identical initial (nose) freestream conditions, this method allows a direct comparison of results in terms of parameters based on these initial conditions.

References

[1] Keel, A. G., Jr., "Low Density Hypersonic Cone Drag," Ph.D. dissertation, 1970, Dept. of Aerospace Engineering and Engineering Physics, Univ. of Virginia.

[2] Ashkenas, H. and Sherman, F. S., "The Structure and Utilization of Supersonic Free Jets in Low Density Wind Tunnels," *Rarefied Gas Dynamics*, Fourth Symposium, Supplement 3, Vol. II, 1966, pp. 84–105.

Substructure Heating on Cracked Ablative Heat Shields

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Nomenclature

b = crack width, typically 0.01 in. to 0.1 in.
H_w = wall enthalpy, Btu/lb
H_0 = stagnation enthalpy, Btu/lb
h = crack height, in.
$\dot{m}$ = ablation rate, lb/ft² sec
$\dot{m}/\rho_\infty u_\infty St$ = blowing rate parameter
q = local heat transfer to crack wall, Btu/ft²sec
q_s = surface heat transfer, Btu/ft²/sec
Re_θ = momentum thickness Reynolds number, $\rho_\infty u_\infty \theta/\mu_\infty$
Re_τ = friction Reynolds number, $(\tau_w/\rho)(\rho b/\mu)$
St = Stanton number
u_∞ = freestream velocity, ft/sec
δ^* = boundary-layer displacement thickness, in.
ρ = local density
ρ_∞ = freestream density
τ_w = wall shear stress, lb/ft²

Introduction

ABLATIVE materials are used to protect re-entry vehicles from the intense heating during certain phases of the flight. However, if cracks develop in the heat shield prior to the re-entry, the substructure may be subjected to excessive heating. The ablative behavior of the heat shield may be altered in the vicinity of the cracks which in turn can affect the aerodynamics of the vehicle. The analytical description of the processes is inadequate to allow a safe design of heat shields. A moderate number of studies have been performed on non-ablating, shallow cavities and rectangular notches of various aspect ratios.[1] The present research program was formulated to look into this matter for ablating surfaces in high-speed flow. It was supplemented by independent analytical and experimental studies carried out by the Aeronautical Research Associates of Princeton, Inc.

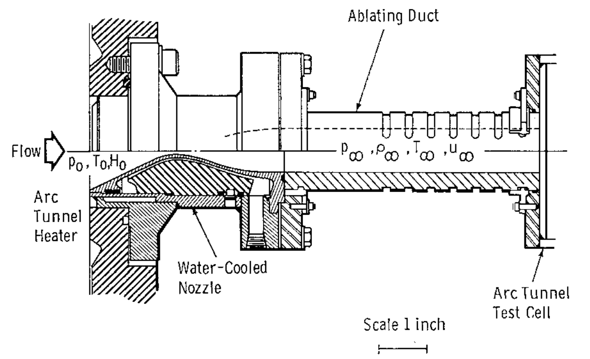

Fig. 1 Schematic of experimental arrangement.

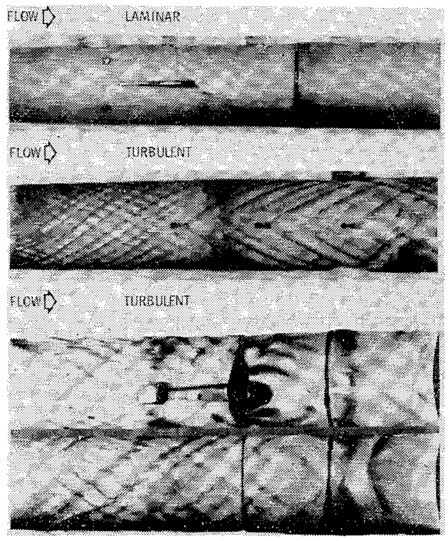

Fig. 2 Striation patterns (top views of ducts cut in half after tests).

Approach

The present investigations are primarily experimental and were carried out in the Naval Ordnance Laboratory's (NOL) 3 Megawatt Arc Tunnel. They were designed for conditions that may occur at the conical part of a slender, blunted reentry vehicle at an altitude of about 60,000 ft. Local Mach numbers between 2 and 3.5, enthalpy ratios H_w/H_0 of 0.2 to 0.4 and heating rates of about 200 to 300 Btu/ft² sec and Teflon as the ablator were chosen. Other parameters that were considered are the friction Reynolds number, Re_τ, and characteristic sizes b/δ^* and h/b.

Experiments

The arrangement is schematically shown in Fig. 1. Two axially symmetric nozzles designed for Mach numbers of 2.3 and 3 were used. The Teflon ducts were instrumented for pressure, in-depth wall temperature and skin-friction measurements. The cracks, up to three in one duct, were instrumented for heat-transfer measurements on the bottom, upstream and downstream walls.[2] For the Mach 3 run, the boundary layer was predicted to be laminar for a supply air pressure of 20 atm and a temperature of 9000°R. The turbulent boundary-layer tests were carried out at a Mach number of 2.3, pressures of 20 and 28 atmospheres and temperatures of 4600°R.

Analytical Procedures

The laminar test results were compared with a numerical code,[3] which gives ablation rates, boundary-layer parameters and in-depth material responses for quasi-steady or transient conditions. For the turbulent data, a numerical procedure was devised that combines a computational program applicable to turbulent boundary layers on nonablating walls, experimental information, and wall-species and temperature data to correlate the substructure heating data.[2]

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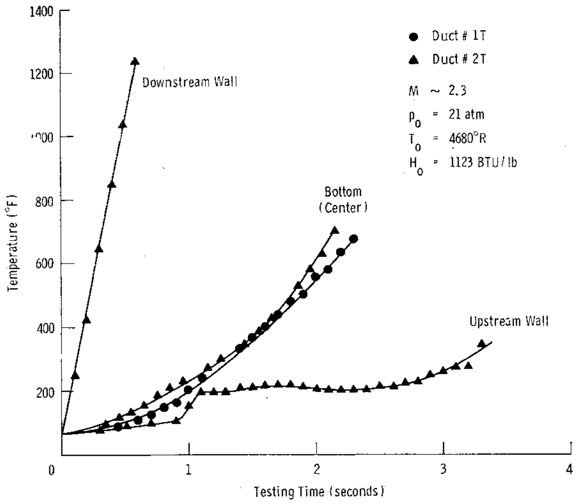

Fig. 3 Temperature variation for longitudinal cracks.

Results

For the laminar tests,[3] it was found that ablation induces transition at a Reynolds number, Re_θ, of 450. This is supported by numerical results[3] and the longitudinal, almost parallel striations shown in Fig. 2. At the downstream side of the longitudinal crack a pronounced wake-like additional ablation pattern is observed. The transverse crack shows only a slight rounding on the downstream side. The heating rates at the bottom of the longitudinal and transverse cracks are 0.24 Btu/ft^2 sec and a maximum of 0.07 Btu/ft^2 sec, respectively. In terms of q/q_s, the values are 0.0042 and 0.0016, respectively, where q_s has been computed by the transient version of the numerical code.[3]

Ablation was very pronounced during the turbulent tests. It was relatively uniform, varying from 0.159 lb/ft^2 sec near the duct entrance to 0.115 lb/ft^2 sec along the duct. This corresponds to $\dot{m}/\rho_\infty u_\infty St \simeq 0.99$. Criss-cross striation patterns (Fig. 2) were exhibited by all ducts of the turbulent test series. The patterns start close to the duct entrance and form in a uniform fashion if a pressure orifice is not located there. The cracks have a pronounced effect on the striation patterns; they alter the spacing or even cause them to disappear. At the downstream side of longitudinal cracks a complex pattern and severe gouging is observed.

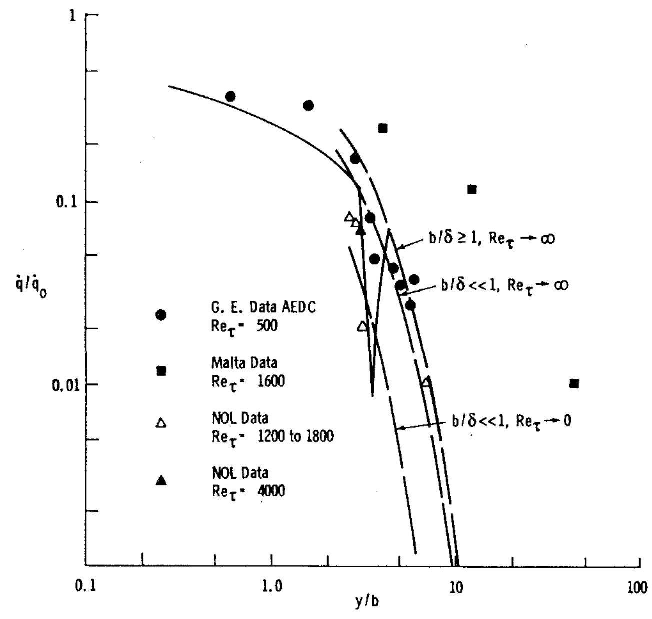

Fig. 4 Transverse crack heating summary (curves and Non-NOL data courtesy of the aeronautical research associates of Princeton).

At the longitudinal cracks, 1 in. $\times \frac{1}{32}$ in., the center of the downstream wall experiences the cold-wall surface heating rate. At the bottom of the cracks the heating rate varies first slowly but it reaches the surface heating rate within two seconds (Fig. 3). A faint pattern of transverse vortices is discernible at the bottom of the cracks. The center of the upstream wall showed an erratic behavior probably indicative of a changing vortex formation. The transverse crack heating rates are moderate.

From the limited number of tests, the following observations can be made for the tests with turbulent boundary layers: 1) For initial aspect ratios of 4, the heat transfer to the bottom of transverse cracks reaches up to 8% of the duct surface heat transfer within six seconds. There is evidence of gouging due to vortices that had established in the cracks. 2) The h/b, b/δ^*, or Re_τ do not seem to be unique correlating parameters. 3) With increasing h, the heat transfer decreases very sharply and is only 1.0–1.8% of the surface heating rate. This behavior is consistent with the analytical predictions,[4] as shown in Fig. 4. 4) In short duration runs, the temperature rises uniformly. For longer runs, a periodic behavior is exhibited. A uniform temperature rise is followed by a period where the temperature remains constant, or even decreases, then the temperature rises again at about the initial rate. This observation strongly suggests that vortex flow exists in the cracks with the number of counter-rotating vortices being some multiple of the crack width. As, with ablation, the crack height is reduced and the width increased so that the vortex at the bottom can no longer be maintained, this vortex breaks up and the gas becomes more or less stagnant. The bottom temperature remains constant until the next vortex has reached the bottom or a reformation has taken place to fit the changed geometry.

References

[1] Haugen, R. L. and Dhanak, A. M., "Heat Transfer in Turbulent Boundary-Layer Separation over a Surface Cavity," *Journal of Heat Transfer, Transactions of the American Society of Mechanical Engineers*, Vol. 89, Series C, Nov. 1967, pp. 335–340.

[2] Winkler, E. M. et al., "Investigation of Substructure Heating on Cracked Ablative Heat Shields," NOLTR 69-122, July 1969, Naval Ordnance Lab., White Oak, Md.

[3] Winkler, E. M. et al., "Supersonic Ablation Studies with Teflon," NOLTR 69-125, Oct. 1969, Naval Ordnance Lab., White Oak, Md.

[4] Donaldson, C. duP. and Dunn, J. E., "Final Report on Flow and Heat Transfer Studies in Transverse Cracks," Rept. 133 (DASA Rept. 2301), June 1969, Aeronautical Research Associates of Princeton, Inc., Princeton, N. J.

Radiative Cooling of Shock-Heated Air in Cylindrical Shock Tubes

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THE purpose of this note is to extend the work of Ref. 1 by presenting parametric computations of enthalpy profiles for nonadiabatic flow of air behind a nonattenuating incident shock wave in a cylindrical shock tube. The parameters and their variations in this study are: shock velocity

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