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FLUID FLOW AND HEAT CONVECTION STUDIES
FOR ACTIVELY COOLED AIRFRAMES

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1. INTRODUCTION

During the reporting period, the Ph.D. dissertation of Chang was completed, namely:

Chang, B., "Computation of Turbulent Recirculating Flow in Channels, and for Impingement Cooling," Ph.D. Dissertation, School of Engineering and Applied Science, University of California, Los Angeles, October, 1992.

A further three papers have been prepared based on this work, namely:

Chang, B., and Mills, A.F., "Turbulent Flow in a Channel with Transverse Rib Heat Transfer Augmentation" accepted for publication, *Int. J. of Heat and Mass Transfer*.

Chang, B., and Mills, A.F., "Computation of Heat Transfer from Impinging Turbulent Jets" submitted for presentation at the Sixth International Symposium on Transport Phenomena.

Chang, B., and Mills, A.F., "Effect of Wall Thermal Boundary Condition on Heat Transfer to Separated Flow" submitted to the Journal of Heat Transfer.

The dissertation and three papers are attached to this report.

2. PROGRESS REPORT

Experimental studies of heat transfer from cylinders in crossflow have shown that the wall thermal boundary condition has a significant effect on local heat transfer coefficients in the vicinity of boundary layer separation. For example, at Re_D = 34,000, Baughn and Saniel (1991) measured minimum local heat transfer coefficients at about θ=80° from the stagnation line, with the value for a uniform wall temperature (UWT) about 50% of that for uniform wall heat flux (UHF). As θ increased from 80°, the coefficient for UWT increased more rapidly than for UHF and, beyond boundary layer reattachment at $\theta \sim$ 100°, became larger than the UHF value. Similar measurements were made by Papell (1981) and O'Brien et al. (1986).

A related flow configuration of current concern is flow over a step or rib, as encountered, for example, when repeated rib roughness is used for heating augmentation.

There have been many experimental and numerical investigations of such flows, but the effect of wall thermal boundary condition has not been explicitly addressed. In general, the choice of wall boundary condition has been dictated by convenience, and in some cases has been neither UWT or UHF, and unknown. In numerical investigations of various such laminar and turbulent flows, we have found that the local heat transfer coefficients on a forward-facing step or on a rib are very sensitive to the wall thermal boundary condition.

For the present computation of constant property laminar flow, the wall thermal boundary conditions were either a uniform heat flux or a uniform temperature. The inlet to the computational domain was located 8 step/rib heights upstream where the parabolic velocity profile for fully developed channel flow was specified together with either, (A) a uniform temperature profile, of (B) a quadratic temperature profile for thermally fully developed channel flow. The outlet was located 8 step heights downstream of the step, and 8.5 channel heights downstream of the rib, where fully developed conditions were specified.

Figure 1 shows local Nusselt number distractions along the wall of a channel with a symmetric contraction caused by a step of height $e/H = 1/8$ located at $x/e = 8$. The front face of the step is indicated by markers. A uniform grid of 60 × 40 was used. For thermal inlet condition (A) there is a continuous decrease of Nu before the step associated with a growth of the thermal boundary layer, and the values of Nu are higher than those for boundary condition (B), for which the inlet temperature profile is fully developed. For both wall boundary conditions, Nu reaches a minimum at the base of the step, and there is a gradual increase in Nu along the front face of the step reaching a maximum on top of the step. For a UWT, the minimum is much smaller and the maximum much larger (2 time) than for a UHF boundary condition, with a rapid increase in heat transfer similar to the quoted results for a cylinder in crossflow. Grid refinement tests showed practically identical heat transfer coefficient distributions along the channel wall for both UWT and UHF boundary conditions. Further grid refinement in x near the top edge of the step for

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the UWT boundary condition produced a further increase in the peak Nu at the top edge of the step. But this phenomenon is similar to the calculation of heat transfer in an entrance region, which produces higher heat transfer coefficients at the leading edge with grid refinement. The UHF calculation showed no change in the peak Nu with further grid refinement. After the step, Nu decreases rapidly for UWT but remains relatively constant for UHF. The outlet was located $1H$ downstream of the step: an increase to $2H$ gave no change in the results.

Isotherms with thermal entrance region for the UWT and UHF boundary conditions are shown if Fig. 2, where the scale of y coordinate has been enlarged. The solution for UWT shows steeper temperature gradients along the front face and top edge of the step compared to that for UHF. At the base of the step, there is a recirculating region, and the velocity of fluid is very small. Thus the fluid next to the wall retains a temperature very close to the wall temperature for a uniform wall temperature, and the fluid acts as an insulating layer: the very low heat transfer coefficient at the base of the step results. The UHF boundary condition establishes a wall temperature gradient along the face of the step, and this leads to steeper temperature gradients in the fluid layer adjacent to the wall, and subsequently higher heat transfer coefficient at the base than that for the UWT boundary condition. Whereas the wall at the top of the step for the UHF boundary condition has cooled to a temperature about 77% of that at the base of the step, the temperature along the front face and top edge of the step for the UWT boundary condition is fixed at a constant value. This effect is similar to the entrance region problem where the temperature gradient at the wall is theoretically infinite.

Figure 3 shows Nusselt number distributions for flow over a transverse rib on opposite sides of a two-dimensional channel, with $e/H = 1/8$, $w/e = 2$, for a uniform inlet temperature. A non-uniform grid of 64 × 28 was used. The results for the front and top of the rib are similar to those shown in Fig. 1 for the forward-facing step. The UWT boundary condition shows a rapid decrease in heat transfer on the rear face and rapid increase in the recirculation region. There is a small flow acceleration at the right edge

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of the rib, and a secondary peak in heat transfer is produced for the UWT boundary condition.

The above results indicate that care must be taken to consider the effect of wall boundary condition when obtaining local Nusselt numbers on steps and ribs, either numerically or experimentally. For numerical studies a solution accounting for coupled wall conduction may be appropriate.

The second part of the work consisted of using PHOENICS to solve the conjugate heat transfer problem of flow over a rib in channel. PHOENICS version 1.4 assumes uniformly spaced grids when calculating the harmonic averages to get exchange coefficients at the cell face, so correct diffusion coefficients were set up in Group 8 of GROUND to overcome this problem. There will be temperature gradients between the rib base and the top of the rib, and the solid-fluid interface temperature will not be exactly either uniform wall temperature or uniform wall heat flux. The present study of the simultaneous heat transfer inside the fluid and the solid will be of importance in determining the effect of conduction and wall thermal boundary condition in separated flow. Computation is under progress. Finally, the algebraic stress model in the TEAM (Turbulent Elliptic Algorithm-Manchester) code has been tested for jet impingement flow, but there needs to be an addition of energy equation to the code. The completed version is expected to be useful in determining the effect of streamline curvature on the prediction of mean-flow and turbulence quantities.

3.   REFERENCES

Baughn, J.W. and Saniei, N., 1991, "The Effect of the Thermal Boundary Condition on Heat Transfer From a Cylinder in Crossflow," *ASME Journal of Heat Transfer*, Vol. 113, pp. 1020-1023.

O'Brien, J.E., Simoneau, R.J., LaGraff, J.E., and Morehouse, K.A., 1986, "Unsteady Heat Transfer and Direct Comparison for Steady-State Measurements in a Rotor-Wake Experiment," Proceedings, 8th International Heat Transfer Conference, pp. 1243-1248.

Papell, S.S., 1981, "Influence of Thermal Boundary Conditions on Heat Transfer From a Cylinder in Crossflow," NASA Technical Paper, 1984.
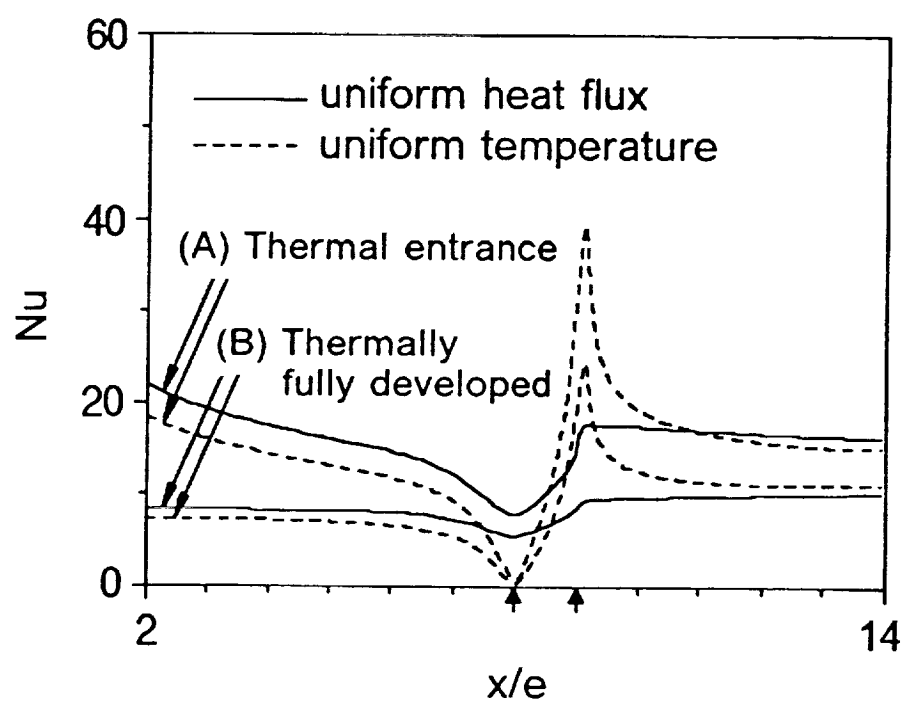
Fig. 1. Local Nusselt number distribution for $Re = 550$ and $e/H = 1/8$.
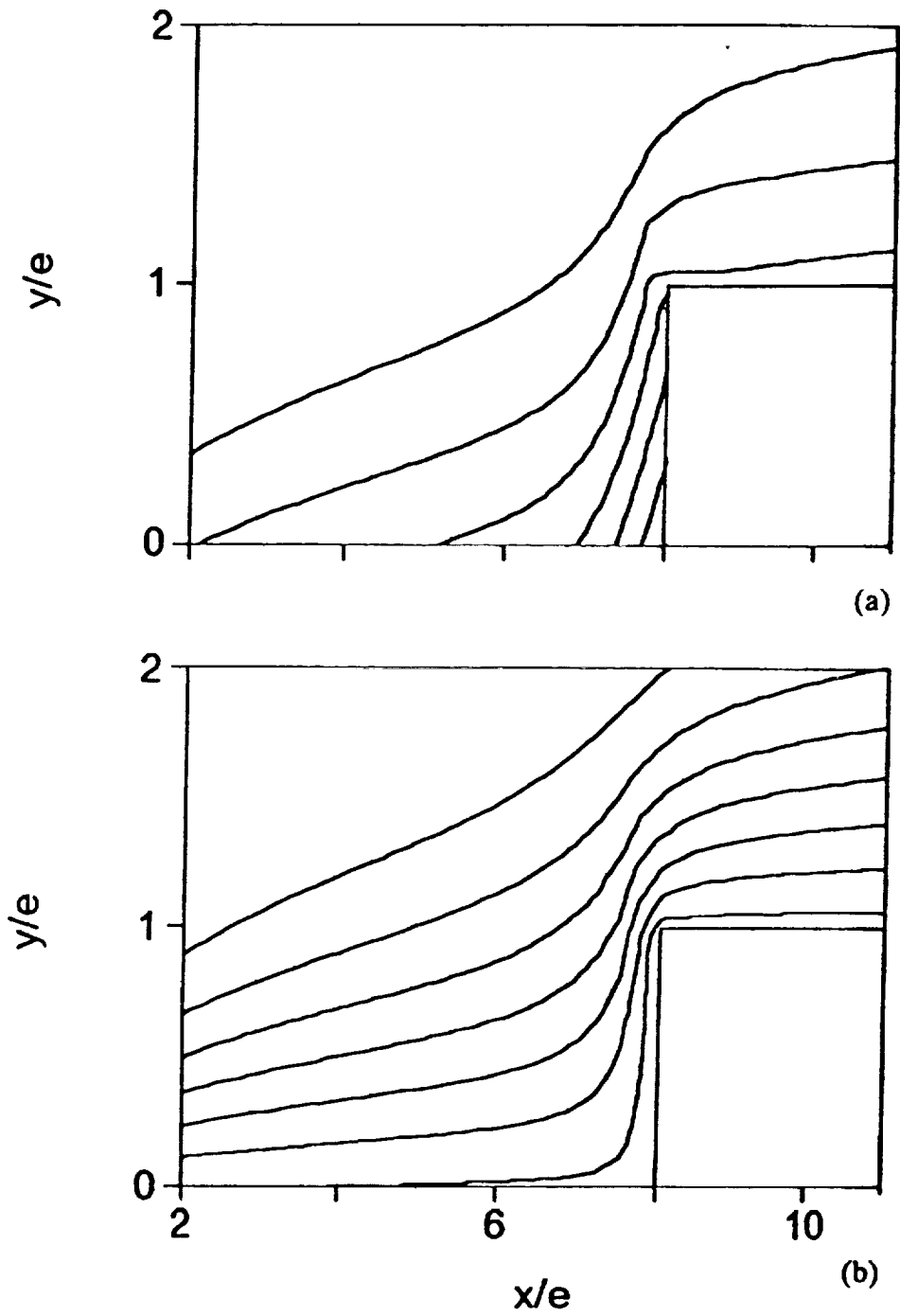
Fig. 2. Isotherms for a forward-facing step with uniform inlet temperature profiles. (a) uniform wall heat flux boundary condition, (b) uniform wall temperature boundary condition.
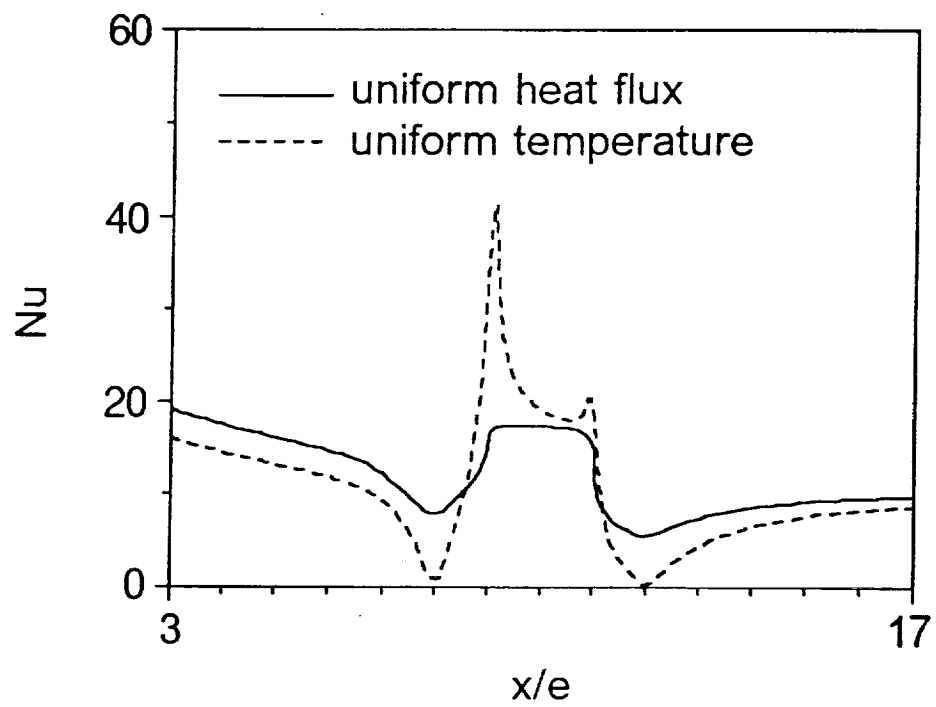
Fig. 3. Local Nusselt number distribution for flow over a rib in a channel with a uniform inlet temperature profile. $Re = 550$, $e/H = 1/8$, and $w/e = 2$.