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Blowing from a Porous Cone with an Embedded Shock Wave

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Massive blowing from a porous cone in a supersonic flow is considered under the assumptions of inviscid, conical flow. The injection is assumed to be uniform, normal, and supersonic. This last assumption requires a straight shock wave in the injected flowfield. The numerically obtained solutions have two noteworthy features. First, the contact surface angle relative to the cone's axis decreases sharply when the embedded shock wave moves off the body. Second, it is possible to have a completely supersonic flow from the outer shock wave to the body, so that any upstream effect due to the presence of the cone's base is eliminated. Detailed solutions are presented and a model for the porous wall is used to relate the position of the embedded shock wave to freestream and plenum conditions.

Nomenclature

C_{pc} = contact surface pressure coefficient
M = Mach number, $q/(\gamma p \rho^{-1})^{1/2}$
$M_\perp$ = $M \sin(\phi - \eta)$
$\bar{M}_b$ = maximum value for M_b [see Eq. (8)]
p = pressure
P = p/p_b
q = flow velocity
R = universal gas constant
T = temperature
β = porosity
γ = (constant) ratio of specific heats
η = ray angle relative to the body
θ_b = body half angle
ρ = density
ϕ = flow inclination angle relative to the body
χ = blowing parameter [see Eq. (5)]

Subscripts

b = conditions on body surface
c = conditions at contact surface
s = embedded shock wave
0 = plenum conditions
1 = conditions ahead of the embedded shock wave
2 = conditions behind the embedded shock wave
∞ = freestream conditions

I. Introduction

In a previous Paper,[1] uniform, normal, subsonic injection of a perfect gas from a porous cone in a supersonic flow was examined in detail. (This type of flow was first proposed by Aroesty and Davis.[2]) The basic assumption was that the solution for the injected flowfield is inviscid and conical. This results in a straight contact surface and a Taylor-Maccoll flow exterior to the contact surface. Another assumption was that the injected flowfield is continuous, i.e., shock free. In this case, supersonic normal injection is not possible, because the injected flow curves in an upstream direction.

The idea of supersonic injection from a porous wall is a novel one. It was first predicted theoretically[3] for the flow downstream of a porous plate located transversely in a duct, and it was subsequently verified experimentally by Shreeve[4]. Supersonic injection (with an embedded shock wave) has also recently been observed[5] in the injected flow from a porous plate.

To remove the aforementioned difficulty with supersonic injection, it is necessary to have a shock wave in the injected flow. With a straight embedded shock, supersonic normal injection is indeed possible. This work extends the inviscid conical theory of Ref. 1 to include this situation.

A number of objections have been raised against the conical flow assumption. It is appropriate, therefore, to examine some of these objections. The first[6] was that the pressure at the vertex of the cone is multivalued both inside and outside the contact surface. Furthermore, since the flow inside the contact surface in Ref. 1 and in some of the cases treated here is subsonic, such a singularity in pressure is claimed to be not admissible.[6] However, this type of flow does occur, as demonstrated by the existence of subsonic Taylor-Maccoll flow.[7]

A second objection is that the upstream effect, caused by the base of a finite cone, violates the conical assumption. When some or all of the injected flow, or the outer Taylor-Maccoll flow, is subsonic this objection is only partially correct. In this situation the conical solution should hold close to the cone's tip, as it is known to hold for ordinary subsonic (or transonic) Taylor-Maccoll flow. With supersonic injection, however, it is possible to have a completely supersonic flow from the outer shock to the body, so that the upstream effect is eliminated. This paper discusses some of the conditions under which this type of flow might be attained.

Another objection is that the analysis in Ref. 1 and in this work yields contact surface angles larger than those found by Hartunian and Spencer.[8] In their experiments, the contact surface was located by the emission of a chemiluminescent reaction; the location of the freestream shock wave was not determined. These experiments, however, failed to satisfy

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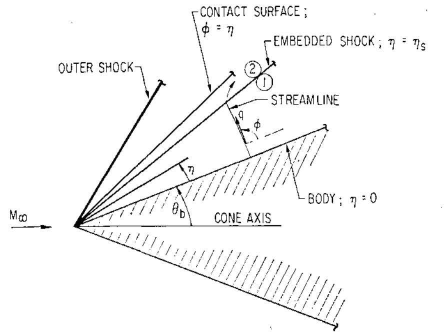

Fig. 1 Flow schematic.

the conical requirement of a freestream Mach number adequate to maintain an attached outer shock wave. Their freestream Mach number was 4.5, which, for a 10° half-angle cone, is well below that needed for an attached outer shock wave.[1] Furthermore, Bott[9] has shown their outer flow to be a low-density, low Reynolds number flow not subject to the inviscid analysis given here or in Ref. 1. Another difficulty with this, and apparently any cone-injection experiment, is the nonporous tip. The significance of this factor has not yet been evaluated. For these reasons, the experiments do not represent a test of the theory given here or in Ref. 1.

In a recent paper,[10] Inger and Gaitatzes present an excellent survey of the literature dealing with experimental and theoretical massive blowing investigations. For purposes of brevity, we will not repeat this material. As they point out, the only existing experimental results for massive blowing from a cone are those of Hartunian and Spencer,[8] which are inappropriate for this work. We stress this point because, in an otherwise cogent discussion that emphasizes the importance of viscous effects, Inger and Gaitatzes[10] dismiss inviscid flow models as failing to provide realistic solutions. They suggest that inviscid solutions are applicable only when the blowing is strong enough to cause a detached bow shock and a highly curved contact surface. In view of the total absence of relevant experimental evidence, it seems premature at this time to dismiss inviscid conical solutions.

II. Analysis

Injected Flow

It was shown in Ref. 1 that the inviscid equations of motion for a conical flow reduce to

$$\phi' = -\frac{\cos(\phi - \eta)}{1 - M_\perp^2}\frac{\sin(\phi + \theta_b)}{\sin(\eta + \theta_b)} \tag{1a}$$

$$(M^2)' = -\frac{2M^2[1 + (\gamma - 1)M^2/2]\sin(\phi - \eta)}{1 - M_\perp^2}\frac{\sin(\phi + \theta_b)}{\sin(\eta + \theta_b)} \tag{1b}$$

$$P = \frac{p}{p_b} = \left[\frac{1 + (\gamma - 1)M_b^2/2}{1 + (\gamma - 1)M^2/2}\right]^{\gamma/(\gamma-1)} \tag{2}$$

where the prime indicates differentiation with respect to η and Eq. (2) is the isentropic relation for the pressure. The radian angles θ_b, ϕ, and η are defined in Fig. 1, and the component of the Mach number normal to a ray is given by $M_\perp = M\sin(\phi - \eta)$. All other quantities have their usual meaning and are defined in the Nomenclature. Initial values for Eqs. (1) are given on the body, where $\eta = 0$, as $\phi = \pi/2$ and $M = M_b$. The tangency condition, which terminates the injected flow thereby defining the contact surface, is $\phi = \eta$. The pressure of the exterior flow must also equal the injected flow pressure on the contact surface. This condition is treated later. It should be noted that the freestream and injected flows may have different ratios of specific heats and different stagnation temperatures.

Conditions across the embedded shock, located on ray η_s, are related by

$$\tan(\phi_2 - \eta_s) = \frac{(\gamma - 1)M_{\perp 1}^2 + 2}{(\gamma + 1)M_{\perp 1}^2}\tan(\phi_1 - \eta_s) \tag{3a}$$

$$M_2^2 = \frac{(\gamma - 1)M_{\perp 1}^2 + 2}{2\gamma M_{\perp 1}^2 - (\gamma - 1)} + \frac{(\gamma + 1)^2 M_{\perp 1}^4 \cot^2(\phi_1 - \eta_s)}{[(\gamma - 1)M_{\perp 1}^2 + 2][2\gamma M_{\perp 1}^2 - (\gamma - 1)]} \tag{3b}$$

$$p_2/p_1 = [2\gamma M_{\perp 1}^2 - (\gamma - 1)]/(\gamma + 1) \tag{3c}$$

where subscripts 1 and 2 refer to conditions ahead of and behind the shock, respectively.

When $M_b > 1$, the Mach number and flow inclination angle ϕ increase as η increases. The quantity $\phi - \eta$, however, decreases as η increases. Therefore, at the embedded shock, $\phi_2 - \eta_s \leq \phi_1 - \eta_s \leq \pi/2$, and the flow downstream of the shock is moving away from the cone's tip. The equal signs apply only when the shock is on the body, in which case it is a normal shock with $\eta_s = 0$ and $(\ )_1 \equiv (\ )_b$.

One purpose of this study was to determine if it is possible for $M_2 > 1$ when $M_b > 1$. The flow is thus supersonic between the body and the contact surface, and under most conditions the flow between the outer shock and the contact surface is also supersonic. The upstream effect is thus eliminated. A detailed examination of Eq. (3b) when η_s is small, say less than 15°, reveals that M_2 is always less than unity, except in one limit. This limit requires $(\gamma - 1) \ll 1$ and $M_{\perp 1}^2 \gg 1$. It stems from the following considerations. The first term on the right side of (3b) is the normal shock value for M_2 and is thus always smaller than unity. In the second term, $\phi_1 - \eta_s$ is smaller but not too different from $\pi/2$, and hence $\cot^2(\phi_1 - \eta_s)$ is small. The previous limit is required if the smallness of this factor is to be overcome. Since this limit is quite difficult to achieve in practice, we do not further consider it. When η_s is large, say 30°, a supersonic value for M_2 is attained, and the upstream effect can be eliminated.

There is an important distinction between the $M_b < 1$ and $M_b > 1$ conditions. When $M_b < 1$, the injected flow solution is straightforward.[1] A knowledge of γ_∞, p_∞, and M_∞ then determines p_b by matching the injected and freestream pressures on the contact surface. An additional unknown parameter, the location η_s of the embedded shock, occurs when $M_b > 1$. With values for both M_b and η_s, the injected flowfield can be determined, again in a straightforward manner, by means of Eqs. (1–3). A knowledge of γ_∞, p_∞, and M_∞ then determines p_b as before. The numerically obtained solutions, given later, thus may be regarded as stemming from arbitrarily chosen values for M_b and η_s.

Porous Wall Model

To remove partially the foregoing arbitrariness, i.e., the need to specify both M_b and η_s, a model was chosen for the flow in the cone's porous wall. This model[3] assumes steady flow through a wall of uniform thickness and porosity β. (The porosity of the wall is the ratio of the cross-sectional area available to the flow to the total cross-sectional area.) A primary reason for this particular choice is that it is applicable to the type of experiment previously performed by Hartunian and Spencer.[8] In addition to the porous wall model, we also make the weak-shock assumption. In other words, if two or more embedded shock locations are possible, the one yielding the weakest shock is chosen. Note that the weak shock assumption and a given value for M_b, without the porous wall model, do not determine η_s.

We assume the gaseous flow through the porous wall is adiabatic and that choking occurs in the wall. Conditions on the outer surface of the cone can be related to cone plenum conditions by means of the Fanno curve equation[3]

$$(p_b/p_\infty)M_b\{1 + [(\gamma - 1)/2]M_b^2\}^{1/2} = \chi \tag{4}$$

$$\chi \equiv (p_0/p_\infty)M_0 = (RT_0/\gamma)^{1/2}\rho_0 q_0/p_\infty \tag{5}$$

where the zero subscript designates plenum conditions, and $\rho_0 q_0 = \rho_b q_b$ is the mass flux through a unit area of porous wall. The approximation $1 + [(\gamma - 1)M_0^2/2] \cong 1$ has been used in the derivation of Eq. (4). In this work, the choice of dimensionless parameters is motivated by what is experimentally determinable, such as χ, or what is of physical interest, such as p_b/p_∞. The blowing parameter χ is similar to one previously used by Bott.[9]

Flow Regimes

To see how Eq. (4) fits in with Eqs. (1–3), let us suppose that we know γ_∞, M_∞, θ_b, γ, and χ. Three flow regimes are then possible.

Regime 1: $M_b < 1$

This regime was considered in Ref. 1, where it was shown that the contact surface angle relative to the cone axis, $\phi_c + \theta_b$, depends only weakly on M_b. A value for M_b is first assumed and the injected flowfield determined. With γ_∞, M_∞, and now $\phi_c + \theta_b$ known, the pressure coefficient

$$C_{pc} \equiv \frac{p_c - p_\infty}{\rho_\infty q_\infty^2/2} = \frac{(p_b/p_\infty)P_c - 1}{\gamma_\infty M_\infty^2/2} \tag{6}$$

can be found from standard cone solutions, e.g., Ref. 11, or approximately by Rasmussen's[12] formula as modified by Wittliff.[13] (This modified formula is appropriate to this work, since it is accurate for large values of $\phi_c + \theta_b$. For example, when $\gamma_\infty = 1.405$, $M_\infty = 10$, and $\phi_c + \theta_b = 55.25°$, it is in error by only 5%.) Equation (6) plus Eq. (2) with $M = M_1$ thus provides p_b/p_∞, which is then compared with p_b/p_∞ given by Eq. (4). The correct solution can be found by iteration on M_b, providing $M_b < 1$. Furthermore, the solution appears to be unique. This conclusion is based on the fact that the results for p_b/p_∞ vs. M_b^2 in Table 1 of Ref. 1 can intersect Eq. (4) only once. If the iteration doesn't converge, then $M_b > 1$ and we have either Regime 2 or Regime 3.

The situation near the wall when $M_b = 1$ is quite similar to that near the throat in nozzle flow. Two injected flow solutions are possible; one solution is subsonic, the other supersonic. (An approximate formula is given in Ref. 14 for the subsonic case that relates χ to $\gamma_\infty M_\infty^2 C_{pc}/2$.) As in the flow at the throat of a nozzle, Eq. (1a) is singular at the wall when $M_b = 1$.

Regime 2: $M_b > 1$ and $\eta_s = 0$

For sufficiently small values of p_b/p_∞, Eq. (4) predicts $M_b > 1$. The basis for choosing the shock to be on the body is that this location yields the weakest discontinuity. This is shown by the relation, which is derived from Eqs. (1) and (2),

$$(M_\perp^2)_b' = \frac{2M_b^2[1 + (\gamma - 1)M_b^2/2]}{M_b^2 - 1}\cot\theta_b$$

Since $(M_\perp^2)_b' > 0$, the shock wave strengthens as it lifts off the body. By considering the equation for $(M_\perp^2)'$, one can also show that as the shock moves away from the body it continues to strengthen until a maximum strength is reached at about $\eta_s \cong 30°$. After the maximum, the shock strength declines slowly such that even at $\eta_s = 50°$ it is still well above its $\eta_s = 0$ value. The idea of a surface shock wave is not new. It was first introduced by Martin[15] in a different context.

Table 1 Maximum value of $\bar{M}_b^2$ vs β

β	0.3	0.4	0.5
$\bar{M}_b^2$	7.558	5.965	4.830

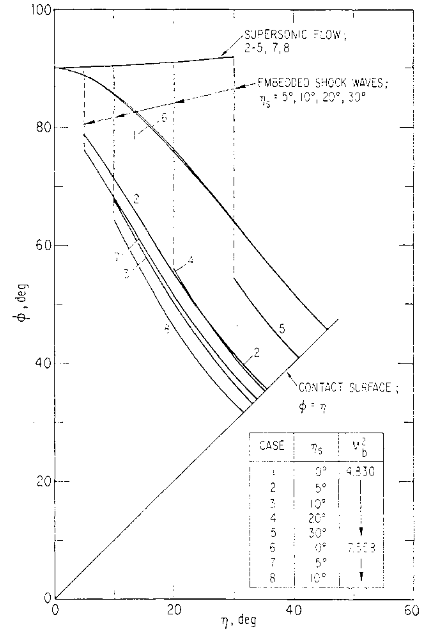

Fig. 2 Flow inclination angle vs ray angle.

With the shock wave adjacent to the body this regime is nearly identical to Regime 1, since $M_2 < 1$. Only the pressure is different. This is reflected in Eq. (6), which now reads

$$C_{pc} = [(p_b/p_\infty)(p_2/p_1)(p_c/p_2) - 1]/(\gamma_\infty M_\infty^2/2) \tag{7}$$

where p_2/p_1 is given by Eq. (3c) with $M_{\perp 1} = M_b$, and p_c/p_2 is given by Eq. (2) with $M = M_c$ and M_b replaced by M_2. For example, if $M_b^2 = 2.2$ and $\gamma = 1.4$, then $M_2^2 = 0.5$ and a comparison can be made with case 1 in Ref. 1, where $M_b^2 = 0.5$, $\theta_b = 10°$, $\gamma_\infty = 1.405$, $M_\infty = 10$, and $C_{pc} = 1.49$, from Ref. 11. For both cases $\phi_c + \theta_b = 55.25°$, but case 1 in Ref. 1 yields $(p_b/p_\infty) = 76.7$, whereas Regime 2 yields $(p_b/p_\infty) = 31.4$.

Reference 3 predicts a maximum value for M_b, denoted here by $\bar{M}_b$, which occurs when the injected flow isentropically negotiates the rapid area change as it leaves the porous wall. It is given by[3]

$$(\bar{M}_b^2)/[1 + (\gamma - 1)\bar{M}_b^2/2]^{(\gamma+1)/(\gamma-1)} = [[2/(\gamma + 1)]^{(\gamma+1)/(\gamma-1)}\beta^2 \tag{8}$$

With $\gamma = 1.4$, Table 1 shows the dependence of $\bar{M}_b^2$ on the porosity β. (An approximate formula is given in Ref. 14 for χ when $M_b = \bar{M}_b$ and $\eta_s = 0$.) Values of p_b/p_∞ smaller than the one that occurs when $M_b = \bar{M}_b$ and $\eta_s = 0$ require the shock to lift off the body, which leads us to Regime 3.

Regime 3: $M_b = \bar{M}$ and $\eta_s > 0$

In this regime, Eq. (4) yields a definite value for p_b/p_∞ that must agree with that given by

$$C_{pc} = [(p_b/p_\infty)(p_1/p_b)(p_2/p_1)(p_c/p_2) - 1](\gamma_\infty M_\infty^2/2) \tag{9}$$

Agreement is achieved by iteration on η_s.

As will be shown, this regime differs markedly from the other two, since as η_s increases, $\phi_c + \theta_b$ at first sharply decreases. This has the important effect of reducing the minimum value of the freestream Mach number necessary for an attached outer shock wave.

III. Results

For the injected flow, Figs. 2–4 show ϕ, P, and M^2 vs η for a variety of conditions listed in the insert in Fig. 2.

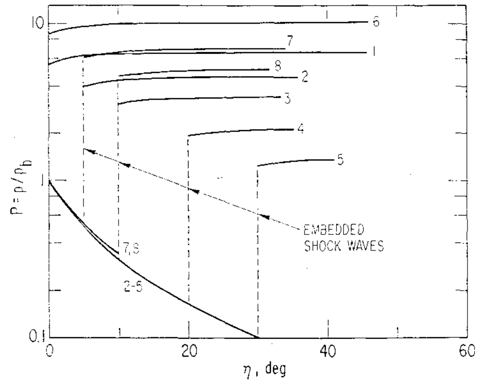

Fig. 3 Pressure ratio p/p_b vs ray angle.

For all cases, $\gamma = 1.4$ and $\theta_b = 10°$, and β is 0.5 when $M_b^2 = 4.830$ and is 0.3 when $M_b^2 = 7.558$. Note that the shock is on the body in cases 1 and 6.

By comparing cases 1 and 2 or 6 and 7 in Fig. 2, we see that ϕ_c decreases sharply as η_s increases from 0. As η_s continues to increase a minimum value is achieved for ϕ_c as approximately exemplified by case 3. Even for a 30° shock wave (case 5), ϕ_c is still less than when the shock is on the body (case 1). Cases 1 and 6, which are similar to those in Ref. 1, again demonstrate the insensitivity of ϕ to the injection Mach number M_b when $\eta_s = 0$.

By comparing cases 1–5 or cases 6–8 in Fig. 3, we find that p_c/p_b decreases as η_s increases. This decrease in p_c/p_b is due to the even faster decrease in p_1/p_b as η_s increases. The rapid decrease in pressure between the body and the shock is due, of course, to the increase with η in cross-sectional area available to the flow. Although the shock wave strengthens as η_s increases from 0° to 30°, the decrease in p_1/p_b more than offsets this.

Figure 4 shows that, as η_s increases, the angular extent of the flow between the embedded shock and contact surface decreases and the Mach number of the flow increases. For case 5, this flow is supersonic, and with $\gamma_\infty = 1.405$, the minimum freestream Mach number for an attached outer shock is 3.4, while the minimum freestream Mach number for purely supersonic flow between the outer shock and the contact surface is 4.5.[11] Thus, if $M_\infty \geq 4.5$, case 5 represents a solution with no upstream effect for a finite cone.

It is instructive to determine p_b/p_∞, as was done in Ref. 1, by setting $\gamma_\infty = 1.405$ and $M_\infty = 10$ and using Ref. 11 for C_{pc}. With the assistance of Eq. (7) or (9), we thus obtain Table 2.

When $M_b^2 = 7.558$ (cases 6–8), we see that p_b/p_∞ has a minimum value of 10.05 at $\eta_s = 2.5$,° as shown by Table 2 and by additional calculations. Two shock locations, both of which are within 6° of the body, seem to be possible when $(p_b/p_\infty) \leq 10.60$. To further examine this situation, let us

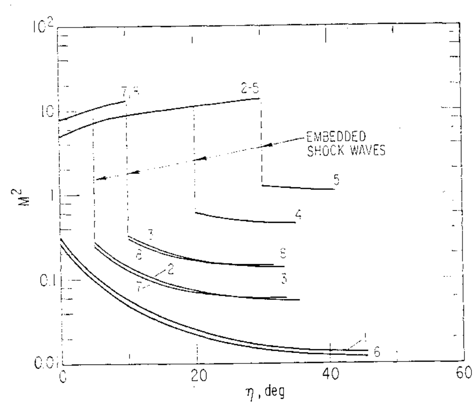

Fig. 4 Mach number vs ray angle.

Table 2 Pressure ratio p_b/p_∞ and χ vs η_s when $\gamma_\infty = 1.405$ and $M_\infty = 10$

Case	1	2	3	4	5	6	7	8
η_s, deg	0	5	10	20	30	0	5	10
p_b/p_∞	16.1	16.7	20.4	35.7	68.4	10.60	10.58	13.10
χ	49.7	51.5	63.0	110	211	46.3	46.2	57.1

consider all freestream and plenum conditions fixed, except for $(\rho q)_0$. When the flow is in regime 3, hence $M_b = \bar{M}_b$, Eqs. (4) and (5) require p_b/p_∞ to increase when $(\rho q)_0$ increases. (The discussion here should not be confused with that pertaining to the three regimes, where χ was fixed.) We also expect η_s to increase. It thus appears that the shock jumps abruptly from the body to $\eta_s \cong 5°$ when $(\rho q)_0$ increases slightly above its value for $M_b = \bar{M}_b$ and $\eta_s = 0$. A further increase in $(\rho q)_0$ moves the embedded shock outward in a continuous manner. A minimum for p_b/p_∞ of 15.8, at approximately $\eta_s = 2°$, also occurs for $M_b^2 = 4.830$ (cases 1–5). Numerous calculations performed with $M_b^2 = 2$ (not shown here), however, did not produce a minimum. The abrupt jump in the shock location would not occur in this instance.

Table 2 also lists the blowing parameter χ. It is apparent that a large χ is required for a purely supersonic flow (case 5). In terms of a more conventional momentum parameter $(\rho q^2)_b/(\rho q^2)_\infty = (\gamma p M^2)_b/(\gamma p M^2)_\infty$ the 8 cases range in value from 0.77 (case 1) to 3.29 (case 5).

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