Progress Report and Renewal Proposal for

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Entitled:

HEAT TRANSFER IN THREE-DIMENSIONAL TURBULENT BOUNDARY LAYERS

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OBJECTIVES

The overall objective of the research program is to develop new physical understanding and predictive capability of heat transfer in three-dimensional, turbulent boundary layers (3DTBL). The first stage of the program is the examination of the effect of relatively mild three-dimensionality induced by a vortex pair embedded in an otherwise two-dimensional boundary layer. Later, the work will be extended to a pressure-driven 3DTBL which is likely to exhibit stronger three-dimensional effects. The experiments will provide spatially-resolved heat transfer data and detailed fluid mechanic data that are needed to interpret the heat transfer results. New techniques for the analysis of detailed 3D data will also be developed.

PROGRESS TO DATE

All of the work to date has been on the study of the effects of embedded vortex pairs. Work has not begun on the pressure driven 3DTBL due to the reduction in the proposed budget. The work on the vortex flows has proceeded much more rapidly than expected. All of the fluid mechanics measurements have been completed and the heat transfer measurements are nearly complete. In addition, we have taken considerably more data than originally proposed in order to take advantage of several opportunities for further understanding. The large amount of additional data was made possible by our highly automated instrumentation and data acquisition system.

Fourteen different vortex pair cases have been examined in varying levels of detail. The different cases include variations in the vortex strength, relative position, and relative sense of rotation. The full mean velocity field, and the spatially resolved heat transfer coefficient were measured for each case. In addition, the skin friction was measured for approximately half the cases. Two counter-rotating vortex pair cases were selected for detailed examination. The two cases encompass the two possible orientations of a vortex pair, that is the common flow between the vortices directed either towards the wall (common-flow down) or away from the wall (common-flow up). The detailed data sets include measured planes of all six components of the Reynolds stress tensor, detailed mean velocity and turbulence profiles at approximately 20 locations, and spatially resolved skin friction measurements, in addition to the mean velocity and heat transfer data already mentioned. Measurements of the turbulence triple velocity correlations and of the temperature field will complete the data sets.

Figures 1 a-c illustrate a typical mean velocity field obtained for each of the fourteen cases. An identical grid was also used for the turbulence measurements. The measurement grid is very fine giving the impression that we are attempting to create massive data sets rather than gain new physical understanding. Quite to the contrary, the fine measurement grid opens entire new avenues of analysis to the experimentalist. For example, in examining the decay of a vortex one must examine the Reynolds-averaged vorticity transport equation. This equation contains terms incorporating spatial derivatives of Reynolds stresses. The highly accurate and closely spaced data allow direct differentiation of the experimental data and have led to new understanding of vortex decay (see below).

The analysis and interpretation of the data is not complete and in any case, full presentation of the data is beyond the scope of the present report. The paragraphs below will highlight the most significant findings to date. Additional details may be found in the attached papers.

The cases in which the common flow is downward provide the most interesting heat transfer and skin friction behavior. A plot of the skin friction for one case is shown together with an axial velocity contour plot in Figure 2. Each vortex causes a small local minimum on the outboard side and a very large maximum on the inboard side. However, the most striking feature is the high plateau of skin friction between the vortices. The heat transfer data looks nearly identical. Clearly, there is a very large change in the average skin friction in contrast to our earlier work on single vortices which cause local variations in the skin friction and heat transfer but only small average increases. An important finding was that the high plateau of heat transfer is maintained up to quite wide vortex spacings of at least 10 boundary layer thicknesses. This indicates that vortices may act as a pair to cause significant average heat transfer increase even when they are very widely spaced.

Because of the importance of the plateau, the centerplane boundary layer was examined in some detail for nine different common-flow-down cases which included varying the strength and spacing of the vortices. The boundary layers appear to be very similar in all nine cases each following the well known logarithmic law of the wall and having very thin wake regions. The skin friction coefficient is apparently uniquely dependent on the value of the lateral divergence (dW/dz) imposed by the vortex pair. This indicates that there is a unique equilibrium boundary layer for a given lateral divergence at a fixed freestream velocity. Since the boundary layer is so thin, this equilibrium is achieved rapidly so that the boundary layer is nearly always in equilibrium with the local value of dW/dz . This suggests a very simple prediction method for the heat transfer augmentation due to a vortex pair.

The lateral divergence near the centerplane also was expected to have a significant effect on the turbulence. Lateral divergence is destabilizing; it stretches spanwise vortex lines. However, the preliminary examination of the data indicates that the turbulence in the centerplane region is only slightly affected. We are presently analyzing the data in detail to understand the effect of this "extra strain rate" on the turbulence.

Another problem of significance is the decay of the vortex. Vortices in free air are known to be extremely persistent while embedded vortices decay considerably faster. The mechanisms for this decay were not understood until the first stage of our data analysis. It is now obvious that the vortex decay is caused by gradients of the secondary shear stress $\overline{v'w'}$ and of the normal stress anisotropy $(\overline{u'^2} - \overline{v'^2})$. Cross stream gradients of these quantities (normally zero in a 2D boundary layer) act to diffuse the vorticity in the vortex core. The mechanism for generating the gradients is now clear; the vortex distorts the boundary layer turbulence by rotating the turbulence and by creating a highly distorted mean velocity field. The resulting distorted turbulence field acts to diffuse the vortex core. Unfortunately, this general mechanism while now understood, may prove to be difficult to implement in predictive schemes.

FUTURE WORK

The experimental work on the vortex pair cases will be completed by Summer 1987. Data analysis is expected to extend well into the next contract year. Mr. Wayne Pauley, the current research assistant, will complete his Ph.D. sometime early in 1988. A technical report covering all of the vortex work will be issued at that time. Mr. Shawn Anderson is expected to join us within the next two months upon the completion of his Ph.D. thesis on three-dimensional boundary layers. He will be initiating the section of the research on pressure-driven boundary layers. A Ph.D. student will be added as the budget allows.

PUBLICATIONS

Two conference papers (copies attached) have been written describing the mean development of the flow. Two additional journal papers will be prepared in the next few months describing the turbulence measurements and the boundary layer development in detail.

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BUDGET

An updated budget for the second year of the program is attached. There will be no remaining funds at the end of the current year.

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VORTEX PAIR SECONDARY FLOW

Figure 1a. Secondary velocity components (v, w) for a vortex pair.
 Successive planes at $x = 66 \text{ cm}$, 97 cm , 142 cm , 188 cm .

VORTEX PAIR VORTICITY DEVELOPMENT

Figure 1b. Axial vorticity contours for vortex pair.

BOUNDARY LAYER WITH VORTEX PAIR

Figure 1c. Axial velocity contours for vortex pair.

Streamwise Velocity Contours

Spanwise Distribution of Skin Friction

- SYMBOL LEGEND
- Measured with Surface Fence
 - Inferred from Symmetry of Flow
 - Normal 2-D Boundary Layer

Figure 2. Skin friction measurements for vortex pair and corresponding axial velocity contours.