Incident Shock Interactions with Boundary Layers

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Theme

INCIDENT shock wave interactions with laminar and turbulent boundary layers were investigated experimentally. The work extends the existing data base used for comparisons with results of analytical methods for estimating: free interaction pressure distributions; extent of the pressure rise upstream of the incident shock location; and peak heat transfer rates. Pressure and heating rate distributions were obtained for wedge-generated shock waves interacting with Mach 8 laminar boundary layers, and for wedge- and sphere-generated shock waves interacting with Mach 6 turbulent layers. The Mach 6 data were obtained for Reynolds numbers up to 440 million, considerably larger than those obtained in most other similar investigations.

Contents

Shock waves that impinge on a surface can greatly amplify the local heat transfer and pressure loads on the surface. A sufficiently strong shock wave causes the boundary layer to separate from the surface. As sketched in Fig. 1, there results a region of reverse flow that terminates where the separated boundary layer reattaches to the surface. M is the undisturbed flow Mach number, and x_i is the distance to where the incident shock wave would strike the surface if there were no boundary layer. A distribution of disturbed to undisturbed flow pressure ratios, characteristic of shock-induced laminar separation, is sketched in the same figure. The pressure ratio rises initially to a "plateau" value, and then rises further to a peak value, P. The pressure rise extends a distance ℓ upstream of the inviscid incident shock location. For laminar separation, as sketched in Fig. 1, the disturbed to undisturbed heat transfer rate ratio is reduced below unity in the separated flow region, but attains a large peak value, H, at reattachment downstream of the separated flow region.

Although the problem of shock-induced separation is well recognized and has received much attention,[1,2] there are still no adequate simple methods for reliably predicting the extent of the pressure rise and the increased heating at reattachment. The purpose of the subject program is to re-examine correlation methods proposed for estimating features of shock-wave interactions with laminar and turbulent boundary layers, and to extend the data base used to establish the correlations.

Wedges and spheres were used to generate shock waves incident to either an instrumented flat plate or an instrumented portion of the Mach 6 tunnel wall.[3,4] By using the tunnel wall as a shock receiver, Reynolds numbers (based on length from the tunnel throat to the incident shock location) up to 440 million were attained in the Mach 6 tunnel. Reynolds numbers based on the instrumented flat plate length ranged from 3.5 to 46 million in the Mach 6 tunnel, and from 0.46 to 2.5 million in the Mach 8 tunnel.

Although the total pressure rise and the upstream extent of the pressure rise depend strongly on the shock strength, the initial pressure rise should be independent of the mechanism generating the shock wave. This concept of a "free interaction" between the viscid boundary layer and the inviscid external flow in the upstream portion of the interaction region has been well established for many years.[5] The "free interaction" portions of the subject pressure distributions fall quite close to the universal curves presented by Carriere, Sirieix and Solignac[6] for both laminar and turbulent boundary layers.[3,4]

The extent of the pressure rise upstream of the incident shock location depends on several parameters such as: the character of the boundary layer; the wall temperature; the boundary-layer thickness; and the overall strength of the pressure rise (P). Based on our data for the wedge-generated shock waves, the following expressions predict satisfactorily the extent of the pressure rise in terms of P and δ, the undisturbed boundary-layer thickness just upstream of the pressure rise. For weak shock waves ($1<P<6$) incident to laminar boundary layers on a sharp flat plate, for $7<M<8$, $0.5<(R_{xi}/10^6)<2.0$ and $T_w \approx 0.5T_t$:[4]

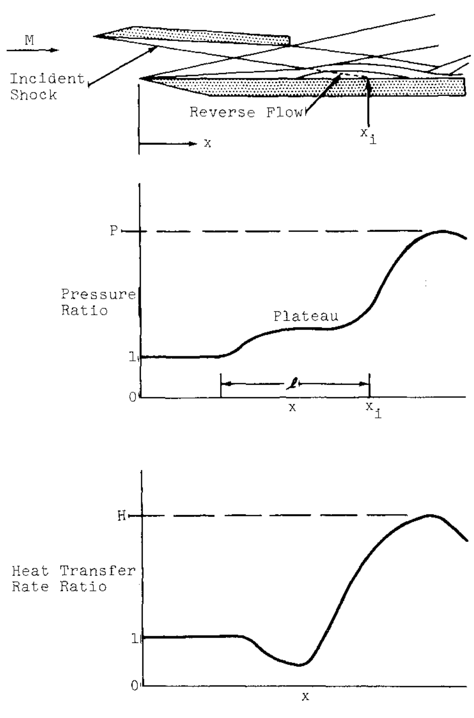

Fig. 1 Sketch of laminar interaction flow and resulting distributions of pressure and heat transfer rate ratios.

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Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Supersonic and Hypersonic Flow.

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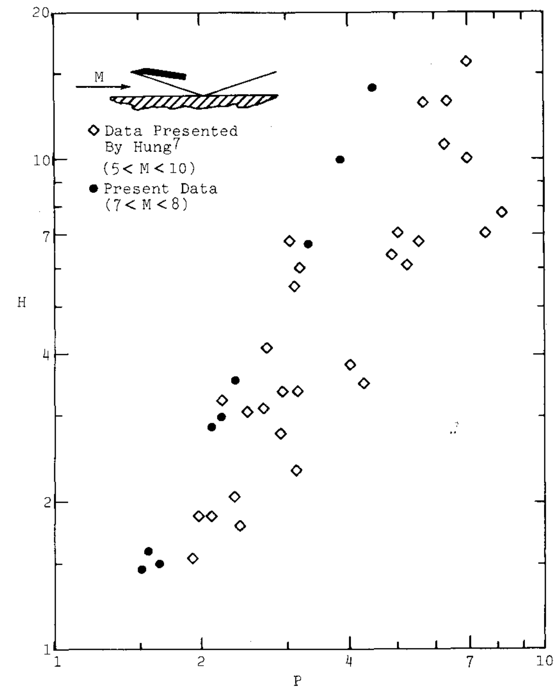

Fig. 2 Peak heat transfer rate amplifications vs peak pressure rise ratios for laminar boundary layers.

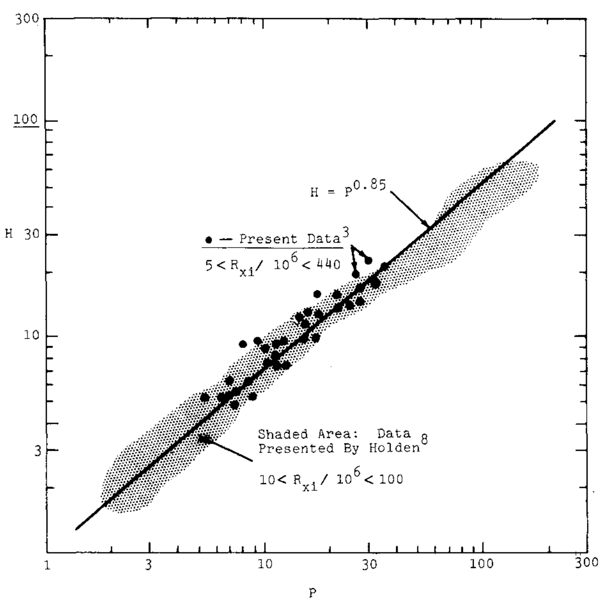

Fig. 3 Peak heat transfer rate amplifications vs peak pressure rise ratios for turbulent boundary layers.

$$\ell/\delta = (P-1)^{0.36}(R_{xi})^{1/2}/75 \tag{1}$$

where R_{xi} is the Reynolds number based on x_i and local undisturbed flow conditions, T_w is the wall temperature, and T_t the flow total temperature. For wedge-generated shock waves incident to turbulent boundary layers,[3] for $M \approx 6$, $5 < (R_{xi}/10^6) < 440$, $T_w \approx 0.6\,T_t$ and for $5 < P < 30$:

$$\ell/\delta = P/3 \tag{2}$$

Within the indicated ranges of flow conditions, these empirical relations represent the measured extents of the pressure rises upstream of x_i very well.

Many investigations have been directed toward obtaining correlations of peak heating rates with peak pressures. Simple correlations of the form:

$$H = P^n \tag{3}$$

have been sought frequently.[7] For laminar boundary layers, there is an unacceptably large discrepancy in the values proposed for the exponent n (proposed values range from 0.7 to 1.3.)[7] Values of peak heating amplifications obtained during the present experiments, along with other data presented by Hung,[7] are plotted vs peak pressure amplifications in Fig. 2 for shock-wave interactions with laminar boundary layers. The sensitivity of laminar boundary layers to many flow parameters evidences itself in the large scatter apparent in Fig. 2 and precludes obtaining a reliable, simple correlation in the form of Eq. (3). More complex expressions are required to estimate reliably the trend of the heat transfer rate amplification at reattachment with the several factors influencing laminar separation.[4]

Turbulent boundary-layer separation, on the other hand, is less sensitive to Reynolds number and other factors. There is general agreement that Eq. (3) is valid for shock-induced turbulent separation for values of the exponent in the range $0.80 < n < 0.85$.[7,8] Holden[8] presented data for turbulent separation from many sources, shown as the shaded area in Fig. 3. Data from the subject investigation, indicated by the symbols shown in Fig. 3, affirm the simple peak heating correlation [Eq. (3)] for turbulent boundary layers, and greatly extend the Reynolds number range of applicability of the correlation.

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