AIAA 81-0349R

Transient Boundary-Layer Flows in Combustion Environments

S.-W. Kang* and J. L. Levatin†
Lawrence Livermore National Laboratory, University of California, Livermore, Calif.

Abstract

UNSTEADY boundary-layer flow equations characterizing hot, burning environments are solved numerically by means of a factored ADI method under transient and/or streamwise varying core-flow conditions. Calculated results for compressible, turbulent flow cases show that high heat fluxes at the wall due to turbulence and changing edge conditions may bring about severe temperature increase at the wall, causing eventually melting and, hence, erosion of the surface itself.

Contents

The present work describes numerical analysis of the surface-temperature history when the surface is exposed to hot, turbulent flow conditions, such as in rocket nozzles and other combustion environments.

The formulation includes equations involving conservation of the mass, momentum, and thermal energy in the unsteady, turbulent, compressible boundary layer adjacent to the wall under assumptions of thermodynamic equilibrium and the Cebeci-Smith eddy viscosity model.[1] Detailed expressions for these conservation equations are given in Ref. 2. An additional equation is needed to account for the timewise response of the surface temperature due to the transient heat flux at the wall transferring energy from the core through the turbulent boundary layer to the surface. Assuming the heat flow direction inside the solid material to be normal to the surface, the surface temperature history for a variable (timewise) heat flux at the surface is determined to be

$$\Delta T_w(t) = \frac{1}{k_s}\sqrt{\frac{\alpha_s}{\pi}}\int_0^t Q(t-\lambda)\frac{d\lambda}{\sqrt{\lambda}}$$

and $Q=(k_f \partial T/\partial y)_w$ is the surface heat flux for the turbulent boundary layer. The subscripts f and s denote conditions for the fluid and the solid, respectively. All other symbols denote their usual meaning in fluid dynamics. In order to obtain solutions to these nonlinear, coupled partial-differential equations, the equations were first transformed by the Levy-Lees method,[3] and a program called TRAVIS (transient, viscous) code is generated, patterned after the ADI scheme of Douglas and Gunn[4] and, more recently, of Beam and Warming.[5] This method is second-order time accurate, spatially factored and noniterative. The conservation equations in the alternate-sweep form are then solved under prescribed (transient and streamwise varying) core-flow conditions applied at the edge of the boundary layer. For the turbulent case a variable grid size scheme is implemented in order to facilitate accurate computations near the wall where very steep flow gradients exist.

Results obtained from the TRAVIS-code calculations include the timewise development of the flowfield, especially in terms of the streamwise velocity u and the temperature T. Figure 1 shows the streamwise velocity profiles for turbulent flow as a function of time and demonstrates sharp changes in the region of viscous influences, i.e., the boundary-layer thickness, as well as steepening of the gradient near the surface. Similar behavior is also observed for the temperature profiles—here expressed in terms of total enthalpy H—as shown in Fig. 2. The high heat fluxes at the surface are expected to raise temperatures along the solid surface over which a hot, turbulent fluid is flowing, as presented in Fig. 3. It shows the surface-temperature history of steel along the surface and displays temperature increases on the order of 20°C in a matter of 1 ms. In the present example the core-flow conditions used were 3000 K at atmospheric pressure, and it is anticipated that higher temperature and pressure conditions would yield larger increases in the same time frame. As a contrast to steel, a material with a lower thermal conductivity was studied next. For this purpose glass was chosen and the results obtained are shown in Fig. 4. Considerably high

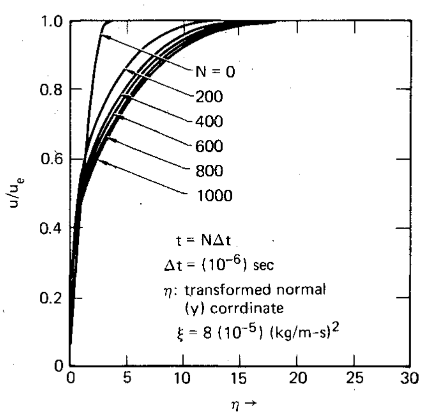

Fig. 1 Timewise development of turbulent velocity profiles.

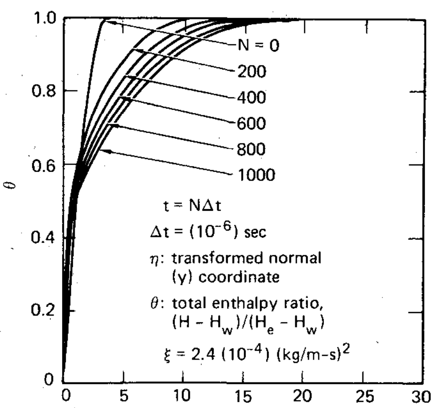

Fig. 2 Timewise development of turbulent thermal-energy profiles.

Presented as Paper 81-0349 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted March 9, 1981; synoptic received June 15, 1981. This paper is declared a work of the U.S. Government and therefore is in the public domain. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: Microfiche, $3.00; hard copy, $7.00. **Remittance must accompany order.**

*Physicist, Fluid Physics Group, Physics Department.
†Mathematician, Computations Department.

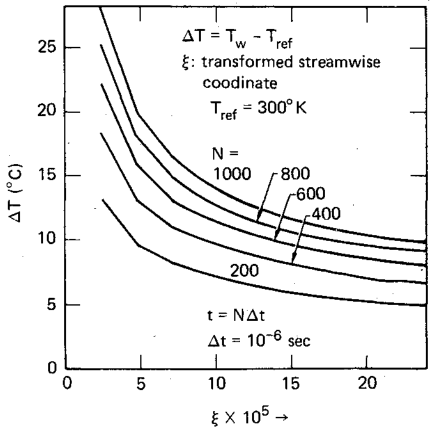

Fig. 3 **Wall-temperature history along a steel surface: turbulent flow.**

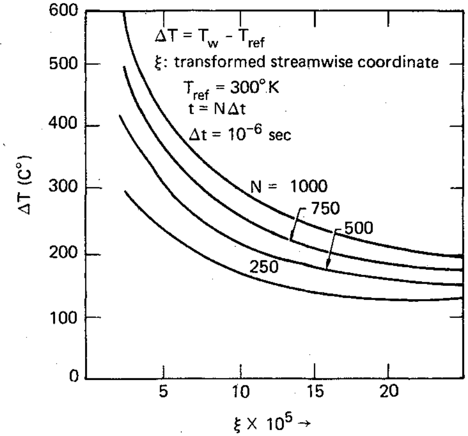

Fig. 4 **Wall-temperature history along a glass surface: turbulent flow.**

temperature increase is noted, some exceeding 500°C, thus approaching rather rapidly the melting temperature of the material.

In summary, a theoretical analysis has been performed of the surface-temperature history due to heat transfer from hot, burning flows and results demonstrate sizable temperature increase at the solid surface. In the future we plan to study the surface behavior when continuous heat transport to the surface from the flow may cause melting of the solid material and introduce a molten liquid layer between the core flow and the solid material under propulsive conditions.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48 and supported by the U.S. Army ARRADCOM Laboratories and the Army Research Office under Contract 15812-MS. The authors acknowledge many useful discussions with their colleague, A. C. Buckingham, during the course of this investigation.

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