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Flow Behind a Step in High-Enthalpy Laminar Hypersonic Flow

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Nomenclature

a	=	Blasius constant (0.332 for a laminar boundary layer)
C	=	Chapman–Rubesin constant ($\rho\mu/\rho_e\mu_e$)
c_p	=	specific heat at constant pressure, $J/(kg \cdot K)$
c_v	=	specific heat at constant volume, $J/(kg \cdot K)$
h	=	step height, m
k_o	=	constant used in Eq. (5)
L	=	plate length, m
M	=	Mach number ($u/\sqrt{\gamma RT}$)
P	=	parameter defined in Eq. (5)
p	=	static pressure, Pa
R	=	specific gas constant, $J/(kg \cdot K)$
Re	=	Reynolds number ($\rho uL/\mu$)
T	=	temperature, K
T^*	=	critical temperature, K
u	=	velocity, m/s
x	=	distance along the plate behind a step, m (Fig. 1)
x_f	=	length of the shear layer to reattachment point, m
x_r	=	reattachment distance, m
x_r^*	=	normalized reattachment distance (x_r/h)
γ	=	ratio of specific heats (c_p/c_v)
δ	=	boundary-layer thickness, m
ε	=	characteristic parameter of the triple-deck theory
Λ	=	parameter defined in Eqs. (2) and (4)
μ	=	viscosity, $kg/(m \cdot s)$
ρ	=	density, kg/m^3
τ	=	normalized step height (h/L)
$\bar{\chi}$	=	hypersonic viscous interaction parameter ($M_\infty^3\sqrt{C_\infty/Re_L}$)
ω	=	viscosity-temperature law exponent

Subscripts

b	=	base
e	=	outer edge of boundary layer
o	=	total conditions
w	=	body/wall
∞	=	freestream

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I. Introduction

THIS Note describes features associated with a separated flow in high-enthalpy high Mach number hypersonic flow. A simple flow geometry of a rearward-facing step (Fig. 1) is considered for analysis. It is assumed that the step height is small and the separating boundary layer is comparable to step height. Under such circumstances, the hypersonic small-disturbance theory is assumed applicable for the flow at the step. Messiter et al. [1] have analyzed the flow behind a step and behind a wedge in supersonic laminar flow at moderate Mach numbers and moderate-to-high Reynolds numbers. They considered two cases wherein the separating boundary layer was either large or small compared to the step height. The analysis was carried out for adiabatic wall conditions and a gas whose viscosity was proportional to the temperature. An asymptotic approach based on the triple-deck theory was used to calculate the base pressure and pressure distribution behind the step.

Use of the triple-deck theory to analyze separating and reattaching flows was pioneered by Stewartson [2], Messiter [3], Neiland [4], Sychev [5], and Matveeva and Neiland [6]. The theory is based on the assumption that the flow over a surface consists of a three-tier structure wherein viscous effects are confined to the inner layer at the wall (the lower deck), and the so-called main deck is made up of a largely inviscid rotational flow and the upper deck is mostly inviscid irrotational flow. This flow structure is further characterized by a small parameter $\epsilon = Re^{-1/8}$. Then the thicknesses of the lower, main, and upper decks are specified as ϵ^5, ϵ^4, and ϵ^3, respectively, and pressure and velocity perturbations are ϵ^2 and ϵ, respectively. The streamwise length scale of the disturbance is also of the order of ϵ^3. The main limitation of the triple-deck theory is that it is an asymptotic theory valid in the limit $Re \to \infty$. However, even for moderate Reynolds number flows, it seems to give surprisingly decent results. An example of this is the Messiter et al. [1] study of the rearward-facing step in supersonic flow.

Herein, some observations are made with respect to the base pressure and the reattachment distance behind the step by a simple extension of Messiter et al. [1] theory to high Mach number hypersonic flows.

II. Analysis

A. Base Pressure

The base pressure is an important parameter in the analysis of near wakes of slender bodies and several investigations (see, for example, Chapman et al. [7], Weiss and Weinbaum [8], and Weiss [9]) have attempted to predict this quantity in high Mach number and high-to-moderate Reynolds number laminar flows. An ingenious analytical approach, based on the triple-deck theory, has been proposed by Messiter et al. [1] to predict both the base pressure and the pressure distribution behind the step in moderate Mach number and Reynolds number flows. Its applicability to low-to-moderate Reynolds number hypersonic flows does not seem to have been discussed at any length, however.

The Messiter et al. [1] analysis of the base pressure shows reasonably good agreement with experimental data even at moderate Reynolds numbers of the order 10^5, with the restriction that $M_\infty\tau \sim 1$ or less, where $M_\infty\tau$ is the well-known hypersonic small-disturbance parameter and $\tau = h/L$, which takes into account the geometric effect of a small step.

According to Messiter et al. [1], the base-pressure ratio p_b/p_∞ is given as

$$\frac{p_b}{p_\infty} \sim 1 + a^{1/2}(M_\infty^2 - 1)^{-1/4}\gamma M_\infty^2 Re_L^{-1/4} P(\Lambda) \qquad (1)$$

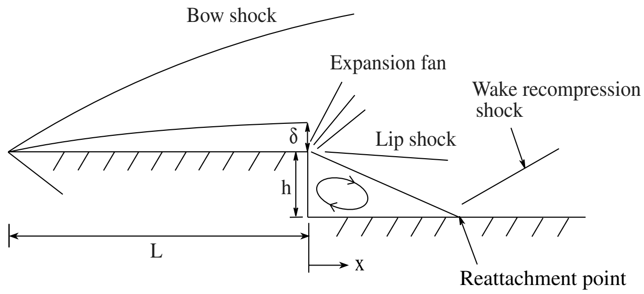

Fig. 1 Schematic of flow behind a rearward-facing step.

where $P(\Lambda)$ is a nondimensional parameter describing the pressure change as a result of discontinuity in the wall in the shape of a step and Λ is another nondimensional parameter given by

$$\Lambda = a^{3/4}(M_\infty^2 - 1)^{1/8}\left[1 + \left(\frac{\gamma - 1}{2}\right)M_\infty^2\right]^{-3/2} Re_L^{5/8}\tau \tag{2}$$

where a is the Blasius constant and is equal to 0.332 for a laminar boundary layer. M_∞ and p_∞ are the freestream Mach number and pressure, respectively. Re_L is the Reynolds number based on the plate length L. The parameter Λ contains all the quantities that are likely to influence the base pressure: namely, the Mach number, the Reynolds number, and the step geometry.

Although the triple-deck theory is strictly applicable to step heights of the order of the sublayer thickness $\mathcal{O}(Re_L^{-5/8}L)$, Messiter et al. [1] show, by comparing with moderate supersonic Mach number and Reynolds number experimental data, that the theory yields quite acceptable results for $Re_L^{-5/8} \ll \tau \ll 1$.

Using hypersonic approximation, wherein $M_\infty \gg 1$, $\tau \ll 1$, and $M_\infty\tau \sim 1$, these two expressions become, respectively,

$$\frac{p_b}{p_\infty} \sim 1 + a^{1/2}\gamma\bar{\chi}^{1/2}P(\Lambda) \tag{3}$$

and

$$\Lambda = \left(\frac{2a^{1/2}}{\gamma - 1}\right)^{3/2} M_\infty\tau\bar{\chi}^{-5/4} \tag{4}$$

where $\bar{\chi}$ is the usual hypersonic viscous interaction parameter $M_\infty^3\sqrt{C_\infty/Re_L}$ and C_∞ is the Chapman–Rubesin constant, defined as $\mu/\mu_\infty = C_\infty(T/T_\infty)$ (Cheng [10]). For a gas with linear viscosity-temperature relation, $C_\infty = 1$.

Equation (4) satisfies the asymptotic flow description $\Lambda \to \infty$ in the limit $\bar{\chi} \to 0$ with $M_\infty\tau$ held fixed.

To evaluate the parameter $P(\Lambda)$, Messiter et al. [1] assume

$$P(\Lambda) \sim -k_o\Lambda^{2/5} \tag{5}$$

where k_o is a positive constant.

The validity of such an assumption is justified by the fact that at moderate Mach numbers, the base pressure is relatively insensitive to changes in Reynolds number based on experimental evidence. Further, based on experimental data obtained with steps and wedges at mainly supersonic Mach numbers, Messiter et al. [1] found that $k_o \approx 0.66$. The data seemed to correlate somewhat better with second order approximation which gave Analysis. Only experimental data pertaining to laminar base flow were considered for analysis. These authors also considered numerical studies by Rott and Hakkinen [11] and Burggraf [12]. Estimation based on these studies suggested values of k_o to be 0.61 and 0.73, respectively. Calculations by Burggraf were based on Batchelor's wake model [13], which assumes that the flow in the recirculation region is a constant vorticity flow bounded by thin viscous shear layers. However, Weiss [9] has shown that for laminar hypersonic base-pressure problem at low-to-moderate Reynolds numbers, the base region is entirely viscous with no inviscid core. It is therefore reasonable to assume that for hypersonic laminar base flow behind a small step with a boundary layer of the order of step height such as the one considered here, the recirculation region is viscous.

It can also be seen from inspection of Eqs. (3) and (4) that

$$\frac{p_b}{p_\infty} \sim 1 - k_o\gamma\left(\frac{2a^{4/3}}{\gamma - 1}\right)^{3/5}(M_\infty\tau)^{2/5} \tag{6}$$

which shows that the base pressure is independent of the Reynolds number but that it is dependent on the parameter $M_\infty\tau$ and γ.

Considering Eq. (6) further, with $\gamma = 1.4$ and the constant $a = 0.332$,

$$\frac{p_b}{p_\infty} \sim 1 - 1.525k_o(M_\infty\tau)^{2/5} \tag{7}$$

With $\tau \to 0$, we recover the flat-plate value. At the other limit, in the hypersonic approximation, $M_\infty\tau \to 1$, so that

$$\frac{p_b}{p_\infty} \sim 1 - 1.525k_o \tag{8}$$

From this relation, it would appear that within the hypersonic approximation, k_o would be restricted to values less than 0.655 (as otherwise p_b would reach the vacuum limit) rather than the range $0.61 \leq k_o \leq 0.80$ inferred by Messiter et al. [1], based on mainly supersonic experimental data. Using their lower limit, yields $p_b/p_\infty \sim 0.07$, a not an unrealistic value for high Mach number hypersonic base flows. On the other hand, Burgraff's [12] numerical value of $k_o = 0.73$ yields a some what unrealistic estimate of the base pressure. Therefore, for hypersonic flows, more realistically, $k_o \leq 0.655$. Experimental evidence seems to confirm this assumption, as will be shown in Sec. III.A. As Messiter et al. [1] state, it is difficult to correctly estimate the value of k_o throughout the Mach number range as it is primarily based on the correlation of a small range of supersonic experimental data.

B. Reattachment Distance

The reattachment distance behind the step is also a parameter of interest. From the knowledge of base pressure, it is possible to estimate this distance. Again, from Messiter et al. [1], the length of the shear layer to reattachment is given as

$$\frac{x_f}{L} \sim \frac{\gamma M_\infty^2\tau}{(M_\infty^2 - 1)^{1/2}}\left(1 - \frac{p_b}{p_\infty}\right)^{-1} \times \left\{1 - \frac{(M_\infty^2 - 2)^2 + \gamma M_\infty^4}{4\gamma M_\infty^2(M_\infty^2 - 1)}\left(1 - \frac{p_b}{p_\infty}\right)\right\} \tag{9}$$

The assumption made here is that the shear layer is thin and that the dividing streamline inclination is small, which would be approximately true for a small step height. In these circumstances, the reattachment distance would be approximately the same as the shear layer length. Then, if x_r is the reattachment distance, the above equation can be rewritten and simplified, after hypersonic approximation as discussed earlier,

$$\frac{x_r}{L} \sim \gamma M_\infty\tau\left\{\left(1 - \frac{p_b}{p_\infty}\right)^{-1} - \frac{(\gamma + 1)}{4\gamma}\right\} \tag{10}$$

which shows that the reattachment distance is dependent on $M_\infty\tau$, the base pressure, and γ. It also satisfies the hypersonic small-disturbance limits $0 \leq M_\infty\tau \leq 1$.

The above expression does not, however, indicate any dependence on wall cooling/heating, as the analysis is based on adiabatic wall assumption. While it is known that the base pressure is relatively insensitive to cooling/heating, there are some studies that indicate that in hypersonic flows, the reattachment distance is affected by wall cooling (Reeves and Lees [14] and Park et al. [15]). This aspect is examined further.

It has been pointed out by Cheng [10] that the standard triple-deck analysis, which assumes adiabatic wall and linear viscosity-temperature dependence, needs modifications in order to consider the effects of strong wall cooling in hypersonic flows when the wall temperature ratio $T_w/T_o \ll 1$. In Cheng [10] and also Brown et al. [16], this situation is termed *subcritical*. In subcritical flow conditions, the major effects in viscous dominated flows are associated with separation and reattachment. Brown et al. [16] analyze these effects on the basis that viscosity varies nonlinearly with temperature so that $\mu \sim T^{\omega}$, where ω is the temperature exponent with $1/2 \leq \omega \leq 1$. Particularly, for gases at high temperatures, $0.65 \leq \omega \leq 0.7$. Cheng [10] and Brown et al. [16] also state that a correction then needs to be made to the standard triple-deck based pressure-displacement relation. Brown et al. also state that in the subcritical range when $T_w \ll T_w^*$, where T_w^* is the critical wall temperature, the pressure-displacement relation becomes virtually independent of both Mach and Reynolds number but is primarily dependent on the wall temperature ratio T_w/T_o. For high Mach number hypersonic flows, typically, the critical wall temperature ratio T_w^*/T_o is of the order of 0.5 to 0.7 (depending on the value of γ), while the actual wall temperature ratios obtained in hypersonic short-duration facilities are usually much less. This will be discussed further in Sec. III.B in conjunction with experimental data.

The expression for T_w^*/T_o given by Cheng [10] and Brown et al. [16] is

$$\frac{T_w^*}{T_o} \sim \left[a^5 \gamma^{-1/2} \left(\frac{2}{\gamma - 1}\right)^2 \bar{\chi}\right]^{1/4\omega+2} \tag{11}$$

where $a = 0.332$ is the Blasius constant, $\bar{\chi}$ is the usual hypersonic interaction parameter of the flat plate and ω is the viscosity-temperature index defined above. It is seen that the critical wall temperature ratio is a function of the specific heat ratio γ.

It is thus evident that the adiabatic wall reattachment distance as calculated by Eq. (10) needs to be corrected for wall cooling.

There have been some studies (Nielsen et al. [17] and Gadd [18]) that show that the scale of separation bubble in laminar shock wave/boundary-layer interactions varies as $(T_w/T_o)^n$, where the index n varies between 1.0 and 1.5. Nielsen et al. [17] analysis shows that for a 60% reduction in wall temperature ratio (compared to the adiabatic value), the separation bubble length reduced by 30% and the temperature index n varied between 1.25 and 1.34 being inversely proportional to the wall temperature ratio. Further examination of their results shows n takes an asymptotic value of about 1.6 for very low values of wall temperature. This is not too far different from their statement that n varies between 1.0 and 1.5. Estimations based on this analysis and their comparison with experimental data are discussed in Sec. III.B.

III. Comparison with Experiment

A. Base Pressure

Figure 2 shows the base-pressure data for rearward-facing steps correlated in terms of $-P$ and $\Lambda^{2/5}$ as suggested by Messiter et al. [1]. The data cover moderate-to-high supersonic and hypersonic Mach numbers and cover data obtained in a range of facilities, from cold wind tunnels to hot facilities like shock tunnels and expansion tubes. The value of k_o obtained using a linear curve fit is 0.63 and accords with our discussion in Sec. II.A that $k_o \leq 0.655$. The expansion-tube data of Hayne [19] shown in the figure deviates somewhat due to large uncertainties in the measurement of base pressure. This data point represents an average 17 measurements. The experimental value of p_b/p_∞ so obtained is 0.075, which from Eq. (8) yields a value of $k_o = 0.606$, so within the limiting value $k_o \leq 0.655$. Numerical computations [20] in the separated region behind the step assuming both perfect and real gas flow for the same experimental conditions as in Hayne [19] yield a slightly better value. Figure 3 shows some of the available high supersonic and hypersonic Mach number data on base pressure behind steps. We note that the experimental data are all close to the theoretical line for $M_\infty \tau \sim 1$ except the data of Hayne [19] for the reasons stated above. As regards the data of Hama [21] and Shang and Korkegi [22], they were obtained with a step formed behind a wedge and that of Batt and Kubota [23] on the base of a wedge.

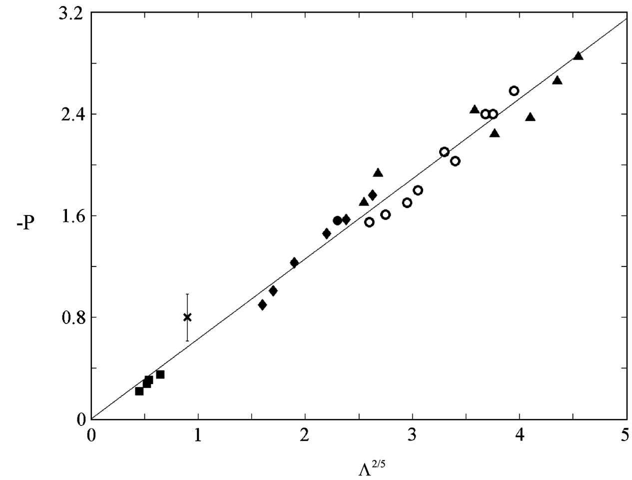

Fig. 2 Base pressure correlation (after Messiter et al. [1]). ◆, Chapman et al. [7]; ▲, Rom [25]; ○, Hama [21]; ■, Gai [24]; ×, Hayne [19]; ●, Shang and Korkegi [22]; and —, $-P = 0.63\Lambda^{2/5}$.

B. Reattachment Distance

Figure 4 shows the normalized reattachment distance x_r^* (x_r/h) of the separation bubble behind the step plotted against the parameter $(1 - p_b/p_\infty)^{-1}$. The data show results of hypersonic flow separation behind a step or a wedge from various authors. The closed symbols indicate experimental values, and the open ones indicate estimations based on the theory as discussed in Sec. II.B. It is seen that the theory consistently underestimates the experimental values, on average by about 30%. It is also interesting to note that in the case of Batt and Kubota data [23], while the experimental values of the reattachment distance for adiabatic and cold walls are the same, there is a small difference in the theoretical estimations. Similarly, in the case of Gai [24], where the experimental reattachment distance for the two wall temperature ratios of 0.07 and 0.0322 are nearly the same, the difference in the theoretical estimation is higher. However, in view of the various assumptions and approximations of the theory and uncertainties in some of the experimental data, the agreement can be considered fair.

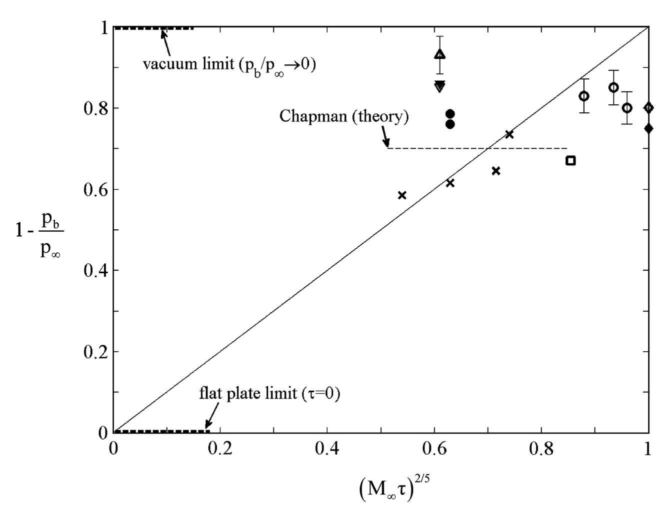

Fig. 3 Base pressure correlation in terms of hypersonic small-disturbance parameter. ○, Gai [24]; △, Hayne [19]; □, Shang and Korkegi [22]; ◇, Batt and Kubota [23]; ◆, Batt and Kubota [23] ($T_w/T_o = 0.19$); ●, Jakubowski and Lewis [26]; ×, Hama [21]; ▼, Deepak et al. [20] (perfect gas); and ▼, Deepak al. [20] (real gas).

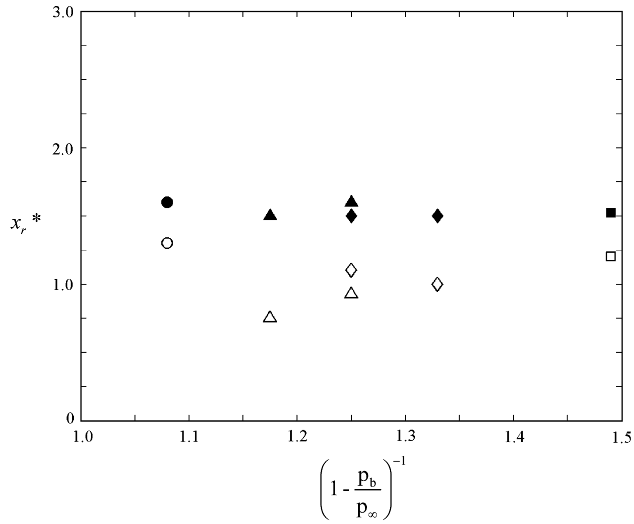

Fig. 4 Reattachment distance against base-pressure parameter $(1 - p_b/p_\infty)^{-1}$. ●, Hayne [19] ($T_w/T_o = 0.0265$); ▲, Gai [24] ($T_w/T_o = 0.0322, 0.07$); ◆, Batt and Kubota [23] ($T_w/T_o = 0.19, 1.0$); ■, Shang and Korkegi [22] ($T_w/T_o = 0.39$); and open symbols indicate theory.

IV. Conclusions

It is shown that within the framework of hypersonic small-disturbance theory, it is possible to extend the Messiter et al. [1] approach to hypersonic flows. The resulting expressions for the base pressure and reattachment distance show reasonable agreement with the limited experimental evidence available.

Acknowledgments

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