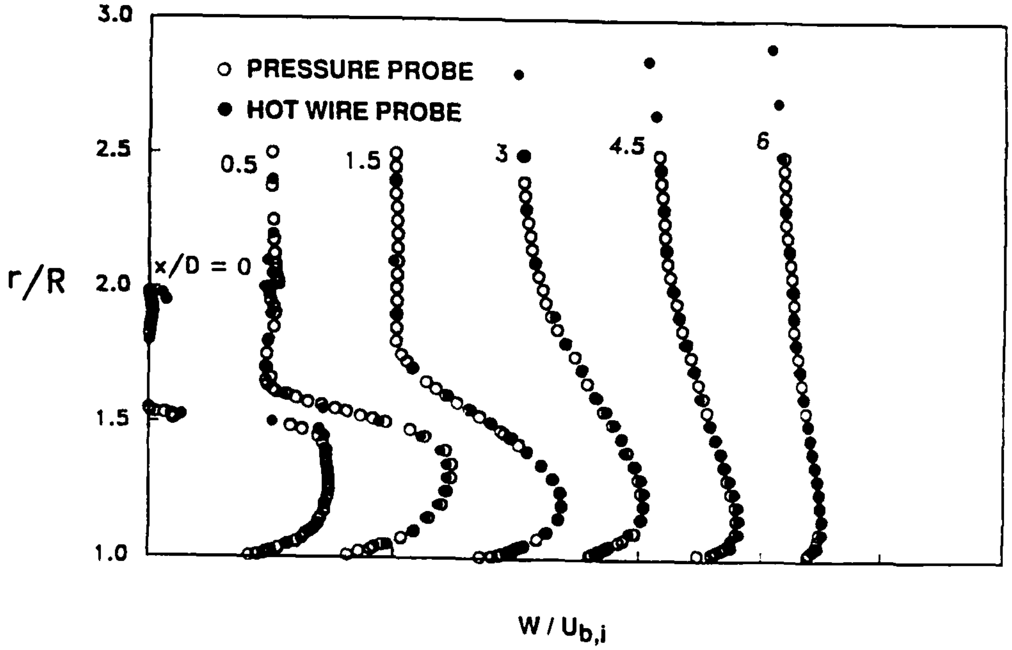


Fig. 2 Static pressure distributions at various streamwise locations.



(a) axial component



(b) tangential component

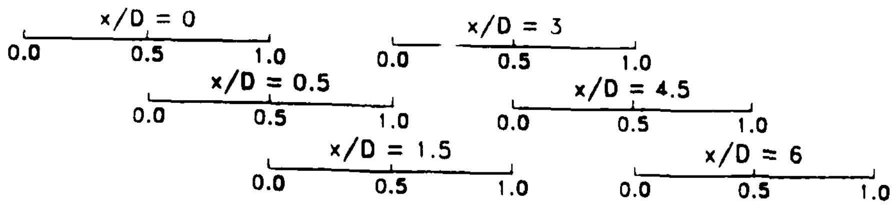


Fig. 3 Mean velocity component profiles at various streamwise locations.

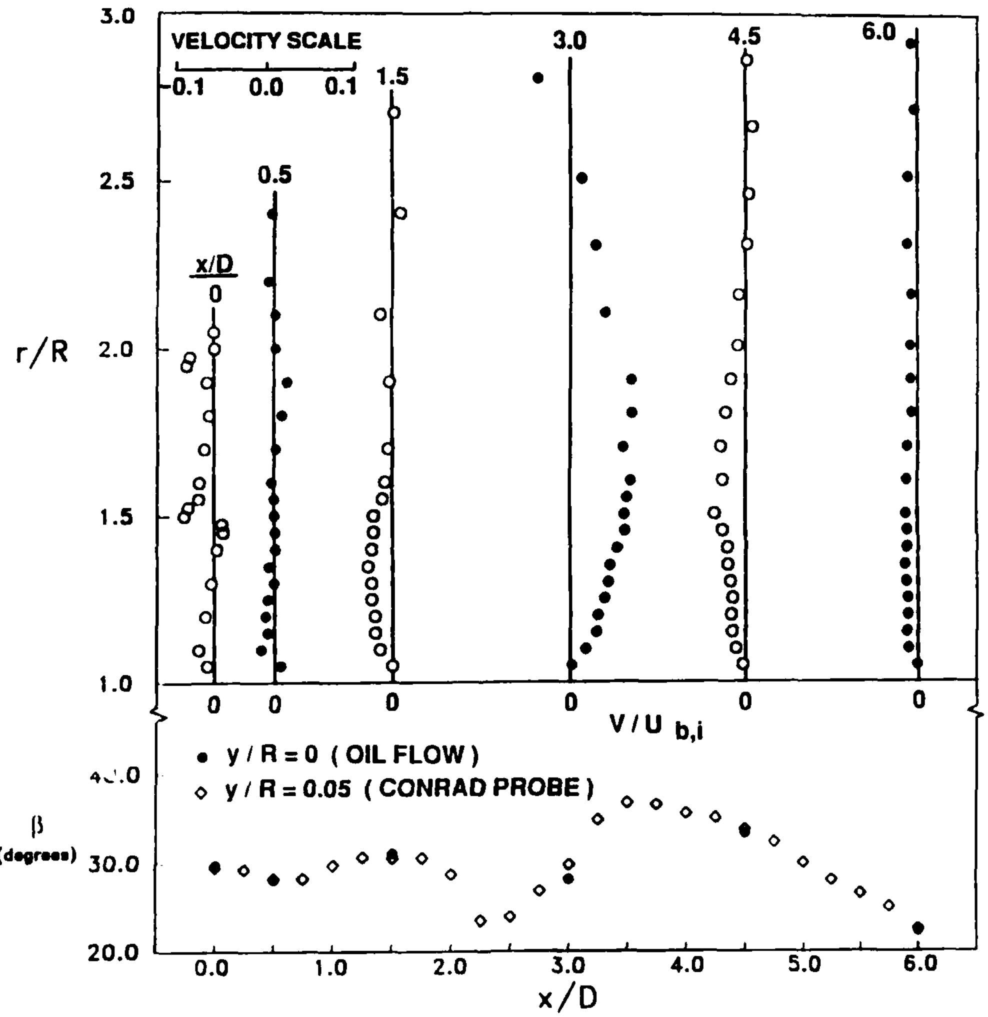


Fig. 4 Radial mean velocity component profiles at various streamwise locations and near-wall flow angle distributions.

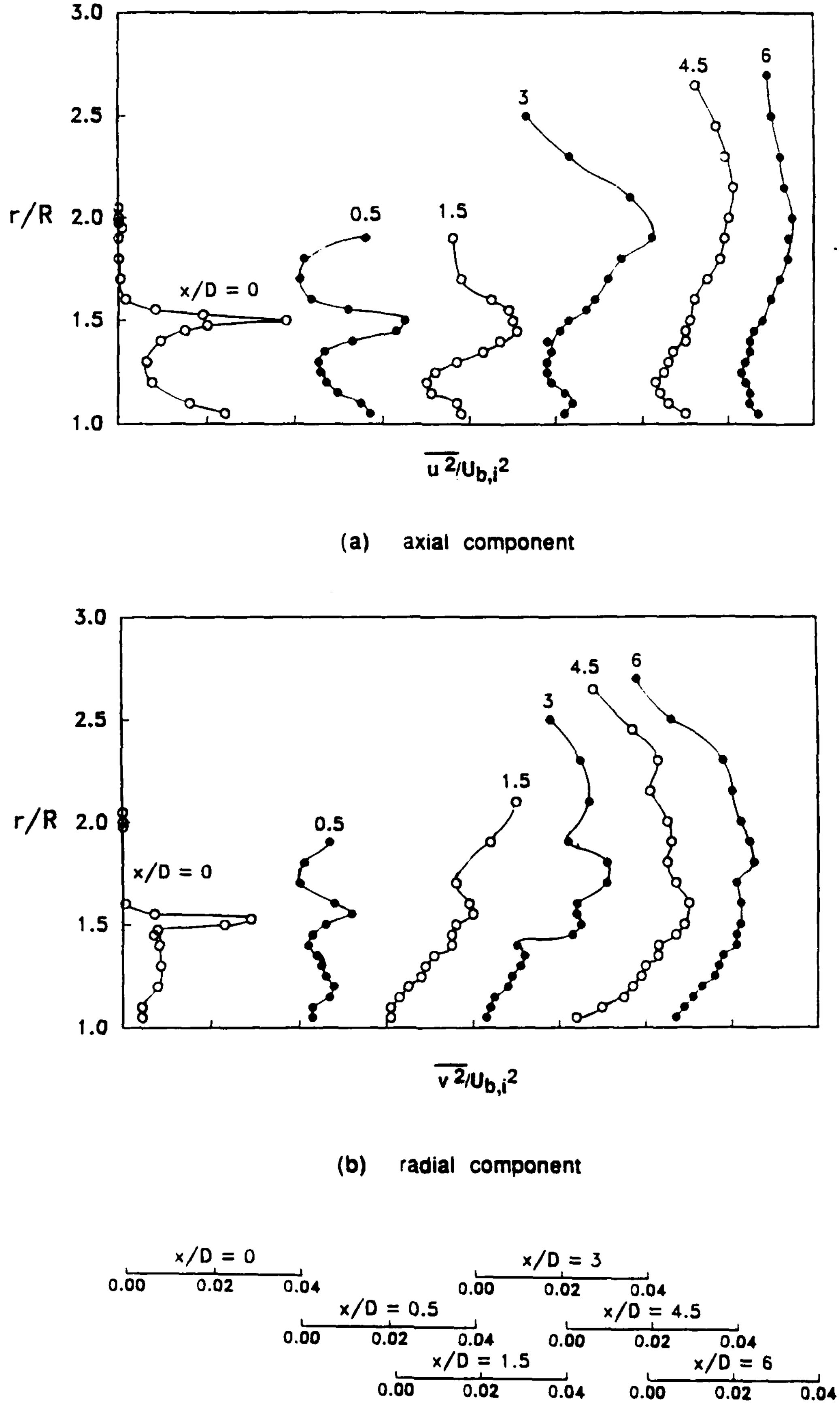
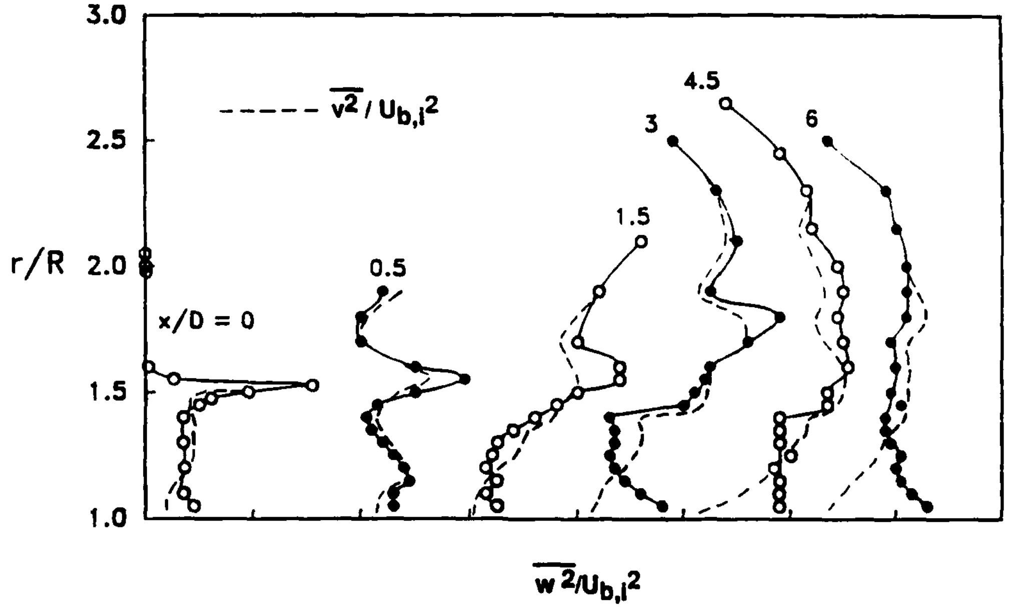
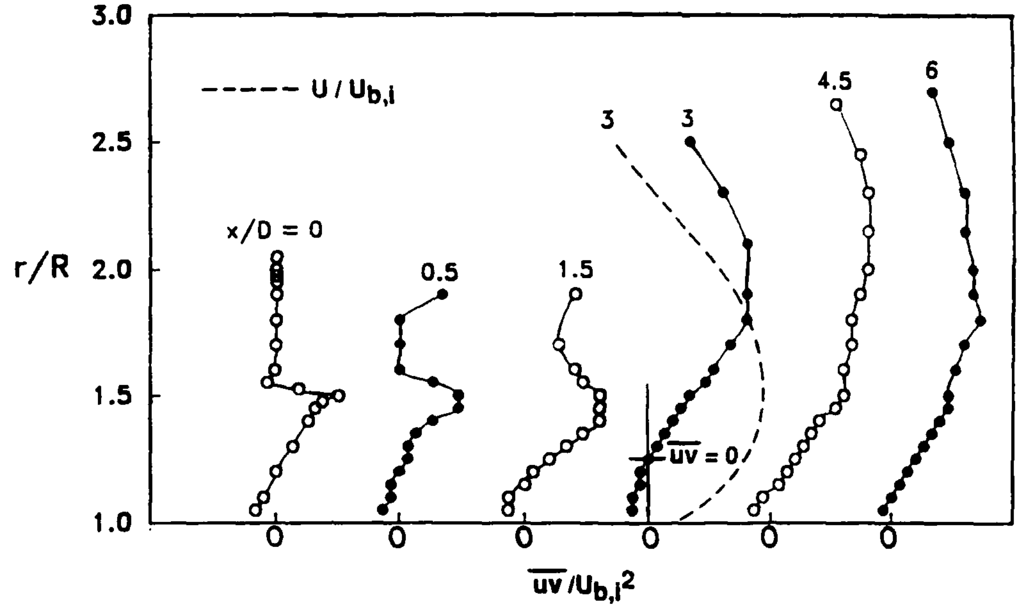


Fig. 5 Reynolds normal stress component profiles at various streamwise locations.

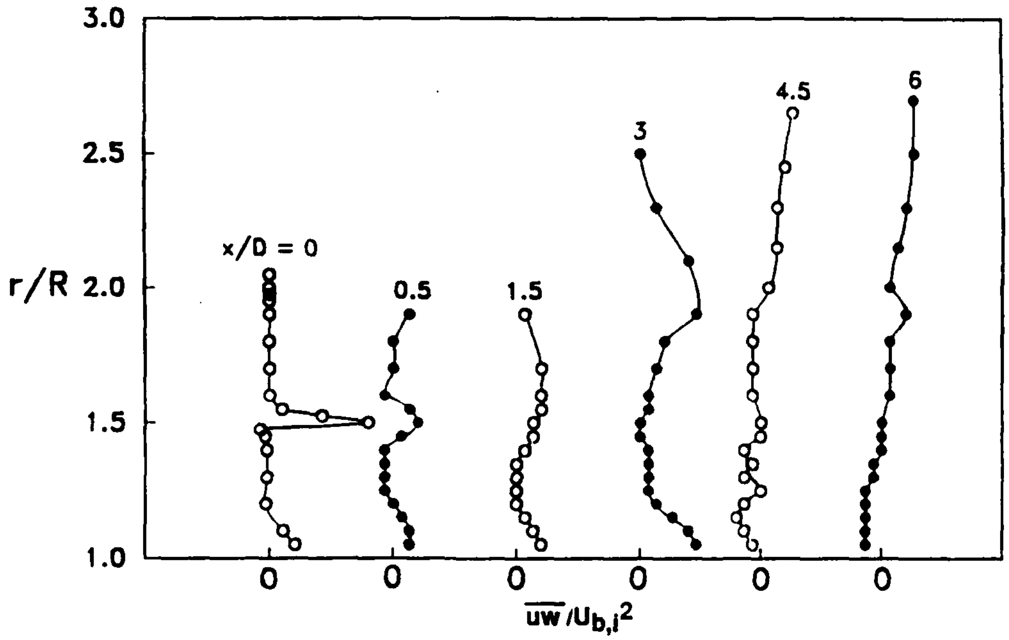


(c) tangential component

Fig. 5 (continued)



(a) rz plane component



(b) θz plane component

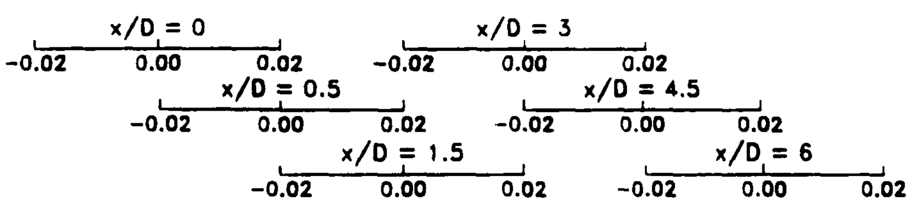
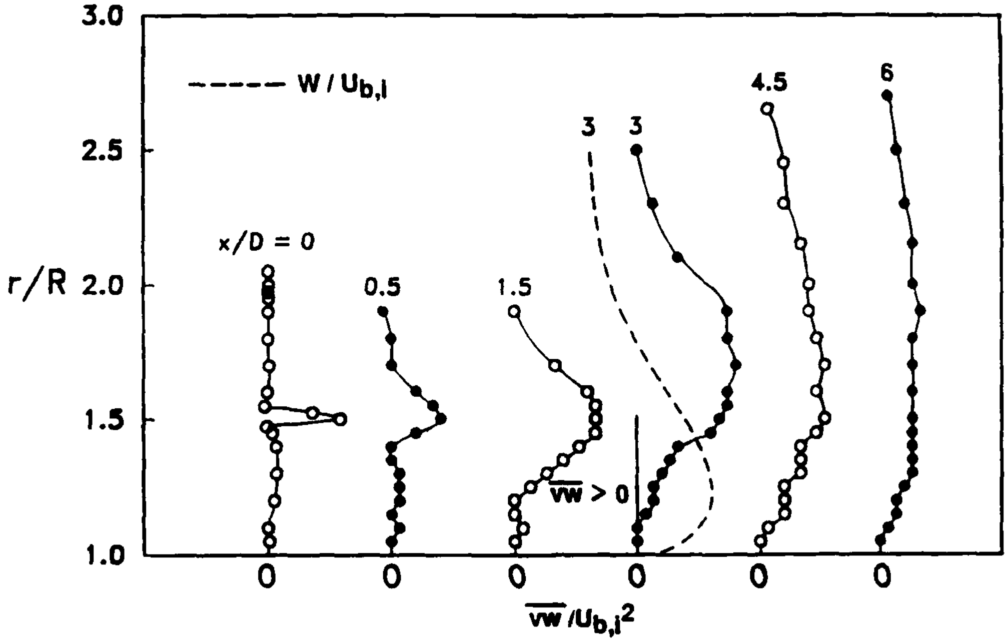


Fig. 6 Reynolds shear stress component profiles at various streamwise locations.



(c) rθ plane component

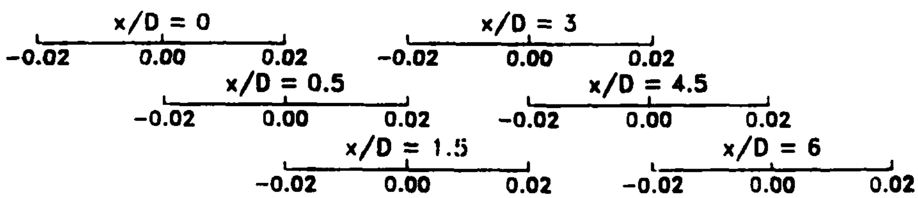


Fig. 6 (continued)

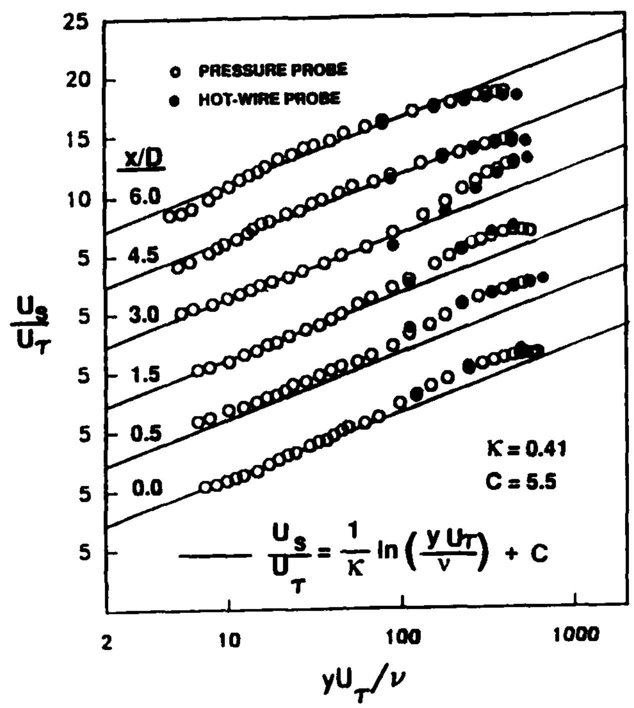


Fig. 7 Law-of-the-wall velocity profiles in the near-wall region at various streamwise locations.

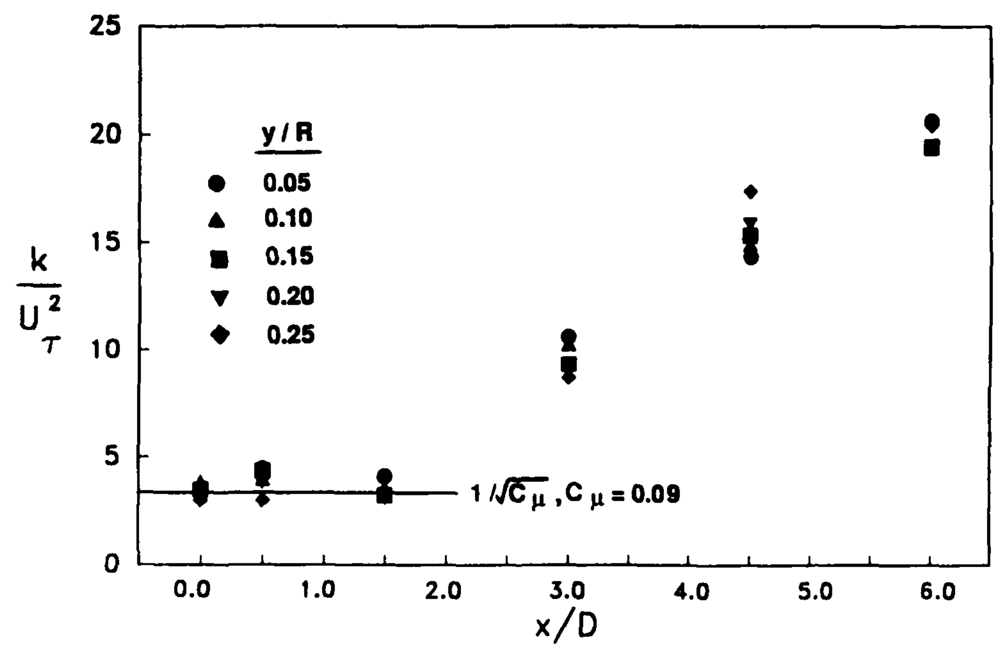


Fig. 8 Turbulence kinetic energy distributions in the near-wall region.