that, for the Hi-Lo igniter design and pellet geometries used, Eq. (1) worked equally well for ignition materials varying widely in thermodynamic and ballistic properties and for pressure test data resulting from about a three-fold range of igniter and pellet sizes.

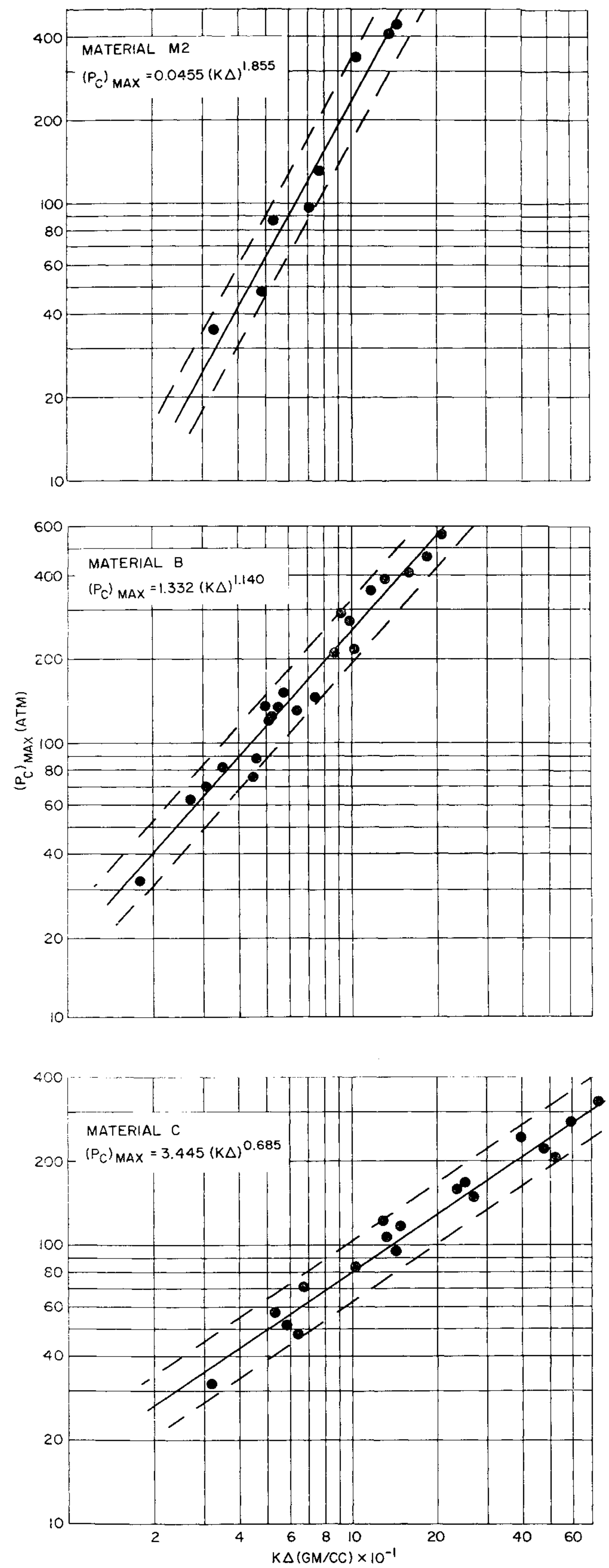

Fig. 2 Plots of igniter maximum pressure vs $K\Delta$ for three ignition materials.

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Heat Transfer in the Vicinity of Two-Dimensional Protuberances

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Nomenclature

h = local heat-transfer coefficient
h_0 = local, flat plate, heat-transfer coefficient
L = distance from protuberance
M = Mach number
Re = local Reynolds number
Y = height of protuberance
X = wetted distance
δ = boundary-layer thickness
θ = angle of leading edge of protuberance

Introduction

BERTRAM'S[1] work in the hypersonic range clearly showed that an empirical equation could be written to define heat-transfer coefficients near protuberances. However, a literature survey failed to yield an analytical approach for calculating heat-transfer coefficients in the vicinity of protuberances in supersonic flow. The present work was performed to develop working equations for the latter purpose. Dimensional analysis was applied to the test data of Burbank[2] to obtain an empirical equation for the heat-transfer coefficient in each of the three regimes; upstream, immediately behind, and downstream of the protuberance.

Burbank's[2] experiments were conducted at freestream Mach numbers of 2.65, 3.51, and 4.44, Reynolds number per foot from 1.3×10^6 to 4.7×10^6, and boundary-layer thickness from 0.7 to 6.0 in. The 6.0-in. boundary layer normally exists at the wall of the test section of the tunnel. The smaller boundary layers, 0.7 and 1.5 in., were achieved by inserting a flat plate in the test section and then fixing the protuberance at the wetted length of flat plate required to give the desired

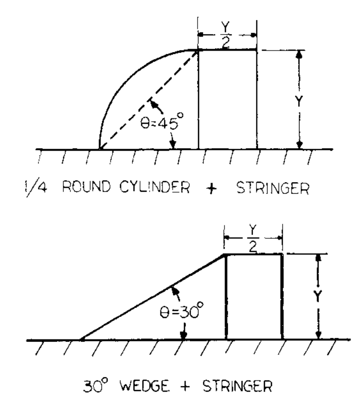

Fig. 1 Protuberances with "swept" leading edges placed in front of basic stringer (Y = 2 or 4 in.).

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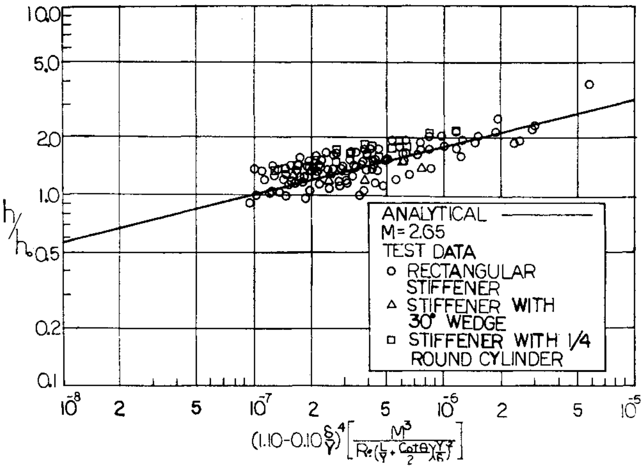

Fig. 2 Correlation of experimental data at Mach 2.65.

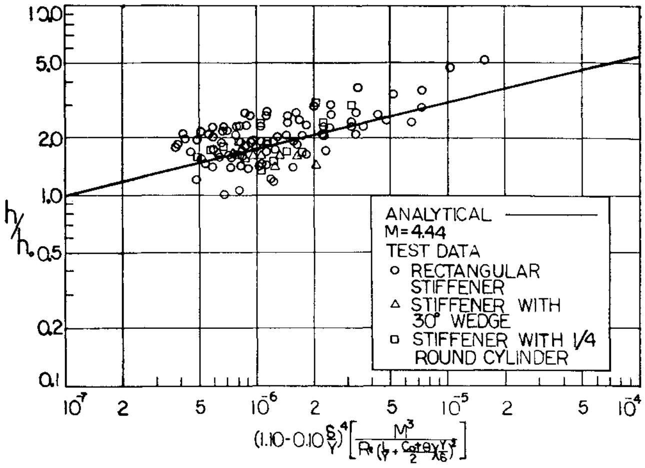

Fig. 4 Correlation of experimental data at Mach 4.44.

boundary-layer thickness at the protuberance. A boundary-layer trip was placed near the leading edge of the flat plate to force turbulence in the boundary layer. The test data for the small boundary layers, 0.7 and 1.5 in., were complicated by the existing oblique shock on the leading edge of the flat plate; corrected stream properties after the oblique shock were used to derive the three equations presented herein. The basic two-dimensional protuberances were the 1- × 2- and 2- × 4-in. stringers. Effects of the leading edge of the protuberance were investigated by adding to the front of the stringer a 30-deg wedge or a $\frac{1}{4}$-round cylinder as shown in Fig. 1.

Discussion of Results

Heat-transfer coefficients in the upstream regime can be calculated by

$$\frac{h}{h_0} = 60.0\left(1.10 - 0.10\,\frac{\delta}{Y}\right) \times \left[\frac{M^3}{Re[(L/Y) + (\cot\theta/2)]\,(Y/\delta)^2}\right]^{1/4} \tag{1}$$

when $\delta/Y \leq 4$.

This equation can be applied to a two-dimensional protuberance having a leading edge normal to the flow; corrections for a sweptback leading edge are made by the $\cot\theta$ term in the denominator, where θ is defined in Fig. 1. The Reynolds number is calculated by using freestream properties and the wetted length to the point to be analyzed. The length L is the absolute distance from the leading edge of the protuberance.

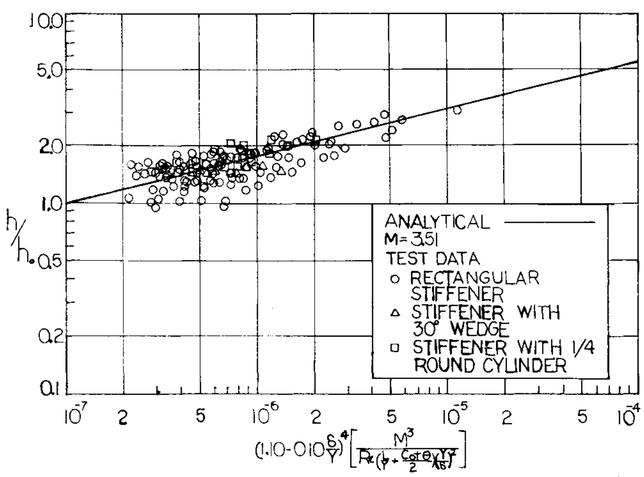

Fig. 3 Correlation of experimental data at Mach 3.51.

Heat transfer behind the protuberance is defined by two equations that are dependent on the distance downstream of the trailing edge. At ratios of $L/Y \geq 2$, the following equation is used:

$$\frac{h}{h_0} = 1.0 + 0.025\left[Re\left(\frac{Y}{L}\right)^2 M^2\left(\frac{\delta}{Y}\right)\right]^{1/8} \tag{2}$$

This equation, therefore, defines the heat transfer after boundary-layer reattachment, which occurs at $L/Y \simeq 2$. This equation holds only for a vertical trailing edge. It should be noted that the angle of the leading edge does not effect the heat transfer behind the protuberance.

In the highly turbulent regime, immediately behind the protuberance, for $L/Y < 2$,

$$\frac{h}{h_0} = \frac{1}{4}\left(\frac{L}{Y}\right)^2\left[1.0 + 0.021\left(ReM^2\,\frac{\delta}{Y}\right)^{1/8}\right] \tag{3}$$

This equation applies only when $L/Y < 2$ and when the trailing edge is vertical to the flat surface.

Figures 2–4 show the correlation of the upstream data by the function in Eq. (1) to the ratio of protuberance-to-flat-plate heat-transfer coefficients. The accuracy of the correlation is somewhat better at Mach numbers 2.65 and 3.51 than it is at Mach 4.44, because of inaccuracies of the test data[2] at Mach 4.44.

Figure 5 shows the over-all picture of the protuberance test data and the correlation of all equations in their respective regimes. In all cases behind the protuberance, the effect of Reynolds number was so small that a single line was shown for the range of Re shown in Fig. 5.

Throughout the analysis of the test data, the critical parameters appeared to be the Mach number and the ratios Y/δ and L/Y. The Reynolds number showed small effects on the final result. The preceding equations should be limited to

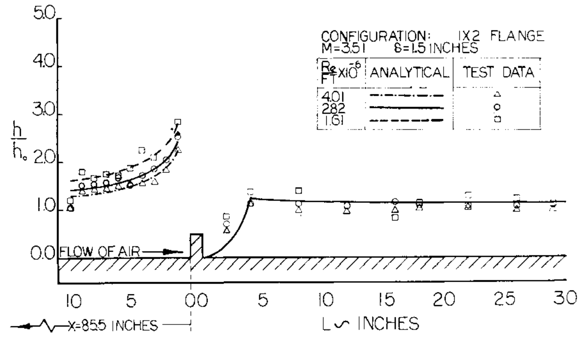

Fig. 5 Comparison of empirical equation to experimental data at Mach 3.51.

the range of the test data,[2] and extrapolation of the equation should be handled with caution especially when the ratios of Y/δ and L/Y are concerned. Equation (1) was applied to preliminary, unpublished test data having numerically similar parameters as presented herein with the exception of Mach number which was 5.2; the agreement was within +10% in all cases. Extrapolation to higher Mach numbers is not recommended because of the real-gas effects in the hypersonic regime.

Conclusion

In conclusion, the equations presented herein can be used for aerodynamic heating calculations with reasonable accuracy only if the limitations of the equations are not greatly exceeded. In all cases, the ratio of heat-transfer coefficients immediately behind the protuberance were below unity, and further downstream the ratio of coefficients never exceeded twice the value of the flat-plate coefficient.

The highest ratios occur in the regime immediately upstream of the protuberances where some of the ratios exceed four times that of flat plate. Consequently, maximum heating will occur in front of a two-dimensional stringer where the magnitude of heating approaches that of stagnation-point heating.

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Effect of Rocket Engine Vibration on an Air-Core Superconducting Magnet

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THE behavior of an air-core superconducting magnet in the presence of rocket engine vibration is discussed in this note. Observations reported herein were obtained as secondary information while performing applied research on the effect of an axial magnetic field on rocket nozzle heat transfer.[1,2]

Experimental Apparatus

Project THERMA‡ experiments utilized an 85-lb thrust, water-cooled liquid-fuel rocket engine burning gaseous oxygen and methyl alcohol at a chamber pressure of 20 atm. The reactants were seeded with cesium carbonate to enhance the electron density and electrical conductivity of the combustion products. The instrumented, contoured rocket nozzle had a throat diameter of 0.5 in. and a radius of curvature of 4 in. The injector was of the impinging stream type and gave smooth and efficient combustion over a wide range of chamber pressures and oxidizer-fuel ratios. The rocket engine was mounted coaxially with the air-core superconducting magnet and fired vertically downward into a water-cooled exhaust duct (Fig. 1).

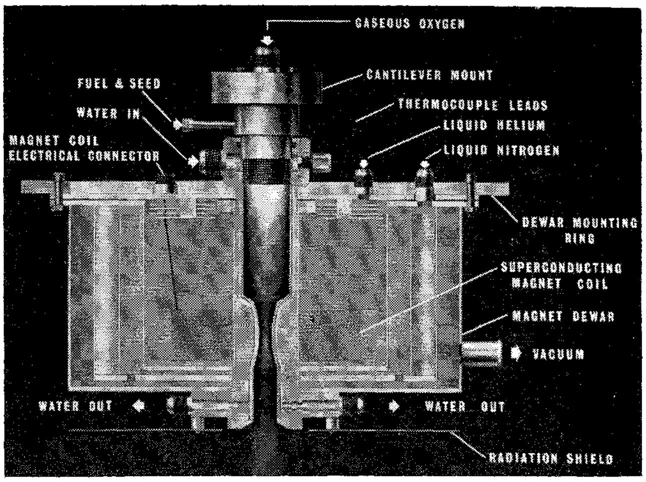

Fig. 1 Simplified cutaway of THERMA II experimental device.

The superconducting solenoid was found on an aluminum mandrel using 55,000 ft of Westinghouse 10-mil niobium-25% zirconium wire. The 40,357-turn solenoid (3.1-in. i.d., 7.25-in. o.d., and 2.12 in. in length) was wound from four lengths of wire with a total of five joints. The wire was restrained by two thin aluminum disks, punched to provide additional direct contact with the liquid helium. Wire ends were brought outside the solenoid and connected through copper blocks around its periphery. The resistance of the dry solenoid was 110,000 ohms; when cooled with liquid nitrogen its resistance was 81,000 ohms, and with liquid helium, zero ohms. The solenoid (Fig. 2) was designed§ so that the flux lines would follow the contoured nozzle wall. It was mounted inside a stainless-steel dewar, which had a 2.5 in.-diam air-core extending for the entire 8-in. length of the dewar. The dewar contained liquid helium at 4.2°K and was insulated from the external environment by vacuum (5×10^{-7} torr) and liquid nitrogen shields.

The solenoid was connected to its transistorized power supply through an energy transfer circuit that disconnected the power supply from the solenoid when a transition to the normal resistive state began to propagate in the solenoid windings. The circuit was opened by an electromechanical switch that actuated in approximately 1 msec upon receiving an indication that a voltage increase was occurring on the solenoid windings. The energy dissipated during a transition was absorbed in the solenoid windings and in a resistive load located in the energy transfer circuit. Oscilloscope data indicated that about 20% of the stored energy was dissipated in the resistive load, the remainder in the solenoid itself.

The pancake-type solenoid could not be charged at rapid rates; to do so was to insure a normal transition. When the total current in the solenoid was low, the charging rate could be relatively high, but, as the current in the solenoid increased, the charging rate had to be decreased to avoid a normal transition. The safe charging rate for the solenoid was determined during 17 hr of superconducting operation in which the solenoid sustained 40 normal transitions. The most energetic transition was from a current of 6.6 amp, corresponding to a measured flux density on the solenoid axis of 26 kgauss and a calculated flux density on the inner windings of about 30 kgauss. Oscilloscope data of transition-induced voltage from each winding indicated that the transitions did

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‡ Acronym for transfer of heat reduced magnetically.

§ The superconducting magnet system was designed and fabricated especially for the project by Advanced Kinetics, Inc., under the direction of Ralph Waniek.