Impact Pressure Behavior in Rarefied Hypersonic Flow

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Introduction

It is well established that, as the rarefied flow regime is entered, the pressure sensed by blunt impact probes under constant stream conditions but with decreasing probe Reynolds number Re_∞ will first decrease and then gradually rise. The rising pressure trend continues with decreasing Re_∞ until free molecule flow conditions are reached where the indicated pressure may be several times greater than the inviscid continuum impact pressure. However, the behavior of blunt-body impact pressures as a function of the pertinent flow parameters has not been quantitatively determined throughout the complete rarefied flow regimes.

The present investigation was conducted for the purposes of 1) extending the knowledge of the governing flow parameters further into the rarefied flow regime, 2) gaining a further insight of the mechanisms affecting the blunt-body impact pressure behavior, and 3) providing experimental data demonstrating the measurement characteristics of blunt impact pressure probes at low Reynolds numbers and elevated hypersonic Mach numbers.

Test Apparatus and Methods

This study was conducted in the Aerospace Research Laboratories (ARL) 5-in. hypersonic, blow down, wind tunnel. Tests were made at the three Mach numbers of 14.20, 16.72, and 18.32 where the corresponding stagnation pressures were 100, 200, and 520 psia and the stagnation temperatures were 2260°, 2160°, and 2160°R, respectively. The various test Mach numbers were all obtained in the same conical nozzle by varying the freestream Reynolds number that affected the nozzle boundary-layer growth, thus changing the effective nozzle area ratio. From detailed flow surveys it was determined that the lateral Mach number variation over the central 0.4 in. of flow was ±0.07, ±0.10, and ±0.15 for the Mach numbers of 14.20, 16.72, and 18.32, respectively. (The maximum probe diameter tested was 0.25 in.) The axial flow impact pressure gradients were determined to be sufficiently small so that corrections of the measured impact pressure P_{0_m} for these gradients were not required.[1] Brief tests were also made to assure that the nozzle flow was condensation-free.[2]

Four different sets of geometrically similar probes, graduated in size, were studied at each of the 3 test Mach numbers. The probe o.d. ranged 0.250 to 0.020 in. Two of the probe sets were flat-ended having diameter ratios d/D (orifice diameter-to-outside probe diameter) of 0.5 and 0.75. One set of probes was sharp lipped with $d/D = 1.0$ and had an internal lip level of 10°. The fourth set of probes had hemispherical tips with $d/D = 0.25$. All probe pressures were measured with a McLeod gage having a reading accuracy of about ±1.0%. It is noted that Re_∞ (based on probe o.d.) was changed independently of the freestream conditions by changing the characteristic probe dimension. The only real gas corrections made in reducing the data were those accounting for caloric imperfections. Viscosity determinations needed in the range of low stream temperatures where the Sutherland formula becomes questionable, were based on Bromley-Wilke data.[3] An analysis of thermal transpiration effects, based on the temperature distribution measurement on several probes, indicated a negligible effect for all but the smallest probe where the error was estimated at less than 2%, which was in the direction tending to decrease the indicated pressure. The effect of probe orifice configuration has been studied[4] in the highly rarefied flow case; it was shown that for probe orifice length-to-orifice diameter ratios l/D greater than 1.5 the measured pressure becomes essentially independent of l/D. In the present case, the l/D values were all considerably greater than 1.5 and, therefore, these effects were neglected.

Determination of P_{0i}, the Ideal Inviscid Impact Pressure

A problem existed here, as it had with most of the earlier investigators of this subject, in that it was not possible to measure the ideal inviscid impact pressure directly because the wind tunnel was not capable of operating at sufficiently high Reynolds numbers. Therefore, the extrapolation technique used in most of the previous similar studies was also applied here. The method involves the plotting of P_{0m} against the inverse of the probe diameter D^{-1} for several sets of probes and then extrapolating to the $D^{-1} = 0$ condition, corresponding to the case of infinite Reynolds number where $P_{0_m} \equiv P_{0i}$. To improve upon the accuracy of the technique, a theoretical evaluation of the viscous effects in slightly rarefied flow was made and the theoretical results served to guide the slope of the extrapolation through the higher range of Re_∞ where experimental data were lacking.

Results and Discussion

Mach number dependence

The experimental results of all probes tested clearly indicated a Mach number dependence that is evident in Fig. 1 where typical data are shown for one set of flat-end probes. It is seen that at the lower Re_∞ values, corresponding to higher levels of rarefaction, the pressure ratio P_{0_m}/P_{0i} increases systematically with increasing Mach number. Also shown in Fig. 1 are some data from Sherman[5] and Matthews,[6] obtained at lower Mach numbers; these data appear to fit well with the Mach number trend indicated by the present data. In the present tests, the diameter ratio d/D ranged from 0.5 to 1.0 for the flat-end probes and had little effect on P_{0_m}/P_{0i}. The hemisphere tipped probes also indicated strong Mach number effects but at higher values of Re_∞; e.g., for the hemisphere probes the value of $P_{0m}/P_{0i} = 1.0$ was reached at an Re_∞ value of about twice the corresponding Re_∞ value for the flat-ended probes.

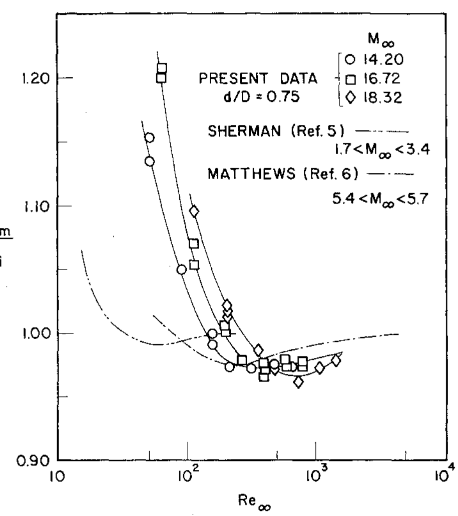

Fig. 1 Characteristic Mach number effect on impact pressure ratio.

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To facilitate the explanation of the impact pressure behavior, Fig. 2 is presented as a qualitative representation of impact pressure ratio P_{0_m}/P_{0_i} plotted vs a range of Re_∞ covering the entire broad domain of rarefied flow. The solid portion of the curves shown represent the range of data covered in the present study; the flow regimes as defined by Hayes and Probstein[7] are indicated. It is seen here, as was shown earlier, that the present results demonstrate a Mach number dependence in the regions of moderately rarefied flow. The Mach number effect trends as found by Liu[8] for the near-free molecule flow regime were applied to the dashed line curves in region 7 of Fig. 2; the dashed extrapolation of the present data to the free molecule regime follows naturally and appears to be justified. The extrapolated curves then qualitatively indicate the expected impact pressure behavior throughout the complete rarefied flow regime, accounting for the Mach number influence.

It is noted that the theory applying to this situation,[9–11] accounts for the viscous effects in the shock layer but not for the rarefaction effects on the shock; the theory predicts only a decrease of impact pressure ratio. Also, it has been pointed out by Van Dyke[12] that for the thin shock layer approximation, which is valid in regions 3 and 4 of Fig. 2, the curvature and slip effects are negligible. Therefore, it is concluded that the decrease of P_{0_m}/P_{0_i} occurring in these flow regimes is due primarily to viscous effects.

As region 5, the fully merged layer regime, is approached and entered, the rarefaction effects on the shock are such that the shock thickens and the detachment distance increases. Associated with these effects is a weakening of the shock strength and an increase in the recoverable dynamic pressure in the shock layer. Also, with adequate rarefaction, direct molecular impact will begin to occur at the probe surface which will tend to increase the measured pressure. Therefore, it is suggested that the rise of impact pressure ratio, which is observed as the fully merged layer flow regime is approached, occurs when the rarefaction effects on the shock predominate over the viscous effects.

Correlation parameters

The determination of a parameter which would properly correlate the experimental results was of primary concern in this study. The parameter $Re_2(\rho_2/\rho_1)^{1/2}$ had been previously shown[1] to apply to the incipient merged flow. (Re_2 is the Reynolds number based on conditions behind the shock; ρ_2/ρ_1 is the density ratio across the shock.)

The quantity M/Re_∞, which is directly proportional to Knudsen number, failed as a correlating parameter.

It was found that $M/(Re_\infty)^{1/2}$ was the parameter governing the flow over the test Reynolds number range of about 50 to 350. The effectiveness of this parameter is shown in Fig. 3 where it is seen that the data collapse to a single curve. It is noted that this parameter can be derived from the Van Dykes[12] viscous hypersonic similarity parameter. Since the derivation is based on the continuum theory, it would not necessarily be expected to remain valid in the flow regimes where the continuum theory breaksdown. However, this parameter may also be derived from the kinetic theory.[13]

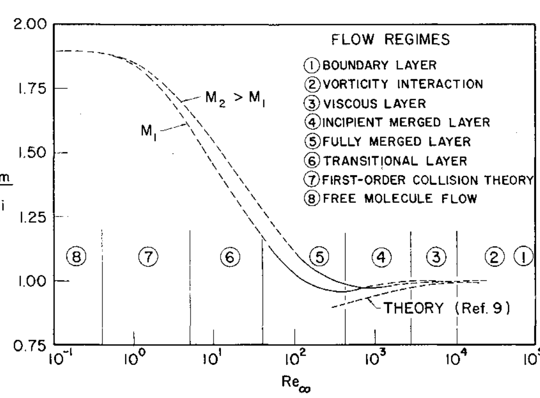

Fig. 2 Suggested impact pressure behavior: extrapolation of present results.

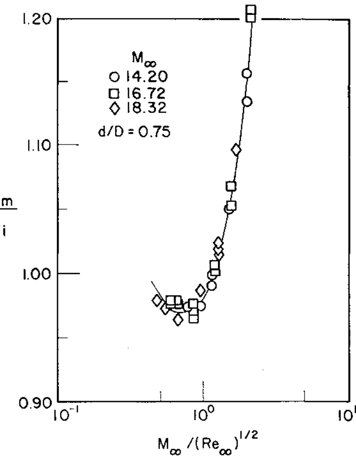

Fig. 3 Demonstration of effectiveness of correlation parameter.

Summary

It has been experimentally demonstrated that the blunt-body impact pressure is Mach number dependent in the fully merged layer flow regime. An explanation offered for the observed behavior of impact pressure under low density flow conditions suggests that the initial decrease in measured pressure ratio is due to viscous effects whereas the eventual increase in pressure ratio is due to rarefaction effects on the shock which become predominant. It has been demonstrated that $M/(Re_\infty)^{1/2}$ is the parameter governing the flow over the Reynolds number range of about 50 to 350.

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Further Results of High Reynolds Number Skin-Friction Tests

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Nomenclature

k = grain diameter
M = Mach number
R_θ = Reynolds number based on momentum thickness, $\rho_1 U_1 \theta/\mu_1$
R_x = Reynolds number based on effective flat-plate length, $\rho_1 U_1 X/\mu_1$
U = velocity
U_τ = friction velocity $(\tau_w/\rho_w)^{1/2}$
y = coordinate distance normal to test surface
γ = specific-heat ratio
θ = bouudary-layer momentum thickness
μ = viscosity
ρ = mass density
τ = shearing stress

Subscripts

1 = local conditions at outer edge of boundary layer
w = wall condition

A RECENT experimental boundary-layer study[1] provided a significant extension of the available Reynolds number range of skin-friction data. Subsequent analytical and experimental efforts have provided additional results pertinent to these very high Reynolds number tests. These results concern the evaluation of the Preston-tube method of determining local skin friction for Reynolds numbers up to $R_x = 1.41 \times 10^9$ at $M = 2.8$ and the study of drag effects of uniform grain-type surface roughness.

The relatively simple technique of experimentally determining local skin friction in pipe flows was introduced by Preston.[2] The method has been extended to external boundary layers[3] and to compressible isobaric[4] and nonisobaric[5] flows. The Preston-tube method is based on the assumption that there exists a valid velocity distribution law for the turbulent boundary layer (or pipe flow) in which one of the similarity parameters is the local skin friction. The mixing length derived law of the wall velocity profile satisfies this condition and for compressible, adiabatic flows may be expressed in functional form as

$$\Phi^* = (\Phi_1/\sigma^{1/2}) \sin^{-1} [\sigma^{1/2}(\Phi/\Phi_1)] = f(\eta) \qquad (1)$$

where

$$\eta = \frac{\rho_w u_\tau y}{\mu_w} \qquad \Phi = \frac{U}{U_\tau} \qquad \sigma = \frac{[(\gamma - 1)/2]\, M_1{}^2}{1 + [(\gamma - 1)/2] M_1{}^2}$$

With the functional relationship established, it can be seen that a single velocity measurement at some known position y above the wall will permit the solution of Eq. (1) for the friction velocity U_τ and hence the local shear stress at the wall τ_w.

The Preston-tube data in the high Reynolds number tests were obtained from the total-pressure probe reading at the wall position just prior to the survey across the boundary layer. Two different evaluations of the function $f(\eta)$ were used in the data reduction, the empirical tabulation presented by Coles[6] and the expression

$$f(\eta) = 2.5 \ln\eta + 5.5 \qquad (2)$$

from the classical mixing length development. The results are presented in Fig. 1 in the form of the ratio of the skin-friction coefficient determined by the Preston-tube method C_{f_P} to that measured by the skin-friction balance (as described in Ref. 1) C_{f_B}. It is noted that there is slightly better agree-

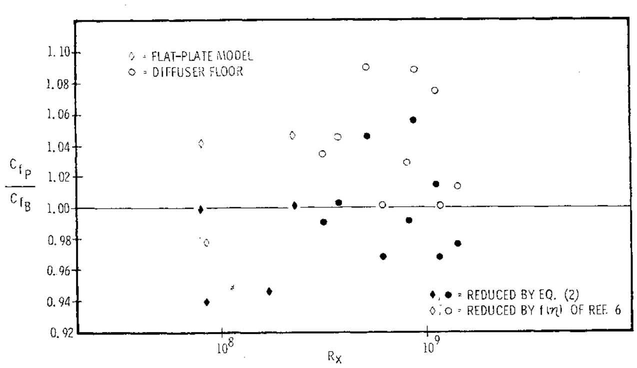

Fig. 1 Comparison of surface probe measurements with skin-friction balance measurements.

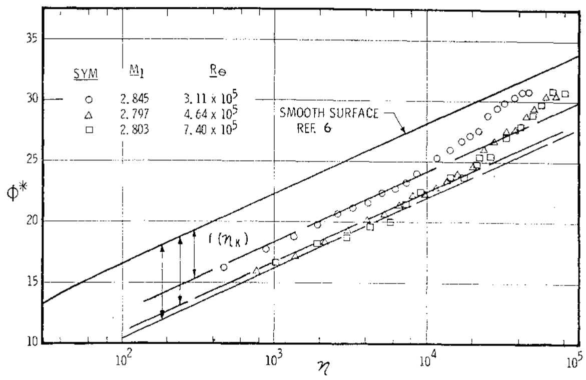

Fig. 2 Law of wall velocity profile with grain roughness, $K = 0.004$ in.

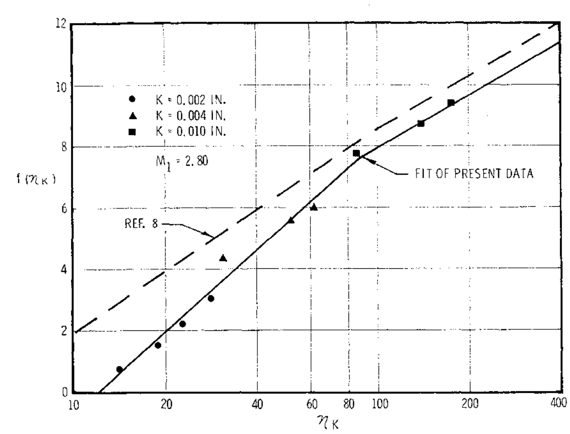

Fig. 3 Roughness function with uniform grain-type roughness.

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