linear disappearance. An interval of parameter strengthening appears, in which a wave of the main frequency reaches a higher level.

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References

[1]Saric, W. S. and Nayfeh, A. H., "Nonparallel Stability of Boundary-Layer Flows," *Physics of Fluids,* Vol. 18, No. 8, 1975, pp. 945-950.

[2]Klebanoff, P. S. and Tidstrom, K. D., "Evolution of Amplified Waves Leading to Transition of Boundary Layer with Zero Pressure Gradient," NASA Tech. Note DN-195, 1959.

[3]Kachanov, Y. S., Kozlov, V. V., and Levchenko, V. Y., "Nonlinear Wave Evolution in the Boundary Layer," *Izvestiya Akademii Nauk SSSR, Mechanika Zhidkosti i Gaza,* No. 3, 1977, pp. 49-58.

[4]Gaster, M., "The Physical Processes Causing Breakdown to Turbulence," *IUTAM Symposium on Laminar-Turbulent Transition, Abstracts,* Stuttgart, Federal Republic of Germany, 1979.

[5]Zelman, M. B., "On Nonlinear Evolutional Disturbances in Weakly Nonhomogeneous Flows of Unpressured Gas," *Gasodinamika i Fizicheskaya Kinetika,* ITPM SO AN SSSR, Novosibirsk, U.S.S.R., 1974.

[6]Craik, A. D. D., "Nonlinear Resonant Instability in Boundary Layers," *Journal of Fluid Mechanics,* Vol. 50, No. 2, 1971, pp. 392-413.

[7]Volodin, A. G. and Zelman, M. B., "On Resonant Tollmien-Schlichting Wave Interaction in the Boundary Layer," *Sb.Chislennye Metody Mech. Sploshnoy Sredy,* Vol. 9, No. 1, 1978, pp. 31-38.

[8]Volodin, A. G. and Zelman, M. B., "Three-Dimensional Resonant Interaction of Disturbances in the Boundary Layer," *Izvestia Akademii Nauk. SSSR, Mechanika Zhidkosti i Gaza,* No. 5, 1978, pp. 78-83.

[9]Volodin, A. G. and Zelman, M. B., "Pairwise Nonlinear Interactions of Tollmien-Schlichting Waves in the Flows Like Boundary Layer," *Izvestia Akademii Nauk SSSR, Mechanika Zhidkosti i Gaza,* Vol. 2, 1977, pp. 33-37.

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Buried Wire Separation Detector Simulation in Compressible Flow

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Introduction

BOUNDARY-layer separation on aerodynamic airfoils is of prime importance in stalled flows, in shock wave interaction with boundary layers, and in other cases of severe adverse pressure gradient.[1,2] The separation bubble can be extremely thin and very difficult to define by present methods used to detect separation and reattachment (Preston tubes, orifice dams, skin friction balance, oil flows, etc.). Other shortcomings of these methods are the low resolution, slow response, and disturbance to the sensitive flow which might cause premature separation or delay the reattachment.

An instrument designed to overcome these shortcomings is the separation detector.[3,4] Its principle of operation is based on measurement of the temperature differences between two sensors located on both sides of a heat source (Fig. 1). As a result of the heat convection from the source, the temperature of the downstream sensor will be higher than that of the upstream sensor. When the gage is in a separated region, where the flow direction is reversed, the heat will be convected in the upstream direction and the sign of the temperature difference will be changed.

An analysis of the solid temperature field and its interaction with the boundary-layer flow is essential for the design of a gage with maximum sensitivity and minimum disturbance to the flow. Such an analysis can be carried out experimentally, but it will be highly expensive and complex.

A solution of the temperature field around a point heat source for incompressible flow is described by Brosh et al.[5] However, this solution covers only cases of low Mach number where incompressible flow can be assumed.

Principles of Analysis

The model suggested in the present paper is based on a solution of two-dimensional time dependent Navier-Stokes equations for compressible turbulent flow coupled with the solution of the heat conduction in the solid (see Fig. 1).

The strong conservation law form of the Navier-Stokes equations in Cartesian coordinates is

$$\bar{q}_t + \bar{E}_x + \bar{F}_y = Re^{-1}(\bar{R}_x + \bar{S}_y) \tag{1}$$

where

$$\bar{q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad \bar{E} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(e+p) \end{bmatrix}, \quad \bar{F} = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(e+p) \end{bmatrix}$$

$$\bar{R} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ E_R \end{bmatrix}, \quad \bar{S} = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ E_S \end{bmatrix}$$

with

$$\tau_{xx} = (\lambda + 2\mu) u_x + \lambda v_y, \quad \tau_{xy} = \mu(u_y + v_x)$$

$$\tau_{yy} = (\lambda + 2\mu) v_y + \lambda u_x$$

$$E_R = u\tau_{xx} + v\tau_{xy} + \kappa P_r^{-1}(\gamma - 1)^{-1}\partial_x a^2$$

$$E_S = u\tau_{xy} + v\tau_{yy} + \kappa P_r^{-1}(\gamma - 1)^{-1}\partial_y a^2$$

and

$$p = (\gamma - 1)[e - 0.5\rho(u^2 + v^2)]$$

where p is the pressure and the sound speed a is given by

$$a^2 = \gamma(\gamma - 1)[e/\rho - 0.5(u^2 + v^2)]$$

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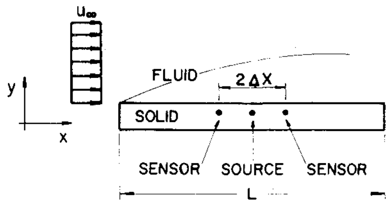

Fig. 1 Computation domain and coordinates systems.

Here λ is taken as $-(2/3)\mu$. In order to resolve the boundary layer and the vicinity of the heat source a variable grid size has to be used in both directions. Therefore, the flow equations are transformed to general coordinates, as done by Steger.[6]

Boundary Conditions: Tangency and no-slip conditions are applied at the wall. At the upstream and upper boundaries the conditions are those of the undisturbed flow. The downstream boundary condition is satisfied by extrapolation.

Viscosity Models: Sutherland law was used to calculate the laminar viscosity. For turbulent flow, the improved two layers eddy viscosity model of Baldwin and Lomax[7] was used.

The numerical procedure requires that the solutions for the temperature distribution in the wall be carried out for steady state only, therefore the time dependent terms are neglected, resulting in the following equation:

$$T_{xx}+T_{yy}=-\frac{\delta\dot{Q}}{k_s} \tag{2}$$

δ defines the location of the heat source $\dot{Q}$ while T and k_s are the solid temperature and conductivity, respectively. All the quantities are normalized by the temperature T_∞, and the conductivity k_∞ of the undisturbed flow and the length of the plate L.

Because of the strong gradients in the vicinity of the heat source, the computation grid in the solid is also not uniform and Eq. (2) is transformed to general coordinates.

Boundary Conditions: The wall exchanges heat with the fluid through the interface only, and is insulated at the other three sides. To satisfy temperature and heat flux continuity the interface matching conditions are

$$T_f=T_s;\quad k_s\frac{\partial T}{\partial y}\bigg|_s=k_f\frac{\partial T}{\partial y}\bigg|_f \tag{3a,b}$$

Numerical Procedure

Equations (1) and (2) with the proper boundary conditions are solved simultaneously. The gage simulation is taken as a steady-state problem although the flowfield equations are time dependent. Therefore, the flowfield is solved as a function of time until a steady-state solution is reached. The quasisteady-state temperature field in the wall is solved at the beginning of each time step of the flowfield computation, using successive over-relaxation (S.O.R.) method, satisfying the matching condition Eq. (3a).

The flowfield equations are solved using a finite-difference implicit method as described by Steger.[6] The boundary conditions are entered explicitly at the end of each time step. The pressure along the plate is updated from the normal momentum equation. Assuming that the solid temperature is known, the fluid temperature along the wall can be calculated using Eq. (3b). Using this temperature and the pressure along the wall, the density of the fluid along the wall is calculated from the equation of state. Then the velocities u and v and the energy e are updated.

Results

The model simulates a gage embedded in a substrate material of nondimensional conductivity $k^*=k_s/k_{f\infty}=5.85$.

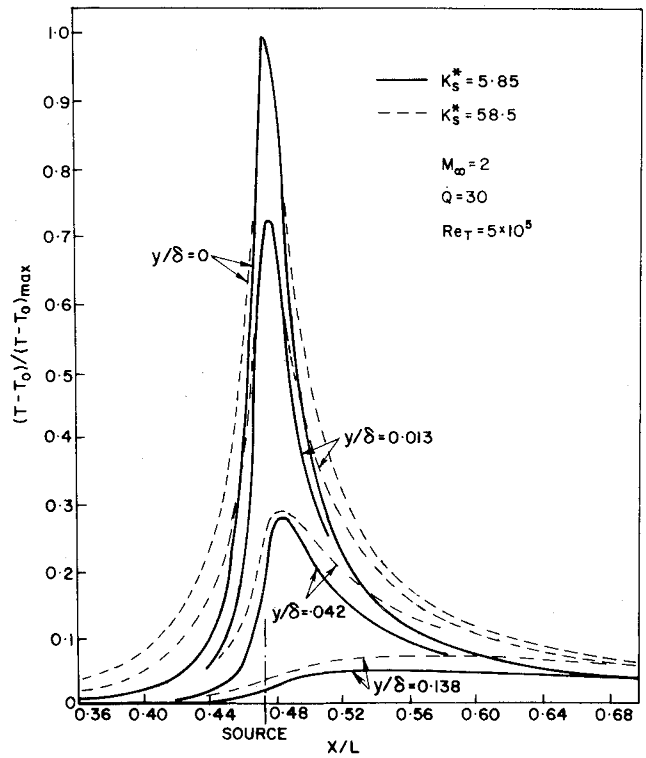

Fig. 2 Temperature distribution in the fluid at various distances from the wall.

This value is therefore used in most of the cases presented in this work. In all cases the source is located at $x_s=x/L=0.475$ and embedded in the wall at a depth of $y/L=0.005$. Figure 2 shows normalized temperature distributions at constant heights y/δ measured from the wall, where δ is the boundary-layer thickness above the source. The peak of the wall temperature distribution (at $y/\delta=0$) occurs at the heat source location. But for $y/\delta>0$ the peaks are moved further downstream as y is increased, because of the strong effect of convection.

Multiplying the conductivity of the solid k_s by a factor of ten expands the source influence both in the upstream and downstream directions (dashed lines, Fig. 2), as a result of the stronger effect of conduction in the solid wall, and the peak values of the distributions increase slightly.

Increasing the source strength $\dot{Q}$ by a factor of 10 has a very little effect on the normalized temperature distributions at the wall and far away from it, but does show a temperature decrease of up to 10% in the intermediate range. One should recall that although the normalized temperature does not change at the wall, the actual temperature rises as the source strength is increased.

The effect of the Mach number on the normalized temperature distributions is very little close to the wall and far away from it, but more significant in the intermediate range. As the Mach number increases the normalized temperature in the intermediate range goes down.

Tests that were run concerning the effect of wall conductivity without heat source, indicated that as the conductivity goes up the growth of the thermal boundary becomes more moderate. This is due to the fact that conduction through the solid wall transfers the heat from the warmer downstream regions to the cooler upstream ones.

The operation of the detector is based on the measurement of temperature difference ΔT between two points, one upstream and the other downstream of the source at equal distances $\Delta x/L$. Figures 3a and b describe the change in the temperature difference ΔT as a function of the sensing elements location $\Delta x/L$ for various parameters. As mentioned before, the interface temperature distribution when nor-

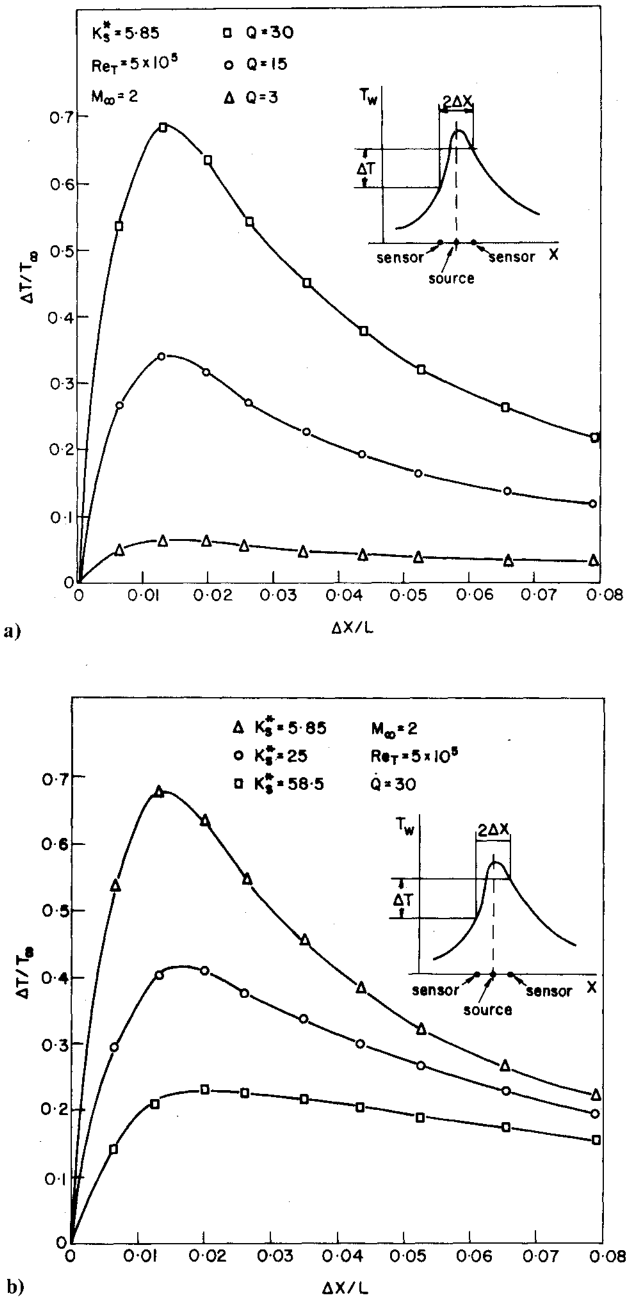

Fig. 3 Temperature differences between the upstream and downstream sensors as a function of their distance from the heat sources; a) effect of source strength, b) effect of conductivity.

malized depends only slightly on the source strength. Hence the distributions of ΔT vs $\Delta x/L$ (Fig. 3a) can be normalized to coincide with each other. The optimum location for the sensors (where maximum ΔT can be detected), is at $\Delta x/L = 0.013$, and is independent of the source strength. The calculations also show that when the Mach number is increased the maximum temperature difference is reduced, and its location $\Delta x/L$ moves toward the heat source. But the ΔT distribution becomes flatter and therefore the distance of the sensors $\Delta x/L$ can be increased without appreciable loss of gage sensitivity. As mentioned before, the effect of Mach number increase is to reduce the source influence on the flowfield. Hence, for higher Mach number flows the use of a stronger source is preferred in order to get detectable temperature differences without disturbing the flowfield.

Figure 3b shows the effect of conductivity ratios. An increase of solid conductivity lowers the temperature difference ΔT, and shifts the peak of the curve away from the source. It is therefore required that the gage material be of the lowest conductivity possible, even when the heater element is embedded under the surface as in the simulation.

The computational results indicate that the sensitivity of the gage increases with the increase of the source strength and the decrease of the conductivity of the solid substrate. The computations show that the heat source influence on the flow is minimal even in cases where measurements of significant temperature difference exist.

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References

[1] Kooi, J. W., "Experiment on Transonic Shock-Wave Boundary Layer Interaction," AGARD Conference on Flow Separation, AGARD CPP-168.

[2] Mateer, G. G., Brosh, A., and Viegas, J. R., "A Normal Shock-Wave Turbulent Boundary Layer Interaction at Transonic Speeds," AIAA Paper 76-161, Jan. 1976.

[3] Brosh, A. and Mateer, G. G., "Separation Detector," U.S. Patent 4,061,029, Dec. 1977.

[4] Rubessin, M. N., Okuno, A. T., Mateer, G. G., and Brosh, A., "A Hot Wire Surface Gage for Skin Friction Measurements and Separation Detection," NASA TMX-62-465, Aug. 1975.

[5] Brosh, A., Degani, D., and Zalmanovich, S., "Conjugated Heat Transfer in Laminar Boundary Layer with Point Heat Source at the Wall," TAE Rept. 417, Technion, Israel, 1980.

[6] Steger, J. L., "Implicit Finite-Difference Simulation of Flow about Arbitrary Two-Dimensional Geometries," *AIAA Journal*, Vol. 16, 1978, pp. 679-686.

[7] Baldwin, B. S. and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows," AIAA Paper 78-257, 1978.

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Dry-Surface Coating Method for Visualization of Separation on a Bluff Body

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Introduction

AN indispensable aspect of any investigation of flow about a bluff body is the visualization of separation since it supplies an immediate physical insight into the overall flow structure. Methods of visualization of separation on a bluff body are useful when they: 1) apply over a wide range of Reynolds numbers and for incident laminar and/or turbulent streams; 2) produce an accurate trace of the separation line within a reasonable time period; and, 3) generate a permanent record available after the removal of the oncoming flow.

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