On the stable shape of subliming bodies in a high-enthalpy gas stream

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This paper describes a series of experiments carried out in a high-enthalpy stream of argon on materials that are known to sublime. The results confirm that an axisymmetric Teflon model ablates to a stable shape which is independent of the initial nose profile. The effect of changing the total enthalpy of the gas is simply to alter the recession rate of the nose. The experimental results show poor agreement with a simple theory which ignores the effects of mass transfer in the boundary layer.

1. Introduction

In the design of an ablation shield, consideration must be given to the change of shape of the shield during the re-entry phase. Since large changes in the profile will alter the aerodynamic characteristics of the vehicle, an effort must be made either to predict the change of shape or, better, to employ a nose profile that maintains its initial shape and recedes at a constant rate, namely the ablation velocity, V_W.

The problem of the equilibrium shape of any ablating material may be subdivided into: (*a*) when the stagnation temperature is approximately the same as the melting temperature of the body material; (*b*) when the stagnation temperature is much greater than the body melting (or sublimation) temperature. In the first case, melting occurs only in the stagnation region so that the nose of the body becomes more and more blunt until the heat-transfer rate is nearly uniform across the face. Examples of such behaviour have been given by Bogdonoff (1957), who describes a number of tests on ice models in a hypersonic stream of Mach number 13, stagnation pressure 100 lb. per square inch and a stagnation temperature of 294 °K. When the stagnation temperature is much greater than the body melting or vaporization temperature, experiments have indicated that after steady-state conditions are reached an equilibrium profile is attained which recedes at a constant rate. The explanation for this behaviour is that if the melting rate exceeds the equilibrium value, the temperature gradient at the surface is increased and more heat is conducted into the body, thus less heat is available for the melting process and the melt rate decreases. Conversely, if the melt rate falls below the equilibrium value the reverse procedure occurs.

McLellan (1955) described a series of experiments in which the melting of hemispherically-ended cylinders and cones was studied. The Woods-metal models were placed in an air stream at Mach number 6·9 with a stagnation temperature of 640 °K. Woods-metal is a eutectoid of tin, bismuth, cadmium and lead with a melting point of 345 °K. The results showed that the hemispheres became blunter on reaching their equilibrium shape, and that the conical-nosed models produced a spherically-blunted profile on melting. More recently, Tate (1959) in England, and Chu & Lee (1959) in America have studied the problems of equilibrium profiles in the region of the stagnation point. In Tate's experiments, a number of long axisymmetric bodies of Cerrobend (Woods-metal) were placed in a supersonic air stream at a Mach number of 2. Three models of each nose configuration were melted at stagnation temperatures of about 390, 420 and 450 °K. The nose shapes of the models were a hemisphere, a 20° semi-angle cone and a flat-ended circular cylinder. The results indicated that the equilibrium profile was independent of the initial nose shape. By using laminar-flow assumptions, a theoretical prediction of the body shape in the stagnation region was found to be in agreement with the experimental profiles. The experiments performed by Chu & Lee were in a heated supersonic wind tunnel at free-stream Mach numbers of 3·01 and 5·64. A variety of model materials were used, their range of the ratio of stagnation point temperature to melting temperature (T_t/T_m) being between 1·255 and 1·75; comparison of the equilibrium nose shapes in the stagnation region was also in good agreement with the theoretical predictions. In all of the work reviewed above, the authors have been concerned with materials which melt on reaching a given temperature, and the two-phase boundary-layer problem created by the molten material on the body surface is overcome by assuming the thickness of the liquid layer to be negligible. By using materials which sublime rather than melt, the problems of stable-shape analysis are slightly simplified, because the boundary condition becomes one of a boundary layer with mass injection which has been the subject of many papers, see for example Low (1955). Christensen & Buhler (1958) commented on the stable shape obtained on a graphite body in an arc-heated air jet, which was found to ablate to a slender ogive. Later Sutton (1959) gave a theoretical solution for the terminal shape found above, making the assumption that the graphite burns to form CO at the surface.

The object of the experiments described here is to extend the study of equilibrium profiles to higher values of the temperature ratio (T_t/T_m), for a subliming material. By using argon, such unknowns as the effects of chemical reaction and combustion at the body surface as well as dissociation of the gas have been eliminated from the generally complex ablation problem.

2. Theoretical background

In order that a theoretical prediction of the equilibrium profile of a subliming body may be deduced, the following assumptions are made:

(i) the effects of heat conduction are small and may be neglected;

(ii) the rate of sublimation is proportional to the local heat-transfer rate;

(iii) the boundary layer is laminar;

(iv) the recovery temperature is equal to the stagnation temperature;

(v) the pressure distribution around the body may be expressed by the modified Newtonian theory.

Assumption (iv) is only true when the stagnation temperature is much higher than the sublimation (or melting) temperature. If this is not the case, there is a possibility that, away from the stagnation point, the recovery temperature will be less than the sublimation temperature and hence an equilibrium profile will be unobtainable. The application of assumption (v) to flows at a Mach number of 2·5 is at first sight questionable; however, a careful examination of the pressure distributions over hemispherically-ended cylinders and blunt cones with spherical noses, shows the agreement with the modified Newtonian theory to be good. A typical comparison between experiment and theory is shown in figure 1, for a hemispherical-cylinder model.

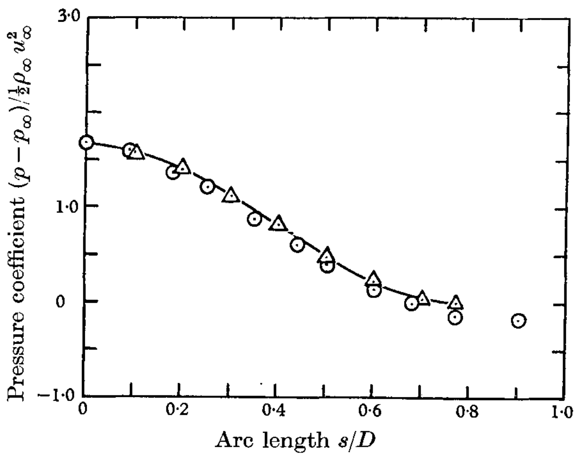


FIGURE 1. A comparison of the modified Newtonian theory with experimental data for a Mach number of approximately 2 on a hemispherically-ended cylinder. △, Modified Newtonian theory, ⊙, Stine & Windlass (1954).

Since the surface recedes uniformly in the direction of the free stream, the rate of sublimation may be expected to be proportional to the sine of the local surface slope θ. Using assumption (ii) and following the analysis of Tate, the local heat-transfer rate per unit area to the body, $\dot{q}_w$ may be expressed as

$$\dot{q}_w = \dot{q}_t \sin\theta = \{h_v + h_f + C(T_v - T_0)\}\, \dot{m} \sin\theta, \tag{1}$$

where $\dot{q}_t$ is the stagnation-point heat-transfer rate, h_f and h_v are the latent heats of fusion and vaporization, respectively, C is the specific heat at constant pressure, T_v is the vaporization temperature, T_0 the initial temperature of the body and $\dot{m}$ is the rate of mass ablation per unit area. Also, the heat-transfer coefficient α may be expressed in terms of the Nusselt number Nu and the Reynolds number R as

$$\alpha = K_w(Nu/R_w^{\frac{1}{2}})(\beta/\nu_w)^{\frac{1}{2}}, \tag{2}$$

where K_w is the thermal conductivity, ν_w is the kinematic viscosity, the subscript w represents conditions at the body surface and β is the local velocity gradient at the stagnation point. Thus, in terms of the local heat-transfer rate per unit area to the surface, defined by $\dot{q} = \alpha(T_t - T_0)$, we may write

$$\frac{Nu}{R_w^{\frac{1}{2}}} = \left(\frac{\nu_w}{\beta}\right)^{\frac{1}{2}} \frac{1}{K_w(T_t - T_w)} \{h_f + h_v + C(T_v - T_0)\}\, \dot{m} \sin\theta, \tag{3}$$

or, rearranging,

$$Nu = \left(\frac{u_e s}{\beta}\right)^{\frac{1}{2}} \frac{1}{K_w(T_t - T_w)} \{h_f + h_v + C(T_v - T_0)\} \dot{m} \sin\theta, \tag{3a}$$

where u_e is the velocity component at the edge of the boundary layer, tangential to the surface, and s is the distance along the surface from the stagnation point.

Using assumption (v), the ratio of the pressure coefficients $C_p/C_{p_{\max}} = \sin^2\theta$, so that the pressure ratio ζ may be expressed as

$$\zeta = p/p'_t = \sin^2\theta + p_\infty \cos^2\theta/p'_t, \tag{4}$$

where the prime denotes conditions behind the bow shock wave. Rearranging the isentropic energy equation

$$p'_t/p = \{1 + \tfrac{1}{2}(\gamma - 1)\, M^2\}^{\gamma/(\gamma-1)}$$

in terms of the free-stream velocity, yields

$$u_e^2 = \left[\frac{2\gamma}{\gamma - 1}\frac{p'_t}{\rho'_t}\right]\left[1 - \left(\frac{p}{p'_t}\right)^{\gamma/(\gamma-1)}\right]; \tag{5}$$

also the density ratio is given by

$$\rho/\rho'_t = (\zeta)^{1/\gamma}. \tag{6}$$

Using the laminar heat-transfer analysis of Bade (1962) based on values of the transport properties for argon, calculated by Amdur & Mason (1958), we may express the Nusselt number as

$$Nu = 0{\cdot}66 s\, (\beta/\nu_w)^{\frac{1}{2}}. \tag{7}$$

By comparing equations (3a) and (7), and using the local stagnation-point velocity gradient $\beta = (du_e/ds)_{s=0}$, we obtain the following relationship

$$\frac{0{\cdot}66(T_t - T_w)\, K_w}{\dot{m}[h_f + h_v + C(T_v - T_0)]} = \sin\theta \left[\frac{s}{u_e}\frac{\mu_w}{\rho_w}\right]^{\frac{1}{2}}. \tag{8}$$

Substituting equations (5) and (6) in terms of ζ into equation (8) and rearranging yields

$$\sin\theta = \frac{Z}{(s\mu)^{\frac{1}{2}}}\left(\frac{2\gamma}{\gamma - 1} p'_t \rho'_t\right)^{\frac{1}{4}} (1 - \zeta^{(\gamma-1)/\gamma})^{\frac{1}{4}} \zeta^{\frac{1}{2}}, \tag{9}$$

where $\quad Z = 0{\cdot}66(T_t - T_w)\, K_w/\dot{m}[h_f + h_v + C(T_v - T_0)].$

Equation (9) is an expression for the body slope in terms of the pressure ratio ζ, the stagnation-point conditions and the material properties. Considering the region close to the stagnation point, and neglecting terms of order η^2 and higher, where $\eta = \frac{1}{2}\pi - \theta$, equations (4) and (9) may be combined to yield

$$n = (Z^2/\mu)\,(2p'_t \rho'_t)^{\frac{1}{2}}, \tag{10}$$

where n is the radius of curvature of the nose, which to this order of approximation is given by $s = n\eta$. Equation (10) is similar to the result obtained by Tate, the principle differences being that the effects of sublimation are included, and that the above value of Z is specifically applicable to a body in an argon stream. This equation is important, since it relates the radius of curvature of the nose to the ablation rate of the surface. It has been shown above that in the neighbourhood of the stagnation point, the equilibrium profile has a constant radius of curvature n; thus locally it will be defined by the parabola $\frac{1}{2}y^2 = nx$. By applying the blast-wave analogy together with assumption (ii), Lees (1959) has shown that the asymptotic form of the equation far from the nose is also parabolic; however, it is not suggested that these parabolas are one and the same.

3. Experimental data

The experiments were carried out at Imperial College, in the arc-heated wind tunnel, the characteristics of which have been described by Harvey & Simpkins (1961). The main objectives were as follows: (*a*) to confirm that an equilibrium profile could be obtained from a variety of nose profiles for large temperature ratios (T'_t/T_v); (*b*) to examine whether this shape, if obtainable, varied with

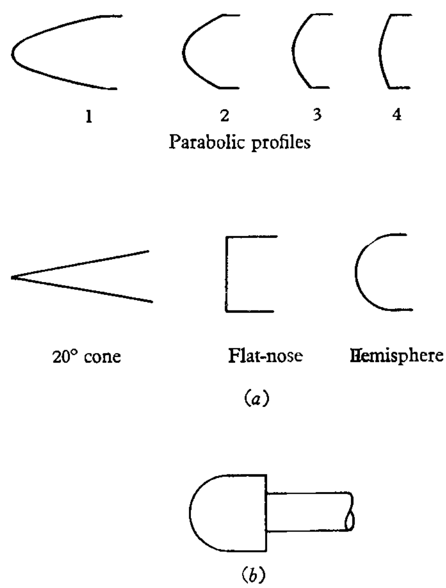


FIGURE 2. (*a*) Teflon model profiles. (*b*) Graphite model used in body temperature measurements.

the model material or the total enthalpy of the gas stream; (*c*) to investigate the possibility of reducing the ablation rate by using separated flow techniques.

The materials used for the models in this test programme were Telflon (Polytetrafluoroethylene) and a high purity graphite (Morganite EY 9 A); these were chosen as they both sublime at high temperatures, and also have very different values of thermal diffusivity.

3.1. *Tests with Teflon*

Initially a number of Teflon models with a variety of nose profiles (shown in figure 2) were tested in argon under the following conditions:

Total pressure $p_t = 0{\cdot}375$ to $0{\cdot}405$ atm ($5{\cdot}51$ to $5{\cdot}95$ p.s.i.a.).

Total enthalpy $h/RT_0 = 165$ to 185 (for argon $RT_0 = 24{\cdot}445$ B.Th.U./lb.).

Mass flow rate of argon gas $\simeq$ 0·20 lb./min.
Equilibrium stagnation temperature $T_t' \simeq$ 10,580 to 10,900 °K.
Degree of ionization $\simeq$ 0·08 to 0·10.
Free-stream Mach number $\simeq$ 2·50.
Arc power input $\simeq$ 44 kW.

The results indicated that the models were all tending towards a unique profile independent of the initial nose shape. However, photographs showed that the more slender bodies (i.e. the cone and parabolas 1 and 2, figure 2*a*) were too short for steady-state conditions to be reached; consequently additional models were made of the transient profiles obtained, and these were then tested under the same conditions as before. Analysis of the films taken during each test showed that all of the profiles in figure 2*a* attained steady-state conditions when the nose profile was similar to that shown in figure 5, plate 1.

Having established that an equilibrium profile could be obtained with the Teflon models for the conditions noted previously, the next step was to examine whether this profile varied with the arc power input. By varying the power input, the total enthalpy and hence the stagnation temperature may be altered, while the mass flow rate of the argon is retained at the values given above. Thus the tests were carried out on equilibrium profile models under the following conditions:

	(*a*)	(*b*)
Total pressure p_t	0·273 atm (4·01 p.s.i.a.)	0·42 atm (5·91 p.s.i.a.)
Mass flow rate of argon	0·20 lb./min	0·20 lb./min
Arc power input	18·0 kW	61·1 kW
Total enthalpy h/RT_0	77·5	255·5
Equilibrium stagnation temperature	8000 °K	11600 °K
Degree of ionization	0·006	0·185

Films taken at 2-sec intervals showed that the nose profile remained essentially constant, throughout the run, indicating therefore that the only effect of varying the total enthalpy of the gas stream is to alter the recession rate of the nose, as would be expected. A typical photograph of the equilibrium profile is shown in figure 5, plate 1.

Finally, some models having the equilibrium nose profile were modified by projecting a graphite spike from it (figure 7*a*, plate 2), in order that the effects of flow separation on the rate of ablation might be examined. These tests were run under similar conditions to the earlier experiments and the photographic records showed that in each run very large heat-transfer rates occurred at the reattachment point, causing the Teflon to sublime in this region, so that the body tended to become more slender (see figures 7*b* and *c*, plate 2). The rate of ablation in these tests was about 0·0629 g/sec compared with a value of 0·0810 g/sec for the equilibrium model without the spike, showing that the total heat transfer to the body was decreased by the presence of the spike.

3.2. *Tests with graphite*

A body of similar nose profile to that of the equilibrium-shaped Teflon model was made of graphite, to determine whether it would be affected by a change in material. This graphite model was tested under similar conditions to the earlier Teflon models, namely

Total pressure $p_t = 0{\cdot}400$ atm (5·88 p.s.i.a.).
Total enthalpy $h/RT_0 = 170$.
Mass flow rate = 0·20 lb./min.
Equilibrium stagnation temperature $\simeq$ 10,600 °K.

Although the total running time with one particular model of this type was over 15 min, the profile remained unchanged and there was no significant weight loss. A number of optical pyrometer readings taken during the tests indicated that the surface temperature of the body under the above conditions was of the order of 2200 °K, well below the sublimation temperature of graphite (3700 °K).

In order to reduce the heat lost from the body by conduction, and thus increase the body temperature, a graphite model was made in the form of a hemispherically-ended cylinder supported by a thin graphite rod (see figure 2*b*). Although this technique was successful in increasing the body surface temperature, the values

Arc power input (kW)	Total enthalpy h/RT_0	Body stagnation-point temperature (°K) Measured	Body stagnation-point temperature (°K) Calculated
24	106	1840	1490
34	154	2090	1740
54	280	2280	2270

TABLE 1

recorded, about 2500 °K for the high enthalpy levels†, were still well below the sublimation temperature. A further series of tests were carried out on two $\frac{1}{8}$-inch rods, one with a blunt end, and the other with a hemispherical nose. Each of these models was kept in the plasma jet for 10 min. Again no ablation took place even at the highest enthalpy levels, indicating that an equilibrium temperature had been reached which was lower than the sublimation temperature.

Having minimized the conductive heat loss from the model, it is reasonable to equate the convective heat transfer from the gas to the radiative heat transfer from the model in order to obtain an approximate idea of the radiative equilibrium temperature. Using Bade's (1962) analysis for argon, we have

$$\dot{q}_t \simeq 0{\cdot}66\,(Pr_e)^{-1}\,(\rho_e\mu_e\beta)^{\frac{1}{2}}\,(h_{s_e}-h_w) \simeq \dot{q}_{\mathrm{rad}} = \epsilon\sigma T_t^4,$$

where σ is the Stefan–Boltzmann constant. Taking the Prandtl number Pr for argon as 0·667, the surface emissivity $\epsilon = 0{\cdot}78$ (see Wright 1956) and computing a value for the velocity gradient β from work by Lees (1956), it has been possible to estimate the value of $\dot{q}_t$ and hence the body temperature at the stagnation point. A typical set of values for the measured and calculated wall temperatures

† It should be noted that the readings quoted for the pyrometer neglect the absorption of the working-section windows and the spectral emissivity of the body surface; these factors could possibly cause the above readings to be underestimated by 100 °K.

is shown in table 1. The discrepancy at the low-enthalpy levels is probably due to the effects of conduction which have been neglected in the above calculation; at the higher enthalpies the radiation from the gas to the body becomes significant and is probably counter-balancing the conduction losses.

3.3. *Reynolds-number range*

The Reynolds numbers have been calculated by using the known mass flow rates of the argon, in order that explicit use of the free-stream velocity might be avoided. By combining the data of Christensen & Buhler (1959) with the known mean enthalpy levels, it has been possible to estimate the free-stream temperature. These values have been used to obtain the gas viscosity from the calculations of Amdur & Mason (1958), assuming the effects of ionization are small. Typical values of the Reynolds number are given in table 2.

Arc power (kW)	18·0	43·7	60·0
Total enthalpy (B.Th.U./lb.)	1900	4810	6240
Mass flow (lb./sec)	0·00335	0·00331	0·00333
Temperature (°K) T_∞	3460	5160	5850
T'_t	9610	14310	16250
Viscosity × 10^5 lb. ft.$^{-1}$ sec^{-1} μ_∞	9·206	12·60	13·91
μ_e	20·23	27·15	29·43
Reynolds number/in. $\rho_\infty u_\infty/\mu_\infty$	796	574	524
$\rho_e u_e/\mu_e$	362	266	248

TABLE 2

4. Estimate of the equilibrium profile

A method of least squares has been used to determine a function which represents the equilibrium profile obtained in the present series of tests. The results of these tests showed that the equilibrium profile became parallel to the axis of symmetry at some distance a along the axis, from the stagnation point. The initial functions were therefore chosen to satisfy the following:

$$\text{(i)}\ x = 0;\ y = 0,\ dy/dx = \infty, \quad \text{(ii)}\ x = a;\ y = b,\ dy/dx = 0,$$

where b is the radius of the cylinder. If the function describing the curve between $0 \leqslant x \leqslant a$ is expressed in the form of a general series as

$$f(x) = \sum_{m=1}^{\infty} A_m y_m,$$

where $m \geqslant 1$ and A_m are unknown constants, then by writing

$$y_m = [1-\{(x-a)/a\}^{2m}]^{\frac{1}{2}}$$

the condition (i) is satisfied identically, and (ii) imposes the constraint

$$\sum_{m=1}^{\infty} A_m = b.$$

If we consider the first two terms, it is only necessary to evaluate the unknown constant A_1. This has been carried out by using a least squares technique (see Buckingham 1957) to fit the best curve of the above function to a set of experimentally determined points on the profile. The computation using eleven intermediate points on the profile yielded a value for A_1 of unity. A plot of the points given by the expression

$$f(x) = [1-\{(x-a)/a\}^2]^{\frac{1}{2}} + (b-1)\,[1-\{(x-a)/a\}^4]^{\frac{1}{2}}$$

is shown in figure 4 and compared with the equilibrium profile obtained from the photographic records. The agreement shows that the first two terms of the series adequately describe the experimental profile.

5. Discussion of results

The initial tests on the various Teflon bodies at constant enthalpy levels revealed that a single equilibrium profile could be obtained, for a wide variety of initial nose shapes. The curves shown in figure 3 are of the stagnation-point recession rates on the parabolic models. The curvature in the initial seconds shows the transient ablation of the nose; this is most noticeable on the very slender parabola (model 1, figure $2a$) where the rate of nose recession is high. The linear portion on the curves indicates that steady-state ablation exists, and it is in this region that the values of the ablation velocity quoted on the curves have been calculated. These values are within 3 % of each other for the blunter nose profiles. In the final seconds of the test, the nose recession rates have been affected by the water-cooled model support.

The curves shown in figure 4 are a comparison of the experimental profile with the theoretical predictions given by equations (9) and (10). It can be seen that there is little agreement between the theoretical solutions and the experimental data, even in the region of the stagnation point, and that unless the profile includes a conical skirt, a discontinuity in slope occurs at the shoulder on the theoretical curves. Attempts have been made to match the conditions at the shoulder by considering the terms containing ζ in equation (9) and expanding these in a series about the point of tangency (i.e. where the body slope is zero); however, the improvement in the Tate solution in this region is only slight and hardly comparable with the discrepancy seen in the curves ahead of the shoulder. The discrepancy between the theoretical and experimental profiles is probably due to the effects of mass transfer which have been ignored in the theoretical calculations. The injection of the gaseous products, created by the thermal decomposition of the Teflon, into the boundary layer reduces the amount of heat transferred to the surface. Hence the effect of the mass transfer is to create a sheath of relatively cool gaseous products around the body, which reduces the heat transfer and consequently the rate at which mass is lost by the body. Roberts (1959) has shown that when a gas is injected into the boundary layer, the amount of heat shielding due to convection is critically dependent on the specific heat of the gas being used as a coolant. The author has been unable to obtain any values, for such properties as specific heat, for the gaseous products of the pyrolysis of Teflon, these being about 95 % tetra-fluoroethylene together with small

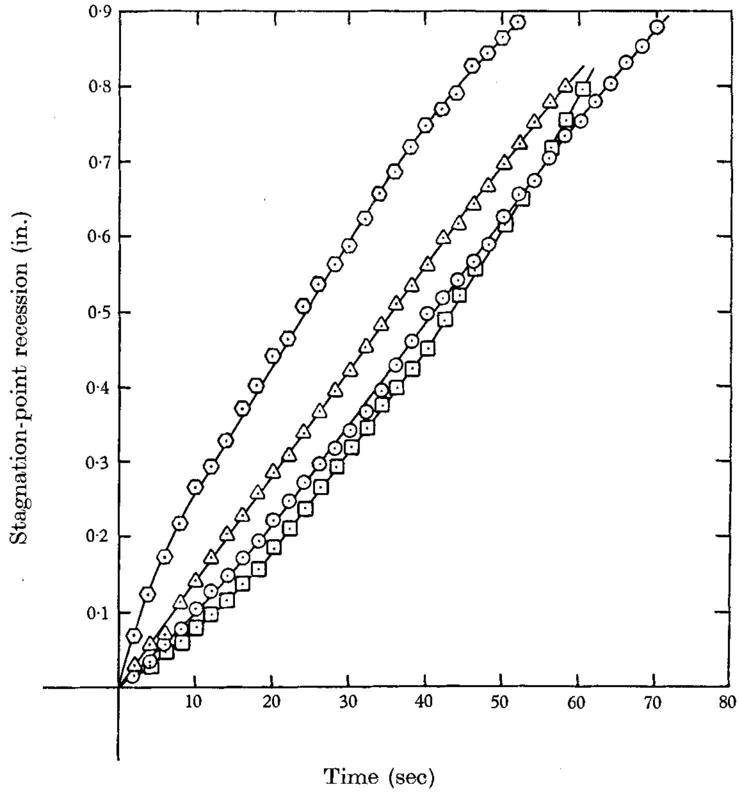


FIGURE 3. Nose recession rate for the parabolic Teflon models at constant enthalpy. Power input $\simeq$ 44 kW, $h_t \simeq$ 4500 B.Th.U./lb.

	Model	V_w(in./sec)
⬡	1	0·0168
△	2	0·0139
⊙	3	0·0135
⊡	4	0·0135

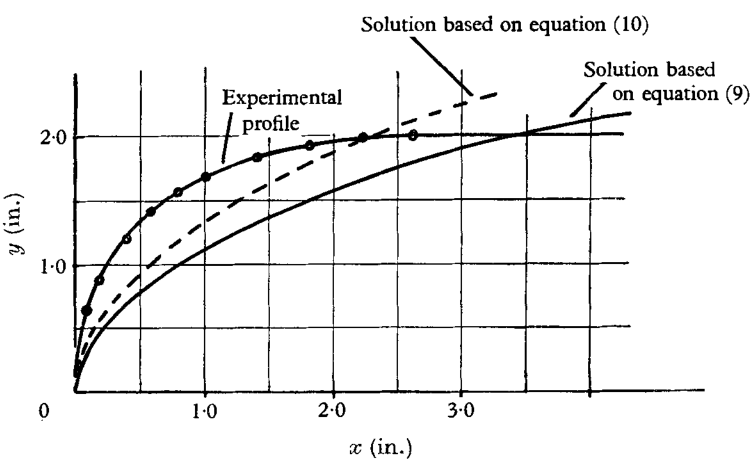


FIGURE 4. Comparison of the equilibrium profile found by experiment with the theoretical predictions. Points shown are of the estimated profile given in §4.

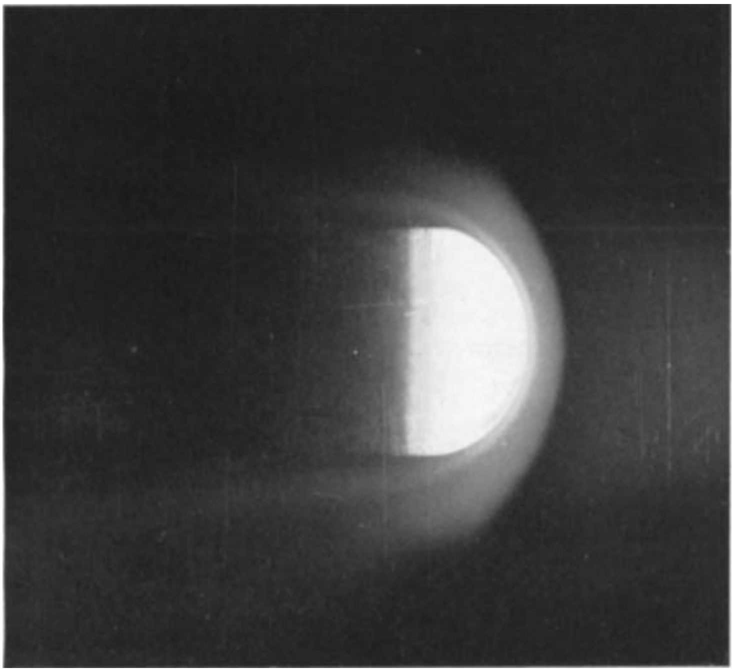
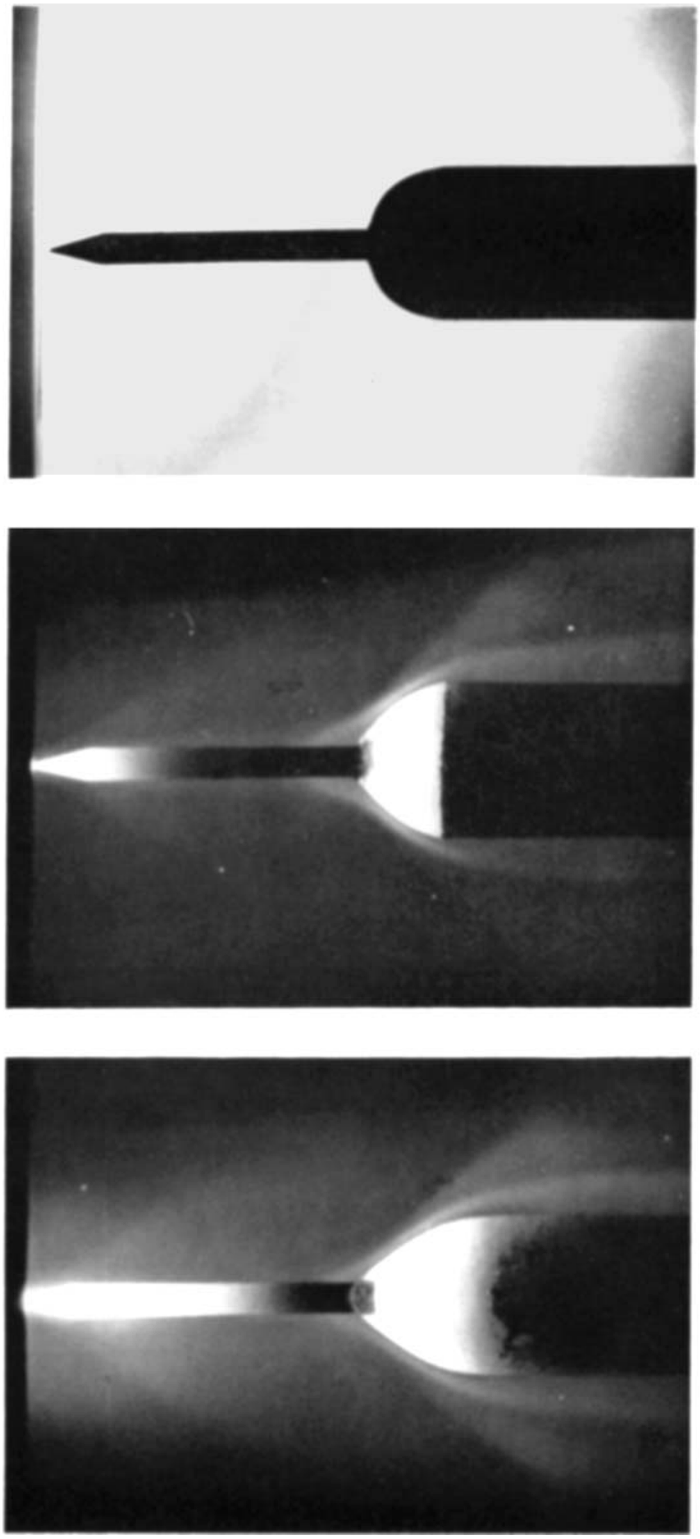


FIGURE 5. Photograph of the equilibrium profile in argon. Stagnation temperature of 8000 °K approx. $t = 12$ sec; $h/RT_0 = 77{\cdot}5$.



(*a*) $t = 0$

(*b*) $t = 5$ sec

(*c*) $t = 15$ sec

FIGURE 7. The effect of a spike, $l/d = 2$, on the ablating profile of the Teflon body.

amounts of other fluorocarbons such as carbon tetrafluoride and hexafluoropropylene. Consequently, estimates of the effects of mass transfer using Robert's analysis cannot be given; however, work by Settlage & Siegle (1961) suggests that the surface temperature of a Teflon body remains at about 950 °K even when the free-stream temperatures are in excess of 2000 °K. In the photograph of the equilibrium profile, figure 5, plate 1 the layer of gaseous products can be seen quite clearly around the nose of the body and the bow shock wave is outlined by the dark régime in the free stream ahead of it.

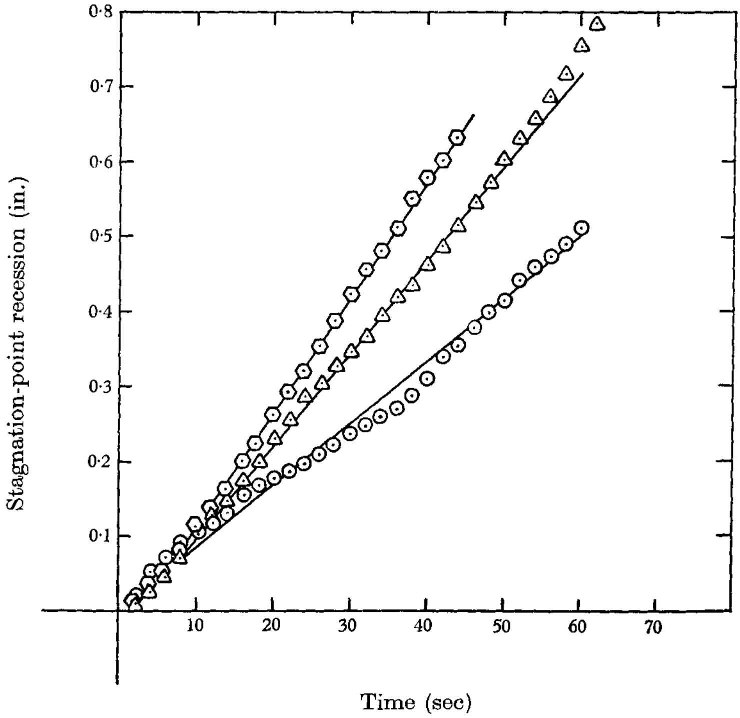


FIGURE 6. Stagnation-point recession rate for the Teflon equilibrium profile at various power levels.

	Power input (kW)	V_w (in./sec)
⊙	61·1	0·0155
△	43·1	0·0129
⊙	18·0	0·0086

For the case where the free-stream gas is air, additional energy is absorbed by the chemical reaction of the decomposed products in the boundary layer. This is confirmed to some extent by comparing the present series of tests with the results of Georgiev, Hidalgo & Adams (1959). This comparison shows that, although the stagnation-point heat transfer rates are about 22 % greater for the case where air is the free-stream gas, the ablation velocity is only increased by 13 % for similar body shapes. It has also been noted that the profiles obtained after a Teflon hemisphere had been ablated in an air stream were very similar to the equilibrium shape obtained in the present series of tests. This would indicate that the equilibrium profile is not strongly dependent on the free-stream gas.

The effect of varying the total enthalpy of the free stream on the models was simply to alter the ablation velocity, without appreciably changing the profile. The results of these tests are shown in figure 6 where an equilibrium profile tested at three enthalpy levels yielded a linear relationship for the ablation rate.

Results obtained by Stetson (1960) indicated that, for the conditions of our experiments, the transition Reynolds number based on conditions behind the bow shock wave and distance from the stagnation point is about 3×10^5. Comparison of this figure with the values shown in table 2 shows that in the present experiments the boundary layers were always laminar.

The preliminary tests carried out on the blunt bodies with separated flows indicated that the total heat transfer to the body had been reduced; however, as can be seen from the photographs in figure 7, plate 2, the heat-transfer rate at reattachment was sufficient for the profile of the body to change radically. In the photographs shown, the gaseous products entrailed into the shear layer caused by the separated boundary layer can be seen, and the effects of separation on the heat transfer to the spike are clearly illustrated by dark region nearest to the body. Thus, it appears that the temperature in the dead-air region is considerably less than the recovery temperature. As would be expected, the separation region diminishes as the body itself becomes more slender due to the ablation in the reattachment zone (see Wood 1962). It should be emphasized that these results are purely qualitative, and that the effects of changing spike length, ratio of diameters, etc., have not been studied.

The results of the experiments using graphite models are interesting, since it has not been possible to obtain sublimation of the material in the argon jet. Careful measurement of the model weights before and after each test revealed no significant change even after tests of some 18 min duration. The pyrometer readings of the body temperature at the stagnation point are in reasonable agreement with the temperatures estimated by the analysis carried out in § 3.2.

In all the calculations presented, the assumption has been made of a perfect gas with constant specific heat and Prandtl number equal to 0·667. Also the flow is assumed to be adiabatic so that $T_t' = T_t$. The values of viscosity that have been quoted are based on Amdur & Mason's analysis which is strictly applicable only to a pure inert gas in its ground state, i.e. when the effects of electronic excitation and ionization are negligible. Since a maximum degree of ionization of some 18 % is estimated to occur in the region downstream of the bow shock wave, there is no doubt that errors exist in some of the viscosity coefficients quoted. However, since in most cases the degree of ionization is much less than the maximum figure quoted above, it is felt to be beyond the scope of this paper to attempt to modify the transport properties to include ionization effects to obtain more realistic values for the Prandtl number and the coefficient of viscosity.

6. Conclusions

The experimental results confirm that an equilibrium profile which appears to be independent of the initial nose profile is obtained when an axisymmetric Teflon body is placed in a gas stream which has a stagnation temperature greater than the sublimation temperature of the model material. Changing the free-stream gas from argon to air appears to have little effect on the equilibrium profile. A comparison of the experimentally determined profile with the theoretical analysis based on a value of the ablation rate measured in the laboratory shows rather poor agreement. This appears to be primarily due to the heat-blocking effect of the vaporizing body surface which has not been considered in the theoretical predictions. An effort will be made to modify the existing theory to account for mass transfer, since the present solution is too conservative. Variation of the free-stream total enthalpy simply alters the rate of ablation and has no apparent effect on the body equilibrium profile. No results have been obtained for the effects on the equilibrium profile of varying the model material. The preliminary results obtained using separated flows indicate that the total heat transfer to the body is decreased.

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