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On Forward Ejection for Thermal Insulation in Hypersonic Flight

by

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ON FORWARD EJECTION FOR THERMAL INSULATION IN HYPERSONIC FLIGHT

by

M. G. Hall, Ph.D.

SUMMARY

A review is presented of recent work on the flow from a single forward-facing orifice in a supersonic or hypersonic stream. The particular aspect of this work discussed here is how to shape the profile of the orifice and the body so that the ejected gas remains attached to the body and thus envelops it in a smooth layer which can be used to reduce heat transfer to the body surface. Dissipative effects are neglected, except across the detached shock wave. The review begins with a more specific formulation of the problem, made with the help of some detailed experimental observations by Tucker. Then accounts are given of Eminton's method for constant-pressure profiles in plane flow, and of the theoretical and experimental work of Baron and Alzner on axially symmetric bodies. The results are discussed and it is concluded that while the aim has in some cases been achieved a reliable method of design does not yet exist. Some suggestions for further work are made.

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ILLUSTRATIONS

1 INTRODUCTION

Before hypersonic flight in the atmosphere can be sustained some method must be found for protecting the surface and especially the nose and the leading edges of the vehicle from over-heating. Ablation and heat-sink techniques are well suited to cases where the heating is of short duration, as in re-entry flight. To reduce aerodynamic heating in sustained flight, attention has been given among others to methods of placing and maintaining a layer of gas over the critical parts of the surface: by distributed transpiration through a porous surface or, alternatively, by forward ejection from a shaped orifice. More attention has been given, hitherto, to the former method, where the difficulties are chiefly mechanical, but the mechanical simplicity of the latter has led some to tackle its aerodynamic difficulties. This aerodynamic problem, namely the design and performance of the orifice-body combination, is the subject of the present review.

The earlier experiments on the ejection of a gas from the nose of a blunt body in a hypersonic stream, by McMahon[5] and by Warren[6], were mainly exploratory. No serious attempt to shape the orifice was made. Separation or large-scale mixing occurred except at the smallest ejection rates, and no appreciable reduction of the overall heat transfer was obtained. The nature of the problem had not been fully recognised but the work inspired new efforts and recently some positive results have been obtained. Lam[2] and Eminton[3] have calculated a family of two-dimensional orifice-body profiles which have constant pressure over the curved part of the profile. Because Eminton's work is more general, the discussion will be confined to her results. For the calculation it is assumed that the flow between the interface and the orifice is incompressible. The resulting pressure distribution along the interface approximates that due to a hypersonic flow. Baron and Alzner[4] have tested a family of axially symmetric bodies with profiles based on approximate incompressible solutions for a hemispherical body in a hypersonic stream. And Tucker[1] has made more detailed experimental observations of a set of axially symmetric bodies with surfaces generated from Eminton's two-dimensional profiles. In both experiments, cases of attached flow were obtained for a range of ejected mass flows.

A common feature of the above more recent work is the consideration of the flow in the vicinity of the orifice in isolation from the remainder of the fluid. Moreover, although the main aim is to obtain a flow field which substantially reduces the heat transfer to the surface, heat transfer itself is not considered. Finally, while the layer of ejected gas offers a means of obtaining a suitable fuel-air mixture required for combustion and also a means of reducing the drag of the aircraft, mixing and viscous effects and drag reduction are not investigated.

This review begins with a more specific formulation of the problem, made with the help of the detailed flow observations of Tucker[1]. This is followed by accounts of Eminton's method[3] for constant-pressure profiles, and of the theoretical and experimental work of Baron and Alzner[4] on axially symmetric bodies. The assumptions, the analyses and the experimental results will be summarized and some of the shortcomings will be discussed.

2 A FORMULATION OF THE PROBLEM

A sketch of the desired flow field is shown in Fig.1. It features a uniform hypersonic flow upstream, a curved detached bow shock-wave, an ejected gas stream, a distinct regular interface and a shaped orifice-body. The chief requirement is that the ejected gas follows the surface without separation, turning to envelop the body so that the oncoming stream has no contact with the surface. For a two-dimensional or axially-symmetric body there will be a free, detached, stagnation point on the interface. Thus an obvious operating condition is that the total pressure of the ejected gas (on the stagnation streamline) equal the total pressure of the oncoming flow on the stagnation streamline downstream of the shock. Since the oncoming flow is hypersonic the flow downstream of the normal part of the shock will be at a low subsonic speed, and it is plausible to regard that flow, and the adjoining ejected flow, as incompressible.

Fig.2(a) is a typical shadowgraph due to Tucker[1], of the flow described above. Tucker constructed his axially symmetric models by the simple expedient of rotating theoretical two-dimensional profiles of Eminton[3], so his observations cannot be quantitatively related to the theory. Nevertheless, the observations are instructive. The orifice cannot, of course, be seen, but the interface is distinct*. In Fig.3 is shown the corresponding measured distribution of static pressure around the profile. The station at which the ejected flow reaches sonic velocity, as calculated by assuming isentropic flow, is marked S. Also shown are pressure distributions for zero ejection rate and for a mass flow so large that separation of the ejected gas and serious distortion of the bow shock occur. This breakdown of the ejected stream is shown in the shadowgraph of Fig.2(b). Note that where the desired flow is obtained the pressure gradient around the profile is nearly zero or favourable but there is a strong adverse pressure gradient in the undesirable flow. The shadowgraph 2(b) shows the adverse pressure gradient to be associated with separation and extraneous shock waves. Note also that in the desired flow the sonic point is reached only after the ejected gas has turned through about 130° whilst in the undesirable flow the sonic point lies well up the orifice, before the ejected gas has turned at all.

The experimental evidence suggests that two conditions should be aimed at in the design of the profile. First, the shape should be such that adverse pressure gradients on the surface are avoided. This would ensure that the ejected gas does not separate and would minimize the risk of large-scale mixing with the oncoming flow. It is possible that the interface is unstable and unsteady but there has not yet been any experimental evidence (with only small density differences across the interface) of such an instability at supersonic speeds. Secondly, and related to the first condition, most of the turning of the ejected gas should be accomplished subsonically, to minimize the risk of over-expansion, which would be followed by compression, extraneous shock waves, and possibly by separation.

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* The ejection rate here is about 25 times the value at which Warren's ejected flow became detached[6], in terms of Warren's mass-flow coefficient.

It is not easy but nevertheless possible to satisfy the above conditions. The existence of a stagnation point on the interface implies that adverse pressure gradients must exist within the ejected flow, close to where they are required to be favourable. This is illustrated in Fig.4, which shows lines of constant pressure (or velocity) and velocity vectors, for one of Eminton's profiles. Note that the curved part of the body is an isobaric surface. Since, in the real flow, the pressure must be continuous across the interface, the ejected gas must accelerate at some stage to supersonic speeds. It might be assumed, as Eminton[3] and Baron and Alzner[4] have done, that both the ejected flow and the flow downstream of the shock are incompressible. The argument is that there will be a limited region where the assumption is valid, and that if the resulting theoretical pressure distribution along the interface in this limited region approximates the actual distribution the method will be justified.

Another simplifying assumption, made by Eminton[3] and by Baron and Alzner[4], is that viscous effects and mixing are negligible. The limited experimental evidence shows that this is not justified for the ejected flow as a whole: an application[1] of the conservation laws to the problem of thrust recovery with forward ejection yields recovery values for inviscid flow that are appreciably larger than the measured ones. However, in the limited region near the orifice, and for the purpose of designing the shape of the curved wall, possible viscous displacement effects are the main concern, and it may be assumed that here, where the wall is highly curved and pressure forces are large, viscous displacement effects along the wall and along the interfaces will be negligible, to a first approximation.

It is worth noting that if a satisfactory inviscid and incompressible solution for the ejected flow is found, the solution will in principle suffice for any ejected gas no matter what the density. This can be deduced from the equations of motion and the condition of continuity of pressure across the interface. For a given free stream, and a given body, flow similarity will be maintained with different ejected gases simply by keeping $\rho_j v_j^2$ constant, where v_j is some characteristic velocity of the ejected gas and ρ_j is its density. In practice, this generalization may fail, if much mixing across the interface occurs or if the interface becomes unstable, for the interface will be a vortex sheet when there is a difference of density across it.

It is also worth noting the close relation between ejection from a two-dimensional profile and ejection from an infinitely long swept leading-edge, a case of obvious importance. As is usual in such cases, two-dimensional flow is assumed in the plane normal to the leading edge. Thus Eminton's method, and her results, apply equally to both swept and unswept leading-edges. An important physical difference in the swept case is that only the components of flow normal to the leading-edge are brought to rest. Although the problem is still essentially two-dimensional, another parameter is at one's disposal: the component of ejected flow parallel to the leading edge.

3 THE METHOD OF EMINTON[3] FOR CONSTANT-PRESSURE PROFILES

Eminton replaces the flow field of Fig.1 by one in which the flow on each side of the interface is incompressible and inviscid, the bold approach noted in Section 2 above. She considers the irrotational two-dimensional flow about a symmetrical orifice-body which is to be shaped so that the pressure on the curved part of the profile is constant. The condition that the pressure at the resulting interface should be that of a body in hypersonic flow is not satisfied specifically, but the analysis is carried out on the hypothesis that the condition will be satisfied approximately in some of the solutions (as it is). To avoid separation a body shape with constant or falling pressure must be found. The two-dimensional problem for a body with constant pressure (or constant velocity) is readily solved by the hodograph method; the corresponding problem in axially symmetric flow cannot be solved with comparable ease.

In the usual manner, a complex velocity ζ and a complex potential ω are introduced, which are analytic functions of the complex variable z, related by

$$\frac{d\omega}{dz} = \zeta . \quad (1)$$

The prescribed quantities are the free-stream velocity v_∞, the initial velocity of the gas to be ejected far upstream in the orifice v_j, and the (constant) speed v_m of the ejected gas as it rounds the profile (in Lam's work[2], $v_m = v_\infty$). From there the essential features of the flow in the ζ or hodograph plane are constructed, and the complex potential at a point ζ is written down:

$$\omega = - m \log(\zeta + v_j) + m \log(\zeta - v_\infty) - \mu(\zeta - v_\infty)^{-1}$$
$$- m \log(v_m^2/\zeta + v_j) + m \log(v_m^2/\zeta - v_\infty) - \mu(v_m^2/\zeta - v_\infty)^{-1} . \quad \ldots (2)$$

The terms on the right-hand side are due, respectively, to a source of strength m at $\zeta = -v_j$, a sink of equal strength at $\zeta = v_\infty$ (the final state of the ejected gas), a doublet of strength $-\mu$ at $\zeta = v_\infty$ (the far free-stream) and such other singularities outside the circle of radius v_m as make the circle a streamline. Since the origin in the hodograph plane is a stagnation point in the hodograph flow, the doublet strength μ and the source strength m are related, from equation (2), by

$$\mu = \left[(v_\infty + v_j)(v_\infty v_j + v_m^2) v_\infty / \{(v_m^2 - v_\infty^2) v_j\} \right] m, \quad (3)$$

and m is related to the initial width 2h of the orifice by

$$m = h v_j / \pi . \quad (4)$$

From equations (1) and (2), and making use of (3),

$$z = -\frac{m}{v_j}\log(\zeta + v_j) - \frac{v_\infty m - \mu}{v_\infty^2}\log(\zeta - v_\infty) + \frac{\mu}{v_\infty}(\zeta - v_\infty)^{-1}$$

$$-\frac{m\,v_j}{v_m^2}\log(\zeta + v_m^2/v_j) - \frac{v_\infty m + \mu}{v_m^2}\log(\zeta - v_m^2/v_\infty) - \mu(v_\infty\zeta - v_m^2)^{-1}$$

$$+ \text{ a constant.} \qquad (5)$$

Equations (2) and (5) enable z and ω to be evaluated from chosen values of the velocity ζ. Thus, to find the shape of a profile, choose $\zeta = v_m e^{i\theta}$ and evaluate z for $0 \leqslant \theta \leqslant \pi$. The shape depends only on the ratios $v_\infty : v_j : v_m$ or v_∞/v_m and v_j/v_m, with h as a scaling factor.

Eminton concludes by showing how the incompressible results may be adapted to the hypersonic problem. If the pressure p at the interface can be approximated by the modified-Newtonian relation

$$\frac{p - p_\infty}{p_s - p_\infty} = \cos^2\theta , \qquad (6)$$

where p_∞ is the pressure of the hypersonic free-stream, p_s is the pressure at the stagnation point and θ is the angle between the normal to the surface and the free-stream direction, the velocity of an incompressible ejected gas along the interface would be given by

$$v = \left[2(p_s - p_\infty)/\rho_j\right]^{\frac{1}{2}} \sin\theta . \qquad (7)$$

In the hodograph plane this represents a circle through the origin with its centre on the axis of symmetry. Now, for many combinations of v_∞/v_m and v_j/v_m the theoretical interface in the hodograph plane does in fact approximate to the above and has a diameter of, say, k. Hence, by identifying the two,

$$\frac{\rho_j\, v_j^2}{\rho_\infty V_\infty^2} = \frac{p_s - p_\infty}{\frac{1}{2}\rho_\infty V_\infty^2}\left(\frac{v_j/v_m}{k}\right)^2 , \qquad (8)$$

where ρ_∞ and V_∞ ($\div v_\infty$) are the density and velocity of the hypersonic free-stream. This is a relation between the momentum flux coefficient of the ejected gas, a free-stream pressure coefficient and a parameter $(v_j/v_m)/k$ related to the shape of the profile. For a given profile in a given hypersonic stream the right-hand side will be fixed. Then, if the rate of ejection is set so that the left-hand side balances the right, and the assumptions are justified, the pressure around the curve of the profile will be approximately constant. A selection of Eminton's profiles is presented in Fig.5. Each is identified by the values of v_∞/v_m and v_j/v_m assigned to it. The approximate value of the diameter k is also given. Only the part of the profile shape which is of interest in the present context has been drawn.

The main doubts about the method concern the assumption of incompressible flow and the neglect of the boundary layer displacement thickness along the wall and of mixing across the interface. These are not easily resolved. An extension of the method to include viscous effects of two different gases would be very valuable. For a direct experimental test of the method, a test of two-dimensional models at hypersonic speeds would be desirable. No tests in hypersonic wind-tunnels have so far been reported.

4 THE WORK OF BARON AND ALZNER[4] ON AXIALLY SYMMETRIC BODIES

Like Eminton, Baron and Alzner replace the flow field of Fig.1 by an incompressible one, but they use a solution previously obtained by Martin[7] for an axially symmetric closed body and construct profiles by following the theoretical stream surfaces inside this body. They place each model in a wind-tunnel with a free-stream Mach number of 4.3 and take shadowgraphs for a range of mass flows.

Martin's solution[7] is intended for the hypersonic flow past a hemispherically blunt body. He assumes that the shock wave is also hemispherical, concentric with the body surface, and that the density downstream of the shock is constant. Diffusion effects are neglected, but vorticity is admitted. This enables him to obtain a solution in closed form for the flow between the shock and the body, by approximately integrating the momentum equations and satisfying the continuity equation and appropriate boundary conditions at the shock and at the body surface. A stream function ψ is used, defined by

$$\left.\begin{aligned} \frac{\partial\psi}{\partial r} &= \rho\, v_r\, r \sin\theta \\ \frac{1}{r}\,\frac{\partial\psi}{\partial\theta} &= -\rho\, v_\theta\, r \sin\theta \end{aligned}\right\} \qquad (9)$$

where r, θ are spherical polar coordinates (Fig.6) with θ measured from the axis of symmetry, and v_r and v_θ denote the corresponding velocity components. A solution of the form

$$\psi = \frac{\rho_\infty V_\infty}{r_o^2} \sin^2 \theta \; f(r), \tag{10}$$

is assumed, and it is shown that

$$f(r) = A(r/r_o)^4 + B(r/r_o)^2 + C(r/r_o)^{-1}, \tag{11}$$

with

$$A = \frac{1}{10}\left[\left(\frac{\rho}{\rho_\infty}\right)^2 - \frac{2\rho}{\rho_\infty} + 1\right]\left(\frac{r_w}{r_o}\right)^{-2}$$

$$B = -\frac{1}{6}\left[\left(\frac{\rho}{\rho_\infty}\right)^2 - \frac{4\rho}{\rho_\infty}\right]$$

$$C = \frac{1}{15}\left[\left(\frac{\rho}{\rho_\infty}\right)^2 - \frac{7\rho}{\rho_\infty} + 6\right]\left(\frac{r_w}{r_o}\right)^3$$

$$r = r_o \text{ on body}, \quad r = r_w \text{ on shock},$$

and where r_w/r_o is given by the condition $\psi = 0$, where $r = r_o$, that is, by the equation $A + B + C = 0$.

Baron and Alzner[4] apply the above solution to the region $r < r_o$, that is to say, to the continuation of Martin's flow inside the body. They take the former body surface, $r = r_o$, now to be the interface between an ejected gas and the oncoming stream, and regard the family of stream surfaces in $r < r_o$, defined by assigning positive values to ψ in equation (10), as a family of body profiles. This continuation of Martin's solution cannot strictly be defended, because the flow between the shock and the interface has a vorticity derived from the curvature of the shock, and the vorticity of the ejected flow bears no relation to this. However, at the interface itself the theoretical vorticity is zero so, provided the vorticity of the ejected flow is not appreciable, a limited amount of continuation might be acceptable. A more serious shortcoming is the need to fair the profiles into parallel ducts as shown in Fig.6, departing from the theoretical surfaces because these all start from a "point source" and give infinite velocity at the origin and sonic conditions at about a quarter radius from the stagnation point.

The ejected mass flow Q is calculated by relating the mass flow through a circular stream tube upstream of the shock to the stream function and assuming that the same relation holds for the ejected flow. The validity of the continuation is taken for granted. The result is

$$Q = \frac{\pi}{f(r_s)} \left(\frac{r_s}{r_o}\right)^2 \psi . \tag{12}$$

Four ejection models were constructed by taking the available combinations of two diameters (1.2 inches and 0.8 inches) and two design mass flows ($Q/(\rho_\infty V_\infty \pi r_o^2)$ equal to 0.014 and 0.028). For each a set of shadowgraphs were taken, covering the range of mass flows from zero to past the design value. The shadowgraphs presented for the model 1.2/0.028 show physical features similar to those of Fig.2. The results are more significant than Tucker's, however, in the sense that the interface detachment distance could be measured and indeed reached the design value at the design mass flow; serious flow separation occurred when the design mass flow was exceeded. The interface then became irregular and the shock became appreciably distorted. Tucker's observations had no such theoretical counterpart. All the other models also showed smoothly attached flow for lower mass flows, but the above breakdown occurred before the design mass flow was reached at values from at most 90% to at most 70% of the design value. The objective of relating flow behaviour to design, apparently achieved with model 1.2/0.028, is proved elusive by the behaviour of the other models.

A number of reasons can be advanced for the above lack of consistency. In the first place, surface pressure gradients are not even considered in the design; in the absence of the duct adverse pressure gradients will certainly be present and it is not known how the substitution of the arbitrarily faired duct for the source flow affects the pressure distribution. Then, the continuation of Martin's solution to within the body (or interface) is not strictly valid, and, even if it were satisfactory for practical purposes, there remains the fact that Martin's solution, like Eminton's, is inviscid and incompressible. Finally, even if the theory were in every other way satisfactory, there is the need to introduce the arbitrarily faired duct which disturbs the flow in some generally unpredictable manner, and which also precludes the establishment of a consistent rational design method.

5 CONCLUSIONS

The aim of shaping the profile so that the ejected gas remains attached has been interpreted as: to shape so that (i) adverse pressure gradients are avoided and (ii) most of the turning of the gas is accomplished subsonically. There is some scope in how these conditions may be satisfied. Both theory and experiment have so far taken the easiest way. For two-dimensional flow, Eminton's method[3] is available as a starting point; it applies equally to swept leading-edges, but no tests of either case have yet been made. For axially-symmetric flow, tests are readily carried out but mathematical difficulties have so far discouraged the development of an adequate theory. It

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* This is about one-third the flow rate successfully used by Tucker[1] to obtain the results presented in Figs.2(a) and 3.

has been established, by the experiments of Baron and Alzner[4] and of Tucker[1], that the desired smooth layer of ejected gas can be obtained, with a shaped profile, but a complete and reliable method of design does not yet exist.

The way to further progress is not easy but is discernible. The use of a sufficiently large wind-tunnel (preferably hypersonic) should enable tests to be made of a two-dimensional model with a cross-section which is both large enough to hold the necessary instrumentation and small enough to eliminate blockage problems and restrict the influence of the side-walls to the ends of the model. Eminton's approach cannot be applied to axially symmetric flows, but axially symmetric bodies with an integral duct and favourable or nearly zero pressure gradients could be obtained from distributions of ring vortices and ring sources, even if the process is tedious. Such tests of two-dimensional and axially symmetric designs are needed to check how far the assumption of incompressible flow is adequate, whether skin friction and displacement effects are important and whether differences in density across the interface lead to much mixing or to instability. It is also highly desirable to apply and extend existing methods for calculating binary boundary layers to the case of nose ejection and to consider the conditions at a free stagnation point with different gases on either side.

SYMBOLS

A, B, C,	coefficients in equation (11)
f	function defined by equation (11)
h	half-width of ejection orifice far upstream - Section 3
k	approximate diameter of interface in hodograph plane - Section 3
m	source strength - Section 3
p	static pressure
Q	mass flow - Section 4
r, θ	spherical polar coordinates - Section 4 (θ also angle between surface normal and free-stream direction - Section 3)
r_o, r_w	radii of bounding stream surface and shock-wave, respectively, Section 4
V	velocity in compressible flow
v	velocity in incompressible flow - Section 3

SYMBOLS (CONTD.)

v_r, v_θ	velocity components in spherical polar coordinates - Section 4
z	complex variable - Section 3
ζ	complex velocity - Section 3
μ	doublet strength - Section 3
ρ	density
ψ	stream function, defined in equations (9)
ω	complex potential - Section 3

Subscripts

j	far upstream in orifice
m	around curve of Eminton's profiles
s	at the stagnation point
∞	in undisturbed free-stream

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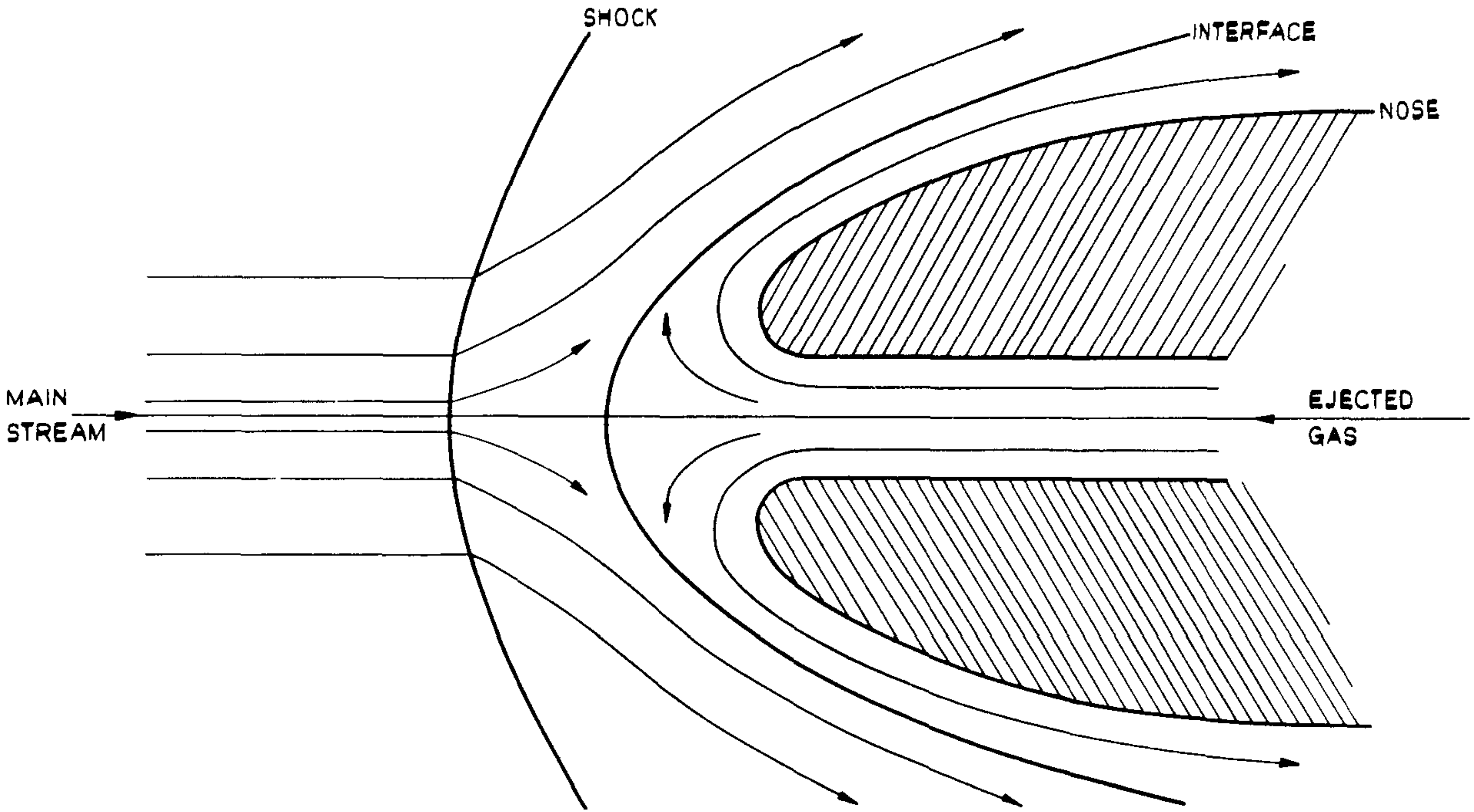

FIG I. QUALITATIVE SKETCH OF FLOW PATTERN.

a) $\frac{\rho_j V_j}{\rho_\infty V_\infty} = 1.35$

b) $\frac{\rho_j V_j}{\rho_\infty V_\infty} = 2.35$

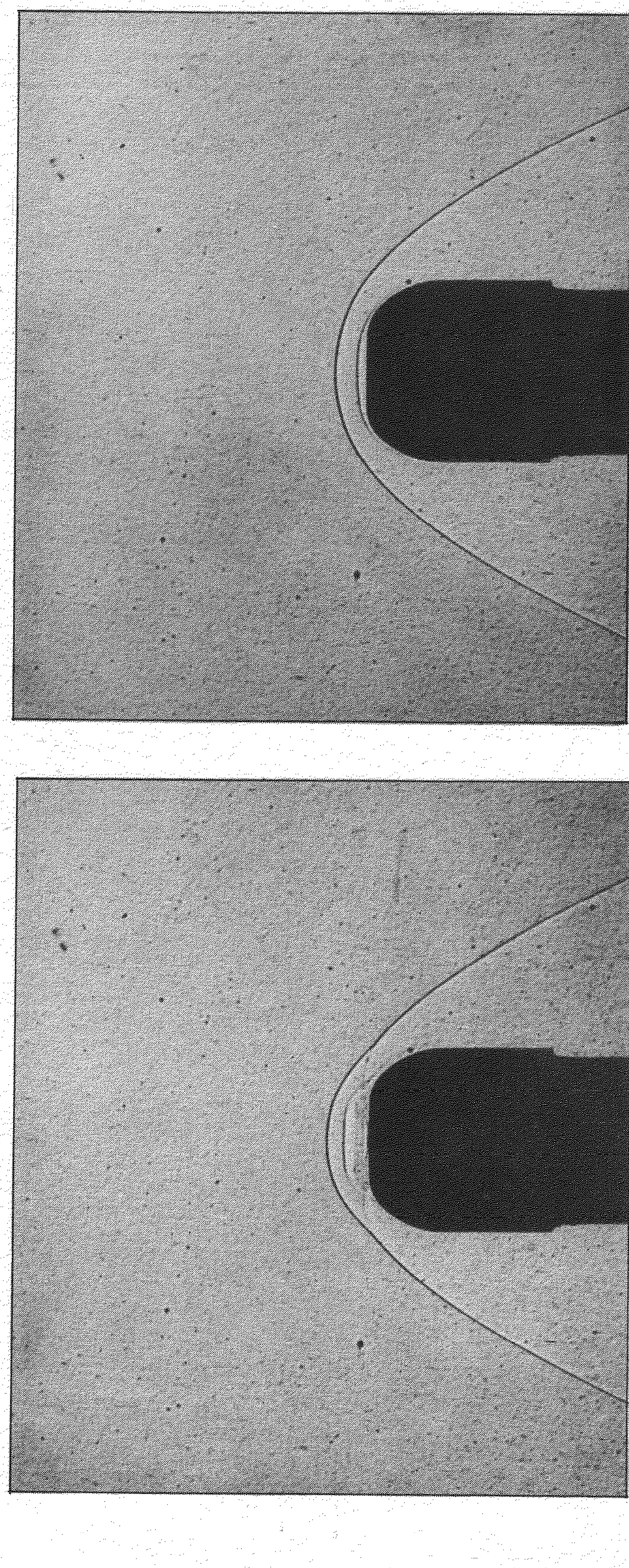

FIG.2. SHADOWGRAPHS BY TUCKER[1]. M = 4·33

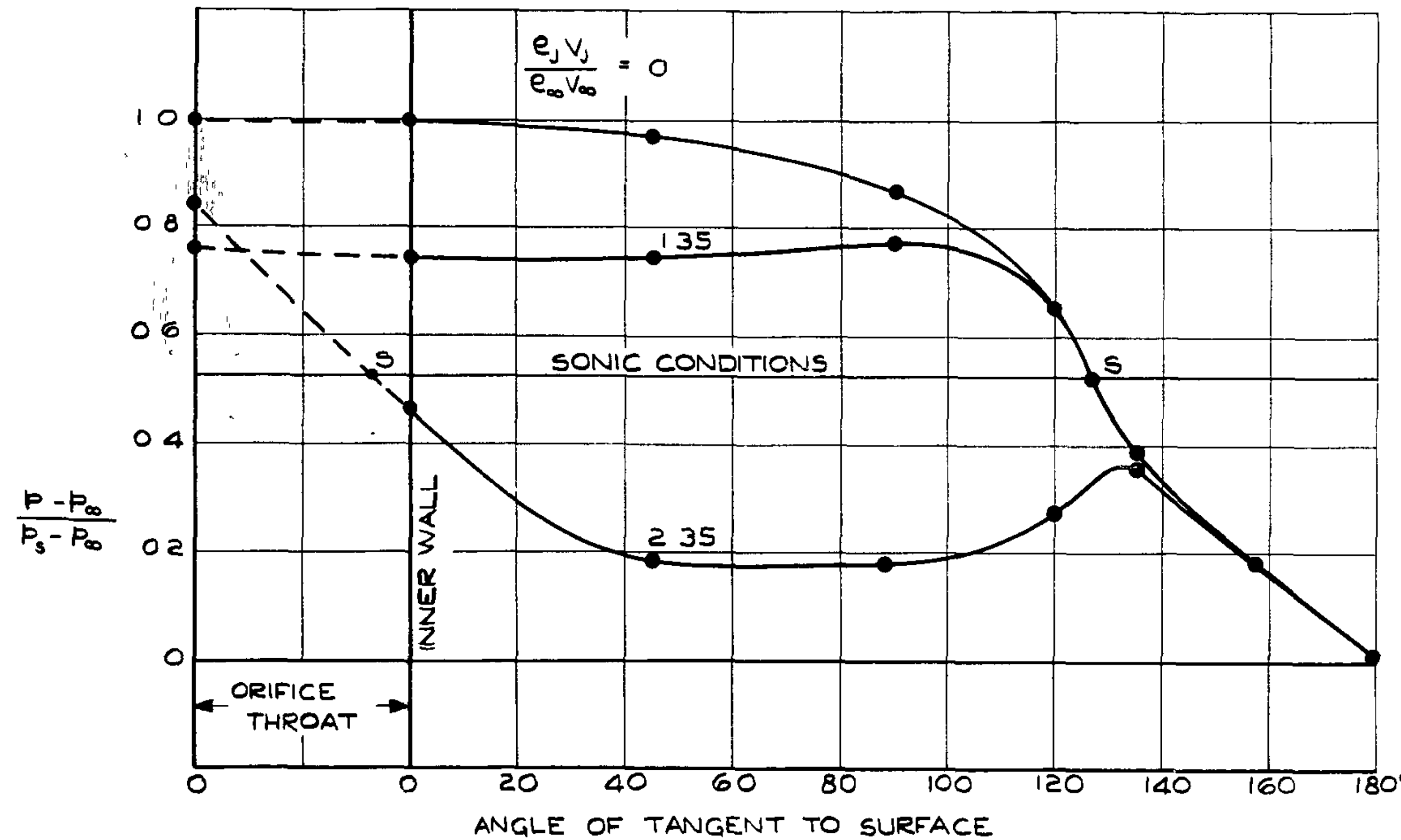

FIG. 3. PRESSURE DISTRIBUTIONS[1] ON ONE OF TUCKER'S MODELS. $M_\infty = 4{\cdot}33$

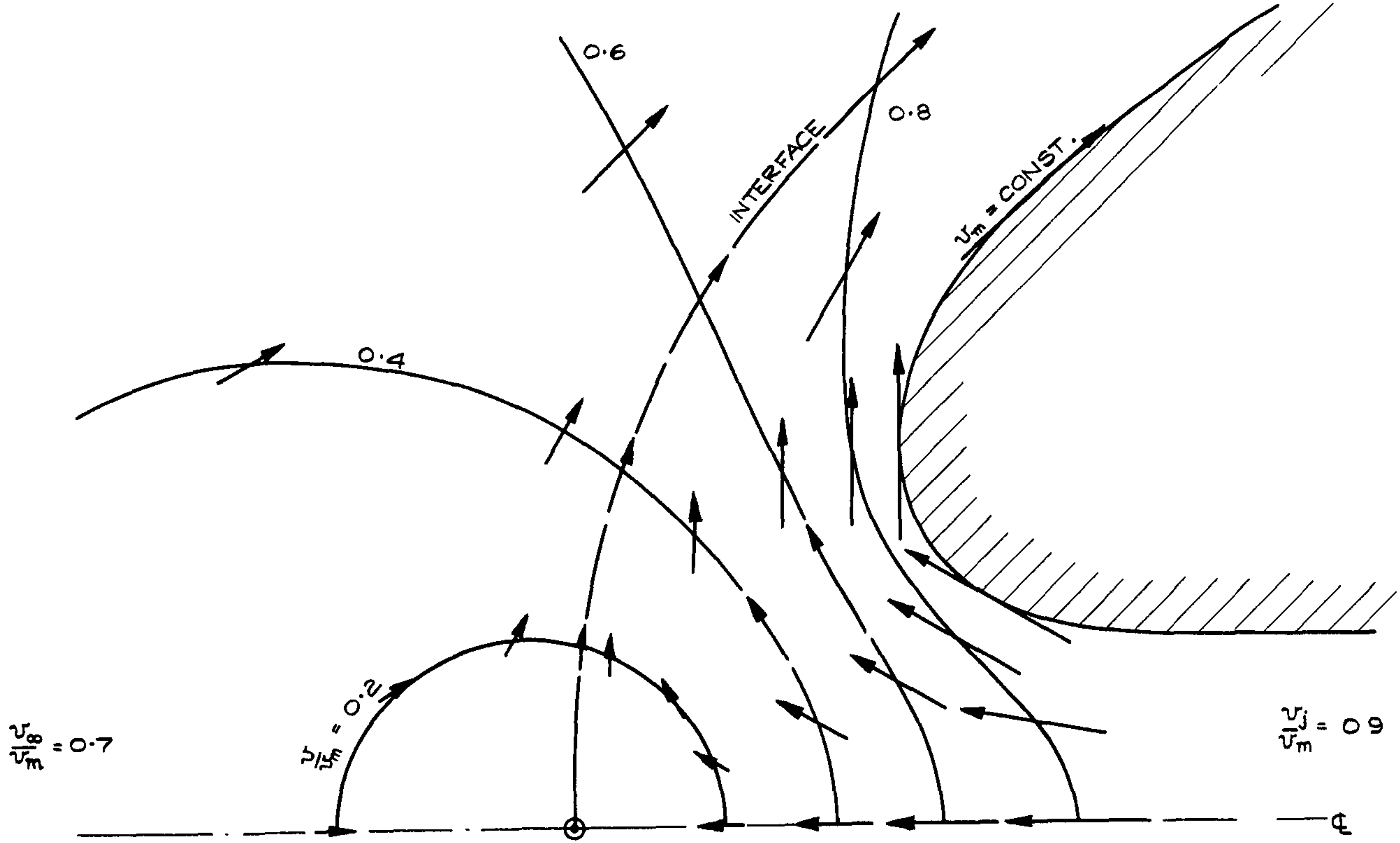

FIG.4. THEORETICAL FLOW FIELD FOR A CONSTANT-PRESSURE BODY PROFILE (EACH ARROW REPRESENTS THE VELOCITY VECTOR AT ITS MID-POINT.) M=O

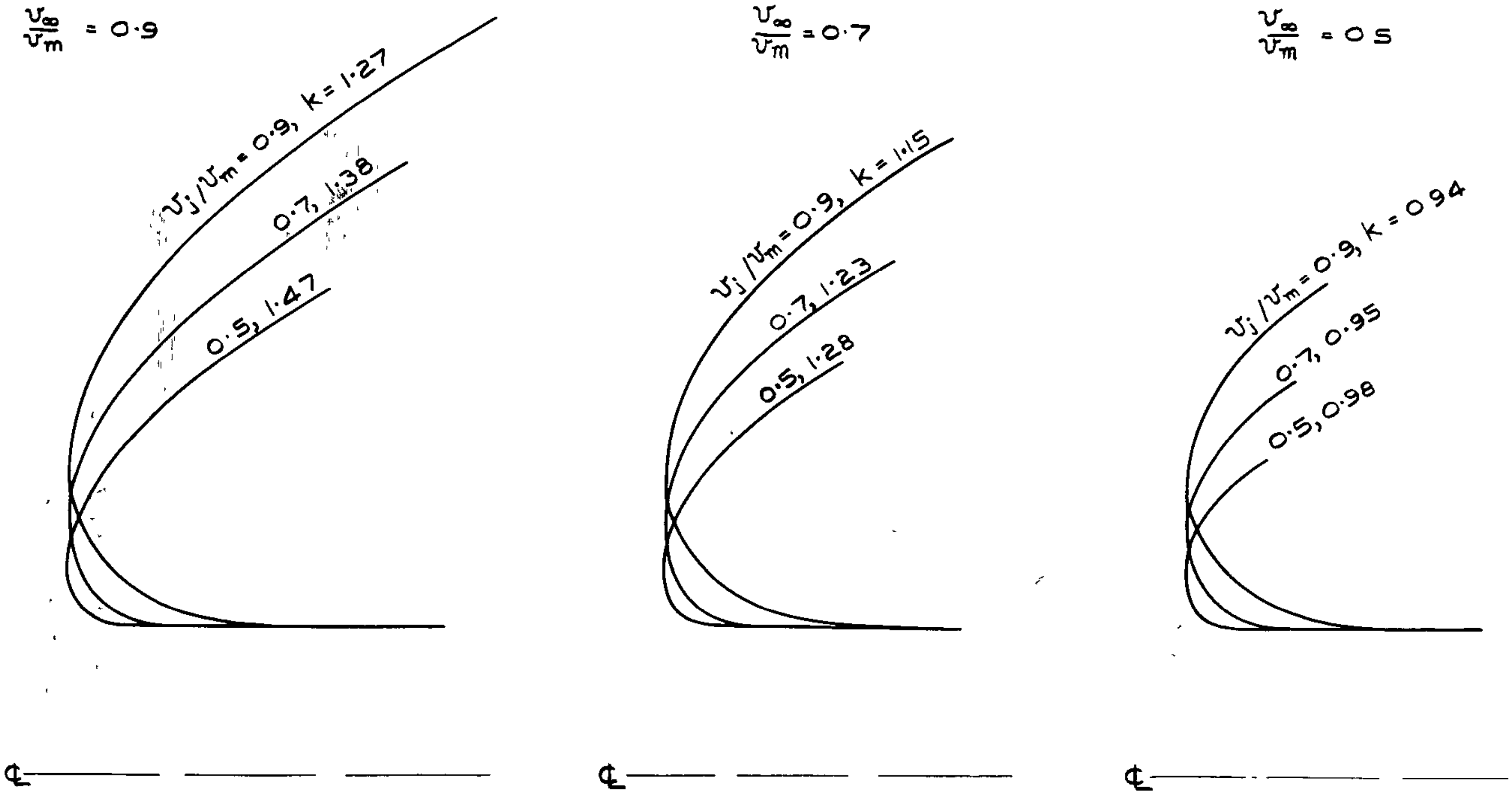

FIG. 5. PROFILES WITH CONSTANT v_∞/v_m, FROM EMINTON.[3]

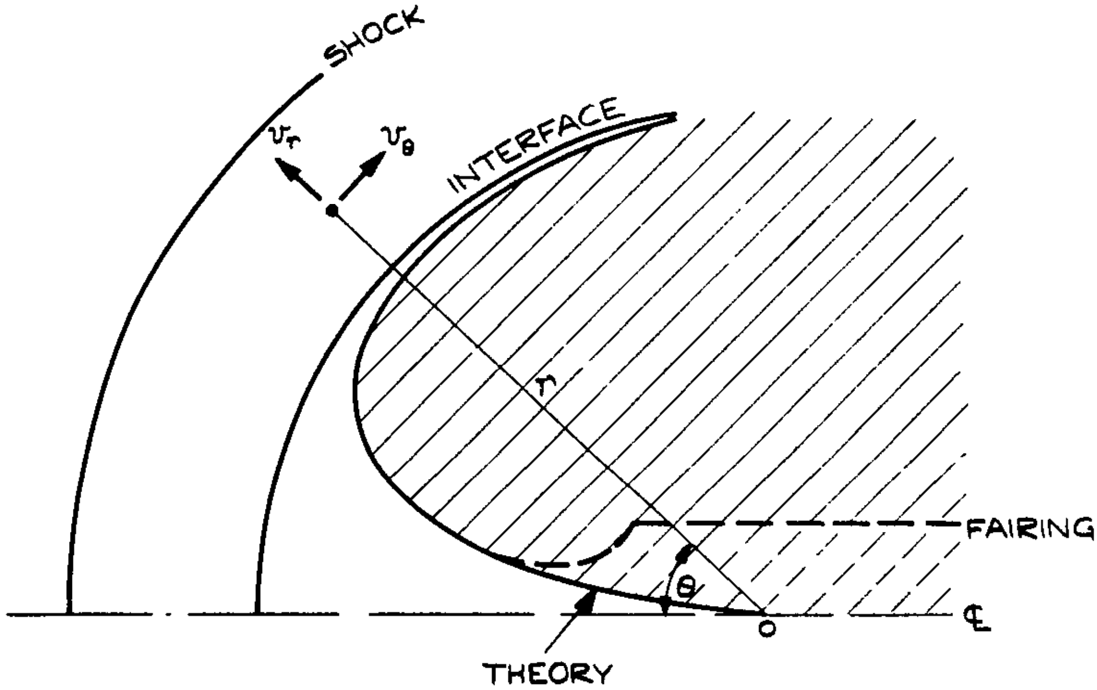

FIG.6. SKETCH OF MODEL WITH FAIRED DUCT OF BARON AND ALZNER.[4]

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ON FORWARD EJECTION FOR THERMAL INSULATION IN HYPERSONIC FLIGHT. Hall, M. G. Aug. 1963.

A review is presented of recent work on the flow from a single forward-facing orifice in a supersonic or hypersonic stream. The particular aspect of this work discussed here is how to shape the profile of the orifice and the body so that the ejected gas remains attached to the body and thus envelops it in a smooth layer which can be used to reduce heat transfer to the body surface. Dissipative effects are neglected, except across the detached shock wave. The review begins with a more specific formulation of the problem, made with the help of some detailed experimental observations by Tucker[1]. Then accounts are given of Eminton's method[3] for constant-pressure profiles in plane flow, and of the theoretical and experimental work of Baron

P.T.O.

and Alzner[4] on axially symmetric bodies. The results are discussed and it is concluded that while the aim has in some cases been achieved a reliable method of design does not yet exist. Some suggestions for further work are made.

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