four steep trajectory flights for which data are presented. The actual data are in general agreement with the base heating results on a 30% blunt vehicle rather than the expected theoretically sharp vehicle. Subsequent boundary layer calculations, however, indicate that the effects of the nose shock wave are felt to the end of these slender vehicles, as in the case of a blunt vehicle.

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Correlations of Peak Heating in Shock Interference Regions at Hypersonic Speeds

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Nomenclature

BS, IP, IS, SL, TS	= bow shock, impingement point, impinging shock, shear layer, and transmitted shock, respectively, Fig. 1
C	= constant in Eq. (1)
c_p	= specific heat at constant pressure
h	= heat-transfer coefficient
M	= Mach number
n	= exponent in Eqs. (1, 2, or 3)
N_{Pr}	= Prandtl number
p	= pressure
R	= Reynolds number
T	= temperature
u	= velocity
X_{SL}	= shear layer length
γ	= ratio of specific heats
ρ	= density, note: $(\rho_w \propto p_p/T_w)$
μ	= viscosity
δ_{SL}	= shear-layer thickness
θ_{SL}	= shear-layer angle relative to local surface inclination

Subscripts

1, 2, 3, 4, 5	= regions in flow pattern Fig. 1
p	= peak value
w, ∞	= wall and freestream, respectively
u,s	= undisturbed and stagnation, respectively

Introduction

A KNOWLEDGE of the peak heating in interference flow regions is necessary for the design of hypersonic configurations such as the space shuttle. Typical areas of interference flows on the shuttle include the flow between the mated booster and orbiter, and the fuselage bow shock impingement on the leading edges of wings and fins. An extensive survey of the state of the art concerning various types of interference flows was made by Korkegi.[1] Edney[2] showed that increases in heating in shock interference regions result from one or more of the following mechanisms: shock/boundary-layer interaction, free shear layer attachment, and supersonic jet impingement. Correlations of peak heating due to shock/boundary-layer interactions for laminar, transitional, and turbulent flows were obtained by Markarian.[3] Back and Cuffel[4] correlated changes in turbulent heat transfer due to shock wave impingement and flow expansion around a corner. Peak heating for turbulent separated flow on wedges was correlated by Holden.[5] Nestler[6] and Bushnell and Weinstein[7] used the concept of shear layer attachment in correlating peak heating for separated flows in the reattachment region.

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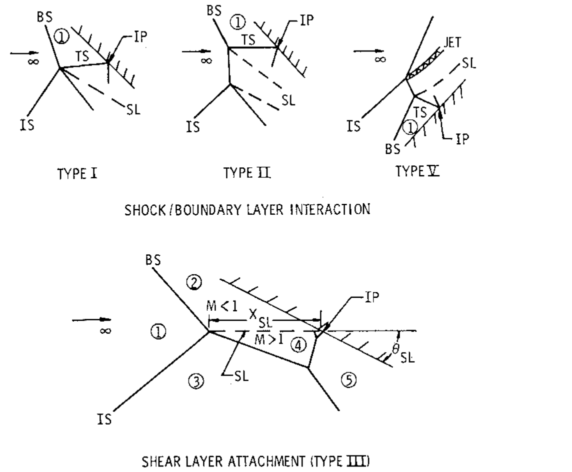

Fig. 1 Shock interference patterns.

This Note presents correlations of measured pressure and heat-transfer peaks for shock/boundary-layer interactions and shear layer attachment on configurations with both two-dimensional and three-dimensional interactions. The peak values were obtained in an extensive investigation of shock interference heating[8] on hemispheres, a 30° included angle wedge, and a 2.54 cm diam cylindrical leading edge fin model. The investigation included data for Mach numbers of 6 and 20 over a freestream Reynolds number range from 3.3–25.6 million per meter and specific heat ratios of 1.4 and 1.67. Flat plate shock generator angles varied from 5° to 25°. Sketches of the types of shock interference patterns as classified by Edney and discussed in the present analysis are shown in Fig. 1.

Shock/Boundary-Layer Interaction

The maximum increase in heating is at the impingement point IP of the transmitted shock (TS shown in Fig. 1). Murphy[9] conducted a critical evaluation of methods used to predict both the pressure and heat-transfer distributions through the interaction region. The most useful approach from a practical standpoint is that of Markarian,[3] who proposed empirical correlations based upon the inviscid pressure rise across the interaction region. These correlations are well-suited for rapid engineering calculations, assuming the peak pressure is known. The expression is of the form

$$h_p/h_u = C[p_p/p_u]^n \tag{1}$$

where C and n depend upon whether the interaction is laminar, transitional, or turbulent. Figure 2a shows the correlation of peak pressures and heat transfer obtained in the present investigation for the wedge and fin models. These peaks are in good agreement with the Markarian correlation curve for a laminar interaction ($C = 1$ and $n = 1.29$). In the present case, the boundary layers in the impingement region are believed to be laminar. Extensive boundary-layer separation

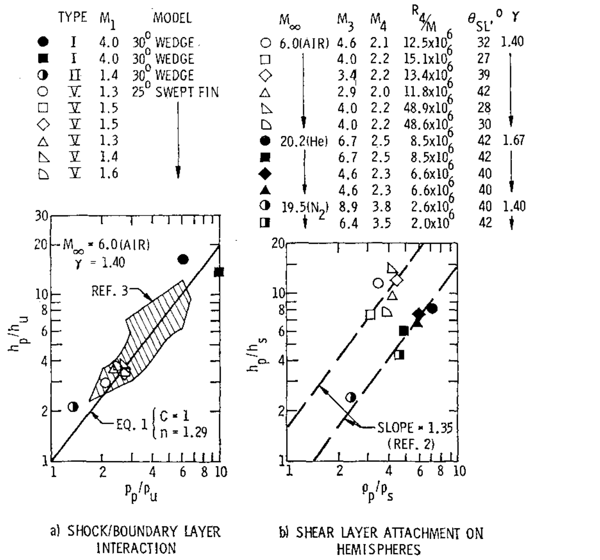

Fig. 2 Correlations of peak pressure and peak heating in shock interference regions.

was present on the wedge and small regions of separation may have occurred on the fin but were not observed in the schlieren photographs or indicated by the surface data.

Shear-Layer Attachment

Heating produced by an attaching shear layer (type III—Fig. 1) produced peak values on a hemisphere as high as 14 times the undisturbed stagnation value.[8] It was shown in Refs. 2 and 8 that the heat-transfer distribution near attachment exhibits the same trend as the pressure distribution. This suggests a simple expression similar to that of Markarian

$$h_p/h_s \propto [p_p/p_s]^n \tag{2}$$

where the subscript s indicates undisturbed stagnation values on the body. Figure 2b shows the correlation of peak pressures and heat-transfer coefficients obtained on a 2-in. diameter hemisphere at Mach 6 in air and on a 1-in. diameter hemisphere at Mach 19.5 in nitrogen and Mach 20.2 in helium. A value of $n = 1.35$ (from Ref. 2) gives a good indication of the slope of the data. The higher heat-transfer data at Mach 6 is approximately $2\frac{1}{2}$ times that at Mach 20 for the same pressure ratio. Comparisons of shear layer transition data from the present investigation with that of Ref. 10 indicates that the shear layers are turbulent at Mach 6 and laminar near Mach 20.

Since the attaching shear layer flow is qualitatively similar to the case of a reattaching separated boundary layer, another correlation may be obtained using a method based on the work of Bushnell and Weinstein.[7]

Bushnell and Weinstein have proposed a correlation for separated boundary-layer reattachment in compression corners which is of the form

$$\frac{h_p}{\rho_w u_5 c_p} \propto \left[\frac{\rho_w u_5 \delta_{SL}}{\mu_w \sin\theta_{SL}}\right]^{-n} \tag{3}$$

where n depends on whether the shear layer is laminar or turbulent. The density (ρ_w) and viscosity (μ_w) are based on the measured wall temperature as suggested by Holden,[11] and the measured peak pressure is also used in computing ρ_w.

Expressions used to compute the shear layer thickness (δ_{SL}) at attachment are: (from Ref. 7)

$$\text{Laminar flow} \quad \delta_{SL} = 5[X_{SL}\mu_4/\rho_4 u_4]^{0.5} \tag{4}$$

$$\text{Turbulent flow} \quad \delta_{SL} = 0.123 X_{SL} \tag{5}$$

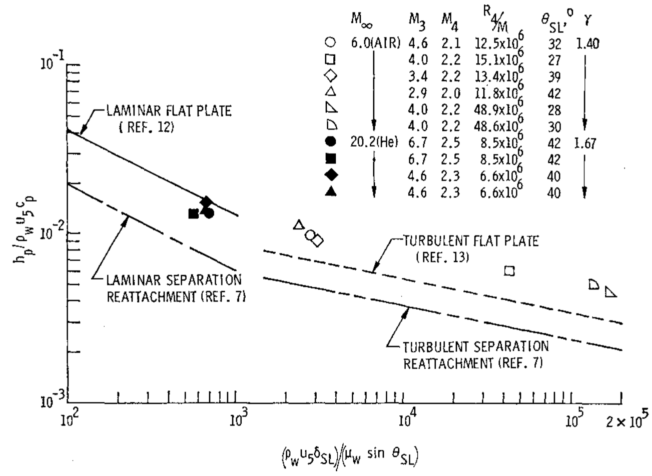

Fig. 3 Correlation of peak heating for shear-layer attachment on hemispheres.

Both of these expressions assumed a zero initial shear layer thickness at the shock intersection (correct in the present case). The shear layer length, X_{SL}, as well as the necessary flow conditions needed for this correlation, were obtained from available computer codes[8] and flow visualization photographs.

Figure 3 shows the correlation of the measured peak Stanton number as a function of Reynolds number based on δ_{SL} for the Mach 6 and Mach 20.2 data. As expected, the Mach 6 data falls along a turbulent slope of -0.2. Due to the distribution of the data, no correlation can be made for the laminar case, although it is believed that if the Mach 19.5 nitrogen data from Fig. 2b were corrected for nonequilibrium effects these data would follow a laminar slope along with the Mach 20.2 helium data. Curves for a laminar[12] and turbulent Stanton number variation on a flat plate are shown for comparative purposes. The levels of heating in the present investigation are approximately double the levels calculated for the separation reattachment cases of Ref. 7. This might be expected, since θ_{SL} is much greater for the present shear layer attachment case than for separated boundary-layer reattachment. Also, the three-dimensional nature of the present impingement flow may be the cause of the higher heating level in the present case.

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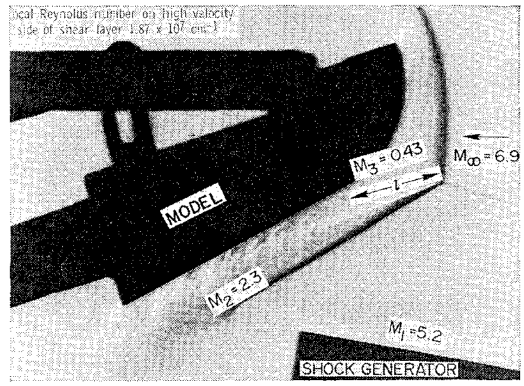

Fig. 1 Shear layer produced by unequal shock interaction.

Transition in Compressible Free Shear Layers

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Nomenclature

l = shear-layer length to transition point
Re_T = $\rho_2 u_2 l/\mu_2$ transition Reynolds number
u = velocity
λ = $(1 - u_3/u_2)/(1 + u_3/u_2)$
μ = dynamic viscosity
ρ = density

Subscripts

o = value when $u_3 = 0$
1 = conditions behind generator shock
2,3 = conditions on high and low velocity side of shear layer
∞ = freestream conditions

Introduction

CURRENT interest in shock-on-shock interaction flows is prompted by the associated increase in surface heat transfer. In 1968, Edney[1] identified six basic types of flow produced by unequal shock interactions. Here, we consider only one of these flows, identified as Type III by Edney. This flow, which results from the interaction of a strong and weak shock, produces a single shear layer with supersonic flow on one side and subsonic flow on the other. It has been shown[2] that the surface heat transfer in the attachment region strongly depends on whether or not this shear-layer flow is turbulent. It is, therefore, of interest to establish the transition Reynolds number Re_T for shear layers produced by these interactions, since no such data appear to be available.

Results

The results presented here are based on two separate studies using the Langley 20-in. (Mach 6) and 11-in. (Mach 6.9) Hypersonic Tunnels.[3] In each case, a variable angle wedge generates a planar shock wave which interacts with the bow wave of a bluff body. The interaction geometry obtained in the two facilities differed in that the bluff body used in the 11-in.-tunnel was two-dimensional, 7.62 cm (3-in.) long, and 6.35 cm (2½-in.) wide, whereas that used in the 20-in. tunnel was a hemisphere/cylinder, 5.08 cm (2-in.) in diam. A side view of the model used in the 11-in. tunnel is shown in the schlieren photograph in Fig. 1, and further details of the apparatus used in the 20-in. tunnel are given in Ref. 4. The transition length l is defined as the length along the shear layer from the shock interaction to the point at which turbulence became visible on schlieren photographs. An average value of l based on a series of photographs was used to determine the transition Reynolds number Re_T, and these results are given in Table I.

Most of the published results on transition in free shear layers are based on shear layers with a velocity u_3 of zero or close to zero. For the present work, the velocity ratio u_3/u_2 is substantial ($u_3 \neq 0$), and its effects cannot be ignored. If these results are to be compared with previously published data obtained for separation geometries where $u_3 = 0$ approximately, it is necessary to extrapolate the measured values of Re_T to the values they would have for a zero-velocity ratio. The literature contains no experimental results for the variation of Re_T with the velocity ratio u_3/u_2, and the variation in the present results is too limited to justify any definite conclusions. Edney[1] suggested that an Re_T based on the velocity difference across the shear layer would be more appropriate when the velocity $u_3 \neq 0$. However, it appears that, unless the transition process is a function of the absolute velocity, the transition length l must increase with u_2 and u_3, simply because of the increase in the average convection velocity in the shear layer, even if M_2 and $(u_2 - u_3)$ are held constant. Thus, as a first approximation, an increase in transition length might be assumed to be proportional to an increase in the average velocity or

$$l_0/l = u_2/(u_2 + u_3) \tag{1}$$

where l_0 is the transition length when $u_3 = 0$. Based on Edney's suggestion that u_2 be replaced by $u_2 - u_3$ and Eq. (1), Re_{T_o} may be written as

$$[\rho_2(u_2 - u_3)/\mu_2][lu_2/(u_2 + u_3)] = \rho_2 u_2 l \lambda/\mu_2 \tag{2}$$

Table 1 Summary of experimental results

M_2	Re_T	u_3/u_2	λ	Re_{T_o}
1.79	3.0×10^4	0.360	0.470	1.41×10^4
1.99	6.1×10^4	0.270	0.574	3.50×10^4
2.06	5.7×10^4	0.289	0.552	3.20×10^4
2.17	5.2×10^4	0.256	0.592	3.10×10^4
2.22	5.6×10^4	0.259	0.589	3.30×10^4
2.22	6.5×10^4	0.259	0.589	3.80×10^4
2.30	4.3×10^4	0.265	0.580	2.50×10^4

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