Measured Reynolds Stress Tensors in a Three-Dimensional Turbulent Boundary Layer

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Abstract

TURBULENT boundary-layer solution techniques for three-dimensional flows have been slow in evolving. The principal difficulties center around questions of the adequacy of the empirical modeling of the turbulent or Reynolds stresses necessary in the computer solution of such flows. Such models include the empiricism of mixing length, eddy viscosity, or turbulent stress-turbulent energy transport equation relationships. Reynolds stress measurements can be very useful in verification of these empirical models. The measurement of all six unknown elements of the Reynolds stress tensor, however, is a significantly difficult undertaking requiring substantial equipment, the development of a technique, and in some cases substantial data reduction. An extensive experimental investigation is reported in which all six unknown elements of the Reynolds stress tensor as well as the mean velocity field were measured through a pressure-driven, three-dimensional, turbulent boundary layer with moderate skewing relative to the freestream direction. The turbulent stresses were measured by the rotating probe technique. Two measured turbulent shear stresses and the mean velocity field data are compared with values obtained from a numerical solution for the boundary-layer flow. There is moderate-to-good agreement between the measured values and those computed for an isotropic mixing length model.

Contents

Reynolds stress tensor measurements were made in a channel specifically designed to show features of skewed turbulent boundary layers. The flowfield consisted of a two-dimensional airstream which impinged on a wall perpendicular to the stream axis. The flow was thus rapidly decelerated due to the back wall and was symmetrically deflected outward to the open sides on either end of the section, thereby giving rise to a skewed pressure-driven, three-dimensional, turbulent boundary layer off the plane of symmetry. This is the impinging jet geometry first studied by Johnston.[1]

Measurements were made both along and off the plane of symmetry. Two sets of numbers were used in identifying the test stations. The first number represented the x distance of the station from the lead-in section of the channel test section. The lead-in section or zero point of the test section was located at the point where the inlet duct joined the test section. The second number, separated from the first number by a hyphen, designated the z distance of the test station from the plane of symmetry. All distances were measured in inches.

The principal method used in mean velocity and Reynolds stress tensor measurements employed a linearized constant temperature anemometer system and hot film probes. Two hot film sensors were used in this study—one was a standard straight film probe and the other was a 45 deg slanted film probe. The diameter of the sensors was approximately 0.002 in. (0.05 mm) and the length-to-diameter ratio was approximately 20. A constant temperature anemometer, a linearizer, an rms voltmeter, a voltage-to-frequency converter and electronic counter, and two X-Y recorders were used to control, process, and read out the hot film signals. A traversing mechanism allowed the probe to move across the entire width of the channel and also to be rotated a full 360 deg about the vertical axis with a constant angular velocity. Analysis of the data followed the method of Fujita and Kovasznay[2] and extended by Bissonnette and Mellor,[3] which treats the data in a statistical multiple linear true regression analysis.

All six unknown elements of the Reynolds stress tensor were measured through the pressure-driven turbulent boundary layer. The measured stress distributions are characterized by occasional irregular stress values in strong disagreement with neighborhood values and trend lines the neighborhood values suggest. Communication with L. R. Bissonnette[4] (the only other person known to successfully use this technique for the complete tensor) confirmed the difficulties in this technique. Rather than omit suspect irregular

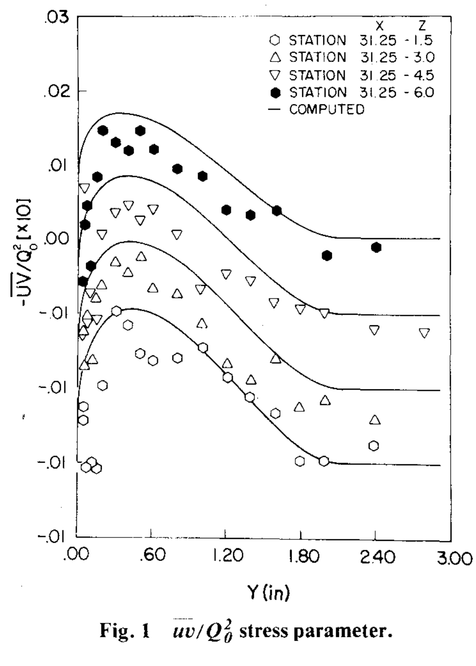

Fig. 1 $\overline{uv}/Q_0^2$ stress parameter.

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Index categories: Boundary Layers and Convective Heat Transfer—Turbulent; Computational Methods.

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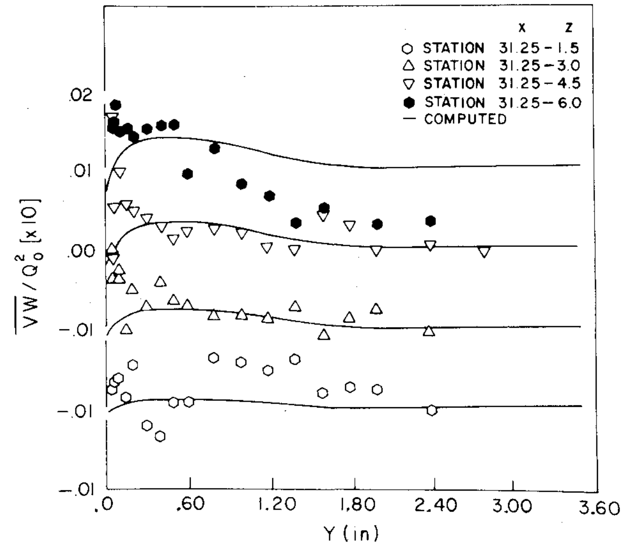

Fig. 2 $\overline{vw}/Q_0^2$ stress parameter.

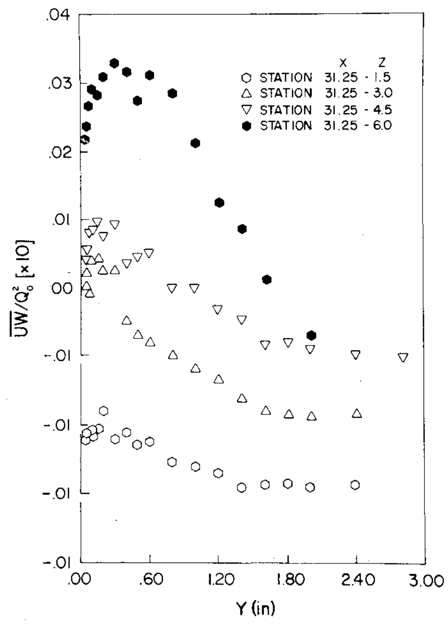

Fig. 3 $\overline{uw}/Q_0^2$ stress parameter.

stress values, all results are reported. Generalizations between the measured stresses and those computed from an isotropic mixing length solution to the three-dimensional boundary-layer equations ignore these occasional irregular data points. Pierce and Ezekwe[5] have compared this rotating probe method with the conventional X-array method and the results were generally in good agreement, but the rotating probe technique resulted in more data scatter with occasional erratic values.

The decision to use the more stable and stronger films over wires in this experiment was based on the recommendation of the manufacturers[6,7] and their assurance that the dynamic response of 2-mil cylindrical sensors would not be subject to the signal falloff reported by Bellhouse and Schultz[8] for hot film cones, wedges, and flush surface sensors. Since the completion of this work, Young[9] has shown that there is a lowered dynamic output even for 6-mil cylindrical split film sensors, with a split film measured $\overline{uv}$ stress about 25% lower than wire measured values. While the 2-mil cylindrical sensors used here have about an order of magnitude less mass and hence less thermal inertial than the 6-mil split film sensors, the question of reduced dynamic output remains and is considered in the discussion of the full paper.

A Cartesian coordinate set with x as the principal upstream flow direction, z the transverse direction, and y normal to the boundary-layer surface was used. Typical Reynolds stress profiles are shown in Figs. 1-3 for the three normalized shear stresses as they developed in the transverse direction away from the plane of symmetry. The stresses shown have been transformed to conform to the Cartesian coordinates previously described.

These figures show that as one proceeded in the transverse direction, marked changes were observed in the relative magnitudes of the shear turbulent intensity parameters. The $\overline{uv}$ shear stress decreased gradually but still maintained a value higher than the $\overline{vw}$ shear stress, which was increasing in magnitude. The $\overline{uw}/Q_0^2$ parameter increased rapidly as skewing increased, and exceeded $\overline{uv}/Q_0^2$ in magnitude. Figures 1 and 2 also compare the measured stresses with values computed from the Klinksiek and Pierce[10] implicit finite difference solution for the three-dimensional turbulent boundary layer. In this formulation, the stresses are treated after Prandtl's early isotropic mixing length model. Note that the ordinates of Fig. 2 for the transverse $\overline{vw}$ stress allow for and show computed negative stresses very near the wall. This sign change is due to the character of the pressure-driven transverse flow with the peaked w velocity profile resulting in a sign change in the w derivative with respect to normal distance. For the isotropic mixing length model, a sign change in this derivative will produce a sign change in the computed stress.

Interestingly, the tendency of the computed stresses to overpredict the measurements is in keeping with the observation of Young[9] on films showing a signal loss relative to wires. In general, there is reasonable agreement between the two computed and measured shear stresses. Surprisingly large values of the $\overline{uw}$ stress were measured. This deserves some attention since this stress is omitted in the usual boundary-layer approach.

Acknowledgment

This work was sponsored by the U.S. Army Research Office-Durham under Contract DAHC04 67 c 0008.

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