An experimental investigation of the effect of ejecting a coolant gas at the nose of a bluff body

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An experimental investigation has been made of the effect of ejecting nitrogen and helium coolant gases at the nose of a bluff body at a nominal Mach number of 5·8. The gases were ejected with 'swirl', to encourage them to flow tangentially to the model surface at ejection, and also straight out. Measurements were made of the pressure and temperature on the surface of the model at incidences of 0, 4, 8°, and for a range of coolant gas flows. From these measurements the flow patterns and distributions of heat flux were deduced.

It was found that ejection with swirl did not in fact lead to an easing of the heating problem because the high tangential velocity with which the coolant was injected into the boundary layer increased the wall shear stress, and hence, by the Reynolds analogy, the heat flux, so that it predominated over the reduced driving temperature difference associated with the cooled boundary layer.

With straight-out ejection it was found that the heat alleviation capabilities of the ejected coolant were reduced considerably if the flow rate was sufficiently large that the bow shock wave was bulged out. However, provided that the external flow is not disturbed, straight-out ejection provides an effective way of reducing the heat flux.

1. Introduction

A body travelling at high speeds through the atmosphere experiences aerodynamic heating. Ways of alleviating the problems so incurred are accordingly of interest. One way is to eject a cool gas from the nose of the body. The gas, by flowing back over the body, forms a 'heat buffer' between the hot air stream and the body. This paper described some experiments that were made to investigate some of the fluid dynamic aspects of such a scheme, and, particularly, to determine the effect on the local rates of heat transfer.

In an earlier investigation McMahon (1958) studied the effect of ejecting a cool gas from the nose of a blunt body. He tried various methods of ejecting the gas, and observed the associated flow patterns. In addition, he measured the pressure distributions on the body, and obtained some measurements of the overall rates of heat transfer over fairly large segments of the body. Initially, McMahon ejected a coolant gas straight out at the nose in a direction opposed to the main air stream, but the flow studies and pressure distributions indicate severe disturbances to the flow field. It was thought, somewhat naturally, that ejection in this manner would not be satisfactory as a means of reducing the rates of heat transfer. Accordingly deflector caps were fitted over the ejection orifice in an attempt to direct the coolant gas tangentially to the body surface. The investigation reported here started from this premise. That is, the aim in ejection should be to make the gas flow tangentially to the body surface, and thereby ensure that the inner part of the boundary layer is composed of cool gas. It was decided, however, that instead of using deflector caps, the ejected coolant would be encouraged to flow tangentially to the body surface by giving it some swirl in the ejection pipe. It was hoped that the centrifugal effect of the swirl would cause the coolant to flow radially outwards at ejection, and that the Coanda effect would subsequently cause it to adhere to the surface. The scheme worked, except at the largest rates of coolant ejection, but it was found that ejection in this manner is not a satisfactory method of easing the heating problem. Although the cool layers of coolant gas reduce the driving temperature difference, the high tangential velocity with which the coolant is injected into the boundary layer increases the wall stress considerably, and hence, by the Reynolds analogy, the heat flux. The results indicate that the effect of the increased shear predominates, at least for the conditions considered here. The matter was not, therefore, pursued further.

In view of these results attention was directed once more to straight-out ejection, for McMahon had subsequently found that this method of ejection actually produced an effective 'blanketing' of the body. Two flow régimes were found. Except at the smaller flow rates the coolant gas emerged as a forward-directed jet, causing the bow shock wave to bulge out in much the same way as with a solid spike (see, for example, Bogdonoff & Vas (1959)). The normal flow pattern is replaced by one in which the main air flow separates ahead of the model, thereby leaving a roughly conical 'dead-air' region in the vicinity of the nose. The flow external to the boundary layer, instead of having a stagnation point at the nose, now has a 'stagnation circle' where the incident flow meets the body. McMahon found that the pressures on the body within the dead-air region are greatly reduced compared with the pressures for no ejection. The results reported here show that, associated with these reduced pressures, there are greatly reduced values of heat flux. However, in the vicinity of the stagnation circle the pressures are somewhat above their values for no ejection. Associated with this there is an increased heat flux in a region around the stagnation circle. The nett result is that, although the region of severest heating is shifted, the overall heating is not greatly reduced, at least not unless large coolant flow rates are employed.

The second flow régime occurs when the coolant flow rate is sufficiently small that the coolant gas does not cause the bow shock wave to bulge out. With the external flow sensibly undisturbed, relatively large reductions in heat flux are obtained. The reductions in total heat transfer over the body are of the order of the 'heat capacity' of the coolant gas, defined for this purpose as the amount of heat that the gas can absorb in having its temperature raised from that just before ejection to the stagnation temperature of the main air stream.

The work reported here is an experimental determination of the local rates of heat transfer over a bluff body for various flow rates of a coolant gas, either nitrogen or helium, ejected either straight out or with swirl, in the manner already described. The momentum flow rate of the ejected coolant was not varied independently of the mass flow rate. To do so would be one way of extending the present work, for it would be extremely interesting to eject coolant gas at larger rates of mass flow, but with insufficient momentum to cause the bow shock wave to bulge out.

2. Brief description of the experiments

The experiments were made in the 5 in. × 5 in. hypersonic wind tunnel of the Guggenheim Aeronautical Laboratory at the California Institute of Technology. The nominal Mach number was 5·8, and the Reynolds number per inch based on free-stream conditions was about 0·2 million. At this Reynolds number and Mach number it was assured that the boundary layer on the model was laminar.

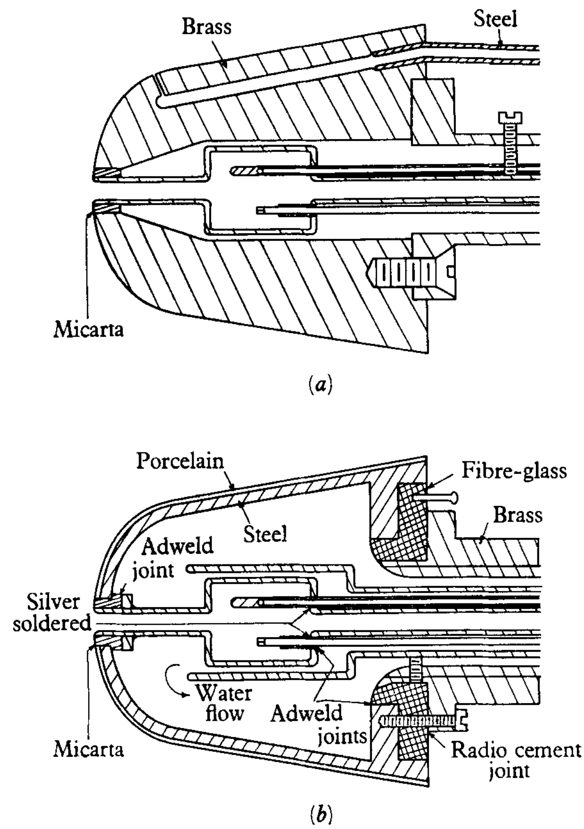

FIGURE 1. Construction of models. (a) Pressure model. (b) Temperature model.

The shape chosen for investigation consisted of a portion of a cone of 10° semi-angle, with the apex rounded to form a portion of an oblate spheroid of eccentricity 0·7315. Two models were constructed: one to obtain pressure distributions and the other to obtain temperature distributions. Figure 1 shows the internal construction of the models.

The pressure model was constructed of brass with nine conventional static pressure orifices of 0·016 in. diameter. Figure 2 shows the position of the pressure orifices, which were located helically on eight meridians. All pressures have been quoted as pressure coefficients, C_P, defined by

$$C_P = \frac{P - P_\infty}{\frac{1}{2}\rho_\infty V_\infty^2},$$

where P_∞, ρ_∞ and V_∞ are respectively the pressure, density and speed of the freestream. C_P has been normalized by dividing it by the pressure coefficient, C_{P_0}, at the nose for zero incidence and with no coolant ejection; which is, of course, the pressure coefficient behind a normal shock at the tunnel Mach number.

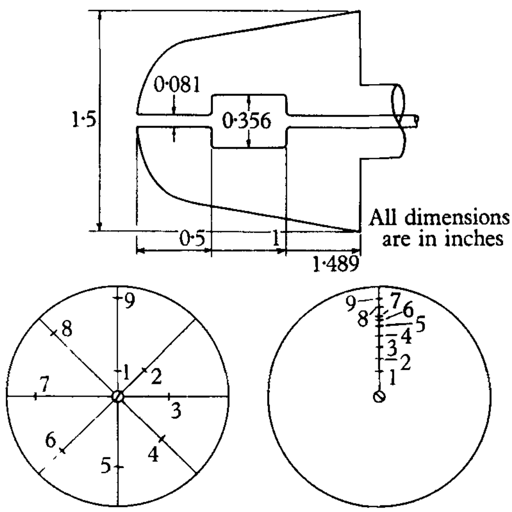

FIGURE 2. Geometry of models.

The temperature model was constructed of a mild steel with a wall thickness of 0·050 in., and coated with a layer of porcelain of thickness 0·020 in. Along one meridian of the temperature model nine thermocouples were formed by cementing a constantan wire of 0·001 in. diameter on the model, and then removing the cement coating at nine precisely located points with a knife blade. It thus became possible to make contact with the wire by means of silver paint at these nine points, thereby forming nine silver-constantan junctions (see figure 2). Painted silver leads connected the thermocouples so formed to turret posts set in fibre-glass on the base of the model. Some heat-meters also were installed on the temperature model with which it was hoped to measure the heat flux directly. However, unsatisfactory results were obtained with them, which will not be reported here.

The temperature model was cooled by water, the inflow being within the return-flow (see figure 1). The flow rate was on the average about 0·17 U.S. gallons per minute, varying at most by a factor of 2. The inflow water temperature whenever measured was always within 1 °F of 76 °F, and the maximum measured temperature rise overall, that is due to the heat picked up not only in the model but also in the attendant piping, was never greater than 7 °F, and usually less than 3 °F. It can be shown (Warren 1958) that the heat flux, $\dot{q}$, at a particular point across a thin skin of low thermal conductivity is fairly uniform, and is given very closely by

$$\dot{q} = \frac{k}{\delta}(T - T_i),$$

where k is the thermal conductivity of the skin material, δ is the thickness of the skin, T is the temperature of the outer surface at the particular point, and T_i is the corresponding temperature of the inner surface.

Since the thermal conductivity of porcelain is about one-sixtieth of that of steel, it is not unreasonable to assume that most of the temperature drop across the wall of the model occurs in the 0·020 in. layer of porcelain, and that the inner surface of the porcelain is not far removed from the water temperature, which, in the model, was about 80 °F. In view of the failure to obtain satisfactory results with the heat-meters, normalized local rates of heat transfer were obtained from the measurements of surface temperature by assuming that

$$\frac{\dot{q}}{\dot{q}_0} = \frac{T - T_i}{T_0 - T_i},$$

where $\dot{q}_0$ is the heat flux at the nose for zero incidence and with no coolant ejection, T is the measured surface temperature, T_0 is the surface temperature at the nose for zero incidence and with no coolant ejection (measured to be 130 °F), and T_i is the inner surface temperature, assumed to be 80 °F.

The nitrogen and helium gases used in the ejection studies were fed into the model via a pipe within the inflow water pipe. This procedure ensured that the coolant gas reached the model at a fairly constant temperature. Within the model the gas entered a plenum chamber (see figure 1) where a pressure probe and an iron-constantan thermocouple enabled the pressure and temperature of the gas to be determined. From the plenum chamber the gas was conveyed to the nose of the model through an ejection pipe of 0·081 in. inside diameter and 0·5 in. long, the edges of the ejection hole being rounded to a radius of about 0·02 in. The same physical parts for the coolant ejection were used in both the pressure and temperature models. The coolant mass flow rate, $\dot{m}$, has been quoted as a mass flow coefficient, $C_{\dot{m}}$, based on the free-stream mass flow rate through a capture area equivalent to the frontal area of the model, so that

$$C_{\dot{m}} = \frac{\dot{m}}{\rho_\infty V_\infty \pi(\frac{1}{2}D)^2},$$

where D is the model base diameter.

The swirl that was given to the coolant in some of the tests was obtained by inserting in the ejection pipe a twisted strip of brass 0·01 in. thick and 0·5 in. long. The strip was twisted through one complete turn clockwise, so that the helical advance angle at the wall was about 63°. It was appreciated that such a device would not produce initially a rotationally symmetric coolant flow, but it was hoped that, once away from the ejection orifice, the flow would even out. On the pressure model the setting of the swirler at the ejection orifice made an angle of about 40° with the meridian through pressure orifices 1 and 9, as indicated in figure 2. On the temperature model two positions were tested: one made an angle of about 45° with the meridian through the thermocouples, as indicated in figure 2, and the other made an angle of about 90°.

Further details of the experiments, together with all the results obtained, are given elsewhere (Warren 1958). Only a selection of the results are presented here.

3. Results for no ejection

Distributions of pressure and heat flux in the plane of incidence with no ejection at incidences of 0, 4 and 8° are shown in figures 3 and 4, in terms of the distance, s, from the model nose along a meridian. It was found that there is no noticeable variation of pressure or heat flux with incidence in the meridian plane normal to the plane of incidence, at least up to an incidence of 8°.

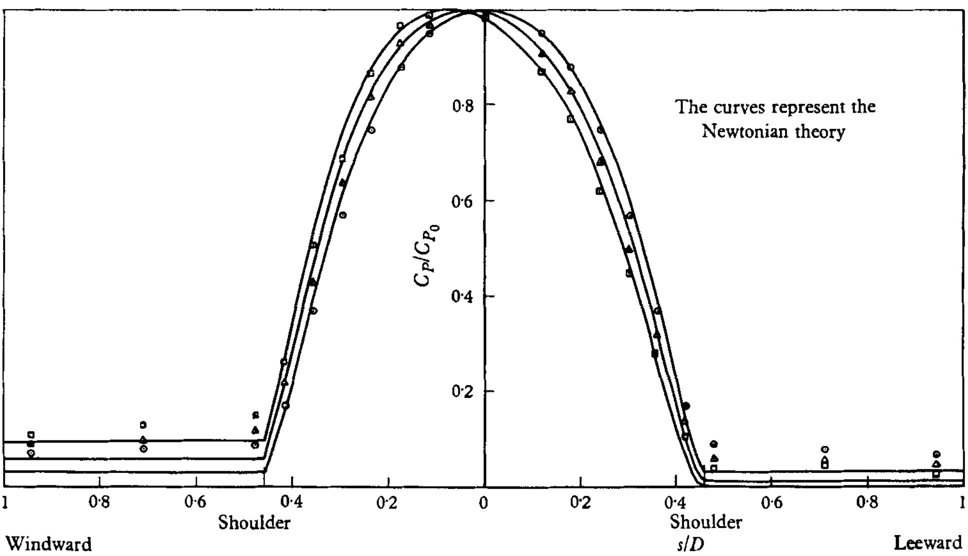

FIGURE 3. Distributions of pressure in the plane of incidence for no ejection ($C_{\dot{m}} = 0$). $\odot$, $\alpha = 0°$; $\triangle$, $\alpha = 4°$; $\boxdot$, $\alpha = 8°$.

The pressure results are in fair agreement with Newtonian theory, which states that the pressure is given by

$$\frac{C_P}{C_{P_0}} = \sin^2 \eta,$$

where η is the angle of the surface to the direction of motion, except on the conical portion, where the Newtonian approach underestimates the pressure. The pressure results are also in good agreement with those of Richards (1957), who earlier tested a model of nominally identical geometry.

The heat flux results at zero incidence are in fair agreement with calculations based on the theory of Lees (1956). In these calculations the measured, as distinct from the theoretical, pressure distribution was used, and allowance was made for the small effects associated with a pressure gradient. The poor agreement over the conical portion may be associated with the measurements, for the method whereby the heat flux is derived is of least accuracy when the heat flux itself is small. Calculations based on the theory of Cohen & Reshotko (1956), although more difficult to perform, were in substantial agreement with those based on the theory of Lees.

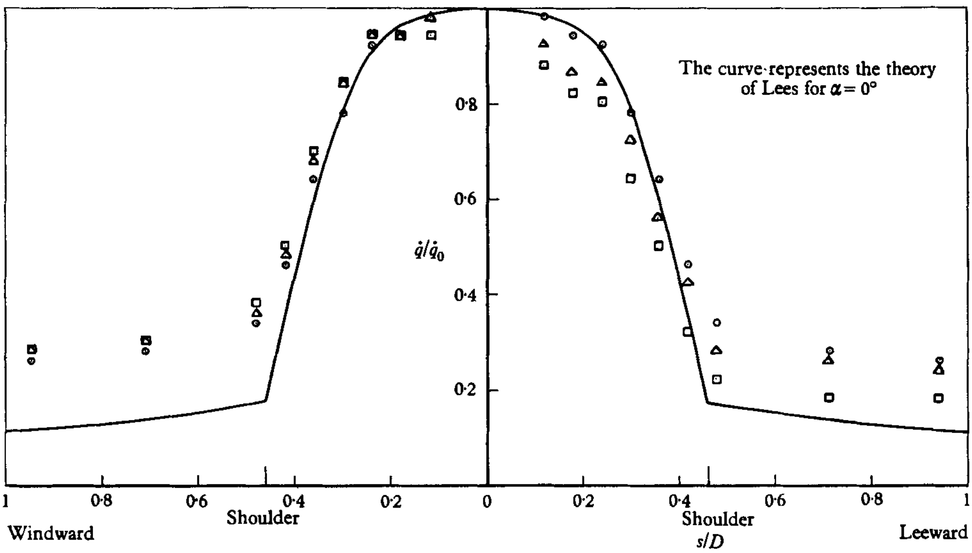

FIGURE 4. Distributions of heat flux in the plane of incidence for no ejection ($C_{\dot{m}} = 0$). $\odot$, $\alpha = 0°$; $\triangle$, $\alpha = 4°$; $\boxdot$, $\alpha = 8°$.

4. Variation of ejection conditions with coolant flow rate

On the assumption of one-dimensional flow in the coolant gas pipe, the Mach number in the plenum chamber never exceeds 0·03, based on the measurements of mass flow rate and of pressure and temperature in the plenum chamber. The plenum chamber pressures and temperatures can therefore be treated as representing total conditions. On this assumption, and again that of one-dimensional flow, the Mach number, M_e, at the entry to the final ejection pipe can be calculated. This Mach number is shown in figures 5 and 6. The constancy of Mach number shown in figure 5 for mass flow coefficients above about 0·005 for nitrogen or 0·0015 for helium is evidence that, for ejection with swirl, the flow in the swirl pipe is choked. Figure 6 shows that for straight-out ejection the onset of choking is delayed to a mass flow coefficient about 0·008 for nitrogen and 0·0025 for helium. The Mach numbers themselves should be treated as qualitative only, owing to the assumption of one-dimensional flow made in their derivation, and to the fact that Mach number is extremely sensitive to area ratio near a Mach number of unity.

For straight-out ejection the momentum flow rate of the ejected gas can be calculated, again on a one-dimensional flow assumption, and ignoring any losses in the final ejection pipe, which are estimated to be small. The calculated momentum flow rates are shown in figure 7 as momentum flow coefficients $C_{\dot{\mu}}$, defined as

$$C_{\dot{\mu}} = \frac{\dot{m}V_{ej}}{\rho_\infty V_\infty^2 \pi(\frac{1}{2}D)^2},$$

where V_{ej} is the velocity of ejection. It will be noted that for small mass flow rates, such that the flow in the ejection pipe is not choked, the momentum flow rate for helium, and hence its speed of ejection, is about seven times that for nitrogen for the same mass flow rate, as would be expected from the relative densities of helium and nitrogen.

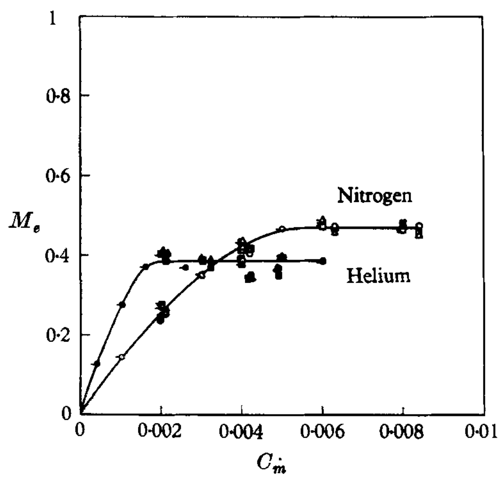

FIGURE 5

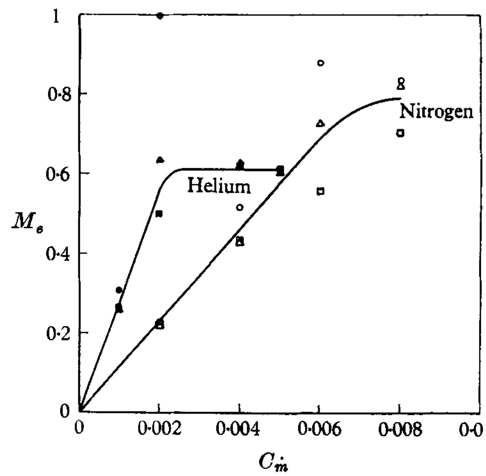

FIGURE 6

FIGURE 5. Mach number of coolant at entry to the final swirl pipe for ejection with swirl. ○ ●, $\alpha = 0°$; △ ▲, $\alpha = 4°$; □ ■, $\alpha = 8°$. The flagged points are for the pressure model, the unflagged points are for the temperature model.

FIGURE 6. Mach number of coolant at entry to the final ejection pipe for straight-out ejection. ○ ●, $\alpha = 0°$; △ ▲, $\alpha = 4°$; □ ■, $\alpha = 8°$.

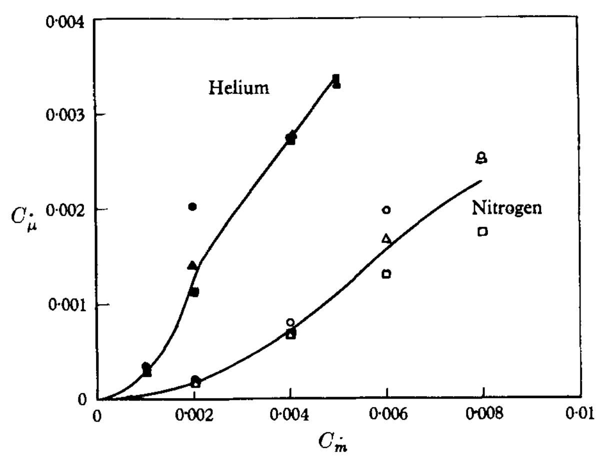

FIGURE 7. Variation of coolant momentum flow with coolant mass flow for straight-out ejection. ○ ●, $\alpha = 0°$; △ ▲, $\alpha = 4°$; □ ■, $\alpha = 8°$.

5. Effects of ejection on the flow pattern

The effects of ejection on the flow pattern can be deduced from an examination of the schlieren photographs and the measured surface pressure distributions.

For straight-out ejection at very small flow rates no noticeable change in the schlieren picture occurs (see figures 8*a*, *b*, plate 1). At a certain critical flow rate, however, the bow shock wave begins to bulge out (see figure 8*c*, plate 1). This critical flow rate appears to increase with increase in incidence (see figures 8*g*, *h*, plate 2). At zero incidence it occurs at a mass flow coefficient of about 0·003 with nitrogen and of about 0·001 with helium. From figure 7 we

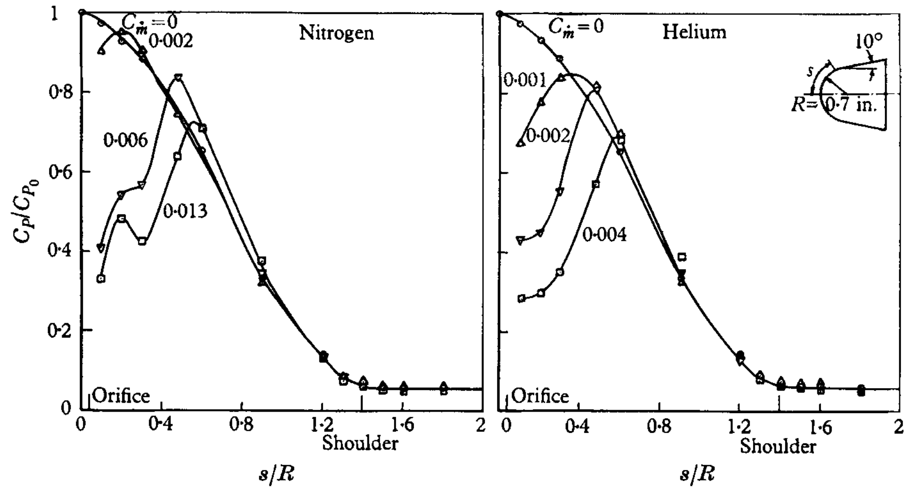

FIGURE 9. Distributions of pressure at zero incidence ($\alpha = 0°$) for straight-out ejection. (McMahon's results for a sphere-cone model.) $C_{\dot m} = \dot m/\rho_\infty V_\infty \pi R^2$.

see that these mass flow coefficients correspond to a momentum flow coefficient in each case of about 0·00035,* thereby confirming the work of Lam (1959) who suggests that the flow pattern is determined, at small flow rates, by the momentum flow coefficient of the ejected gas. Above the critical flow rate the bow shock wave is bulged out, and from the results of McMahon (1958) there is an associated marked change in the surface pressure distribution. McMahon studied the same problem on a model of about the same size, but having a spherical instead of a spheroidal nose, and an ejection orifice smaller by about 25 %. His tests were made at the same Mach number and about the same Reynolds number. His results are shown in figure 9. It will be noted that the surface-pressure distribution is not markedly changed for a mass flow coefficient of 0·002 with nitrogen, corresponding to an unbulged bow shock wave. For all other mass flow coefficients shown, however, there are marked changes, corresponding to bulged bow shock waves. The pressure distributions are in fact similar to those that occur when a spike protrudes from the nose of a model,

* This momentum flow coefficient based on model base area is equivalent to a momentum flow coefficient of 0·12 based on ejection orifice area.

implying that the ejected gas acts as a 'gas spike'. It will be seen from figure 9 that ejection reduces the pressures in the vicinity of the nose. At the smaller flow rates there is, somewhat surprisingly, an associated reduction in the plenum chamber pressure, P_p (see figure 10). Moreover, the plenum chamber pressure varies appreciably with incidence at the smaller flow rates. This is presumably because the conditions at the ejection orifice vary appreciably with incidence. With helium when the mass flow coefficient is above about 0·003 this dependence on incidence disappears: this is no doubt associated with the fact that above this flow rate the flow in the ejection pipe is choked, as mentioned in § 4. With nitrogen the plenum chamber pressure depends on incidence at all flow rates up to that corresponding to a mass flow coefficient of 0·008, the maximum tested: this too is in keeping with the result, obtained in § 4, that the flow in the ejection pipe is unchoked for mass flow coefficients less than 0·008.

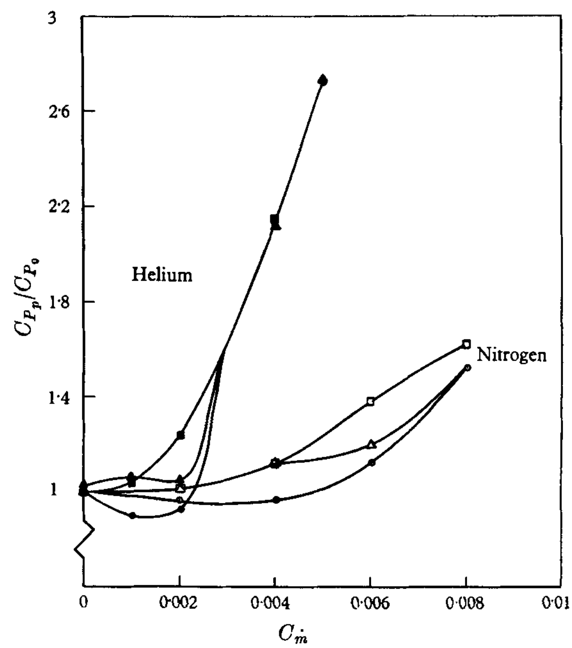

FIGURE 10. Plenum chamber pressure for straight-out ejection. ○ ●, $\alpha = 0°$; △ ▲, $\alpha = 4°$; □ ■, $\alpha = 8°$.

For ejection with swirl the critical flow rate above which the bow shock wave begins to bulge out is greater than for straight-out ejection (see figures 8*c*, *d*, *i* and *j*, plates 1, 2). It would appear, therefore, that the swirler is achieving its desired effect. At zero incidence the critical flow rate occurs at a mass flow coefficient of about 0·008 with nitrogen and of about 0·003 with helium. For ejection with swirl the concept of a momentum flow rate is not so easy to formulate, but it is interesting to note that the ratio of the two critical mass flow rates for ejection with swirl is roughly the same as the corresponding ratio for straight-out ejection, namely about $\sqrt{7}:1$. For ejection with swirl, however, it was found that the critical flow rate decreases with increase in incidence (see figures 8*d*, *e* and *f*, plate 1). The variations in the surface pressure distribution for ejection with swirl (as measured in the model of the present investigation) are shown in figures 11 and 12. As noted also in the results for straight-out ejection the surface-pressure distributions at zero incidence (figure 11) are not

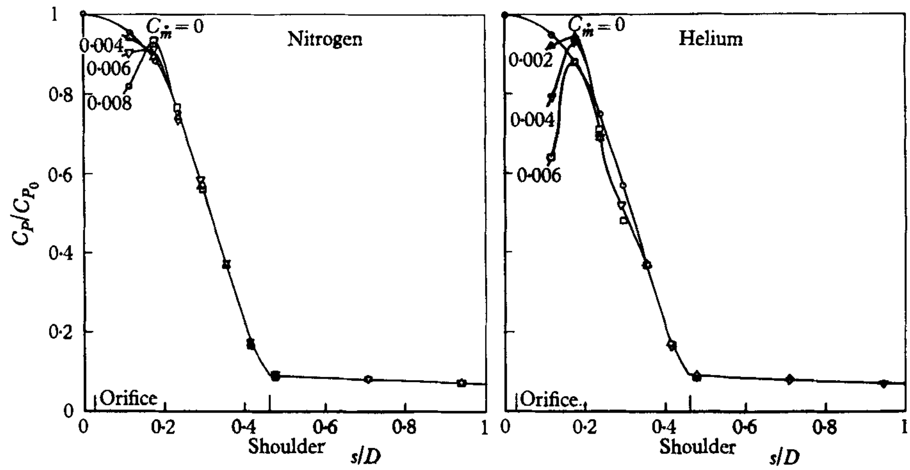

FIGURE 11. Distributions of pressure at zero incidence ($\alpha = 0°$) for ejection with swirl.

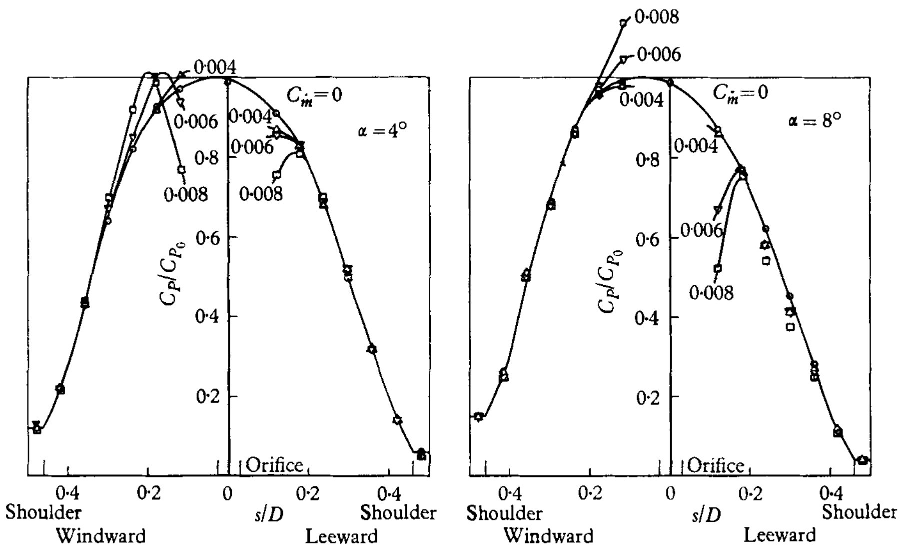

FIGURE 12. Distributions of pressure in the plane of incidence for the ejection with swirl of nitrogen.

markedly changed for mass flow coefficients for which the schlieren pictures indicate an unbulged bow shock wave (mass flow coefficients less than about 0·008 with nitrogen and less than about 0·003 with helium), but there are marked changes corresponding to bulged bow shock waves.

The variations in plenum chamber pressure are shown in figure 13. The plenum chamber pressures do not vary noticeably with incidence: this is no doubt because, with swirl, the flow in the swirl pipe is choked when the mass flow coefficient is above about 0·005 for nitrogen or 0·0015 for helium (see §4); and up to these flow rates, as we have seen, the bow shock wave is not bulged out, the flow ahead of the body is little affected, and the pressures in the vicinity of the nose do not vary much with either incidence or coolant flow rate.

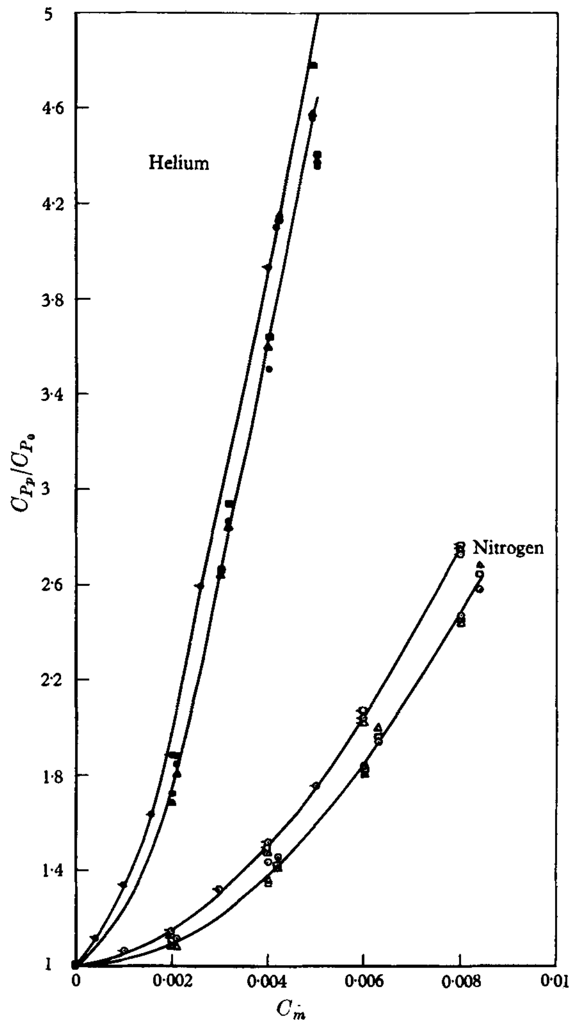

FIGURE 13. Plenum chamber pressure for ejection with swirl. ⊙ ●, $\alpha = 0°$; △ ▲, $\alpha = 4°$; ⊡ ■, $\alpha = 8°$. The flagged points are for the pressure model, which was uncooled; the unflagged points are for the temperature model.

It will be noted, however, by comparing figures 10 and 13 that, for the same mass flow rate, much greater driving pressures are required for ejection with swirl than for straight-out ejection. The slightly greater driving pressures required with the pressure model compared with the temperature model, indicated in figure 13, are because the pressure model was uncooled, and accordingly the temperatures in the plenum chamber were some 100 °F higher than with the temperature model.

6. Effect of ejection on the distribution of heat flux

The distributions of heat flux for ejection with swirl at zero incidence are shown in figure 14. Results are shown for one flow rate with each coolant, the flow rates chosen being ones for which the schlieren and pressure studies considered in §5 indicated that the swirler was working, in the sense that the bow shock wave was not bulged out (see figures 8*d*, *j*, plates 1, 2) and the distributions of pressure were not markedly different from the case of no ejection (see figure 11). The first thing that one notices in figure 14 is that the results depend

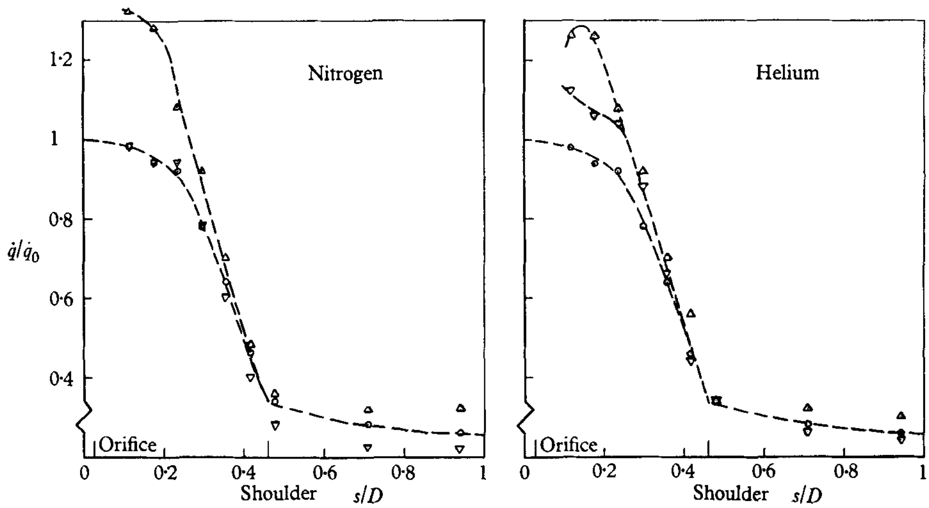

FIGURE 14. Distributions of heat flux at zero incidence ($\alpha = 0°$) for ejection with swirl. Nitrogen: $\odot$, $C_{\dot{m}} = 0$; $\triangle$, $C_{\dot{m}} = 0{\cdot}006$, swirler at 45°; ∇, $C_{\dot{m}} = 0{\cdot}006$, swirler at 90°. Helium: $\odot$, $C_{\dot{m}} = 0$; $\triangle$, $C_{\dot{m}} = 0{\cdot}002$, swirler at 45°; ∇, $C_{\dot{m}} = 0{\cdot}002$, swirler at 90°.

critically upon the setting of the swirler, implying that the swirler is not giving a rotationally symmetric distribution of coolant gas over the model. In view of these results an attempt should have been made to obtain a more nearly rotationally symmetric distribution of coolant gas. However, the main observation obtained from figure 14, and from other results not shown here, is that ejection with swirl seems to lead to an increase in heat flux. Accordingly the matter was not pursued, but attention directed instead to straight-out ejection.

An explanation of the increase in heat flux produced by ejection with swirl is provided by the Reynolds analogy, which states that the ratio of the Nusselt number to the product of the surface friction coefficient and the Reynolds number is a constant depending upon the surface temperature and the longitudinal pressure gradient, or

$$\dot{q} \propto \frac{k(T_a - T)}{\mu V_b}\tau,$$

where T is the surface temperature, T_a is the adiabatic surface temperature (that is the surface temperature for which the heat flux is zero), V_b is the velocity at the external edge of the boundary layer, τ is the surface shear stress, k is the thermal conductivity, and μ is the dynamic viscosity.

Now the main effect of the introduction of a coolant is to reduce the driving temperature difference $(T_a - T)$, and this is the basis on which it works, but in ejection with swirl the coolant is injected tangentially into the boundary layer at the nose with very high velocity, much greater than the average velocity of the uninjected boundary layer, with the result that the surface shear stress is increased manyfold. The results obtained seem to indicate that the increase in τ outweighs the reduction in $(T_a - T)$ and the changes in the other quantities, particularly k and μ. If tangential injection into a boundary layer is to be instrumental in reducing heat flux it must be done with much less momentum for a given mass flow than was achieved in these experiments.

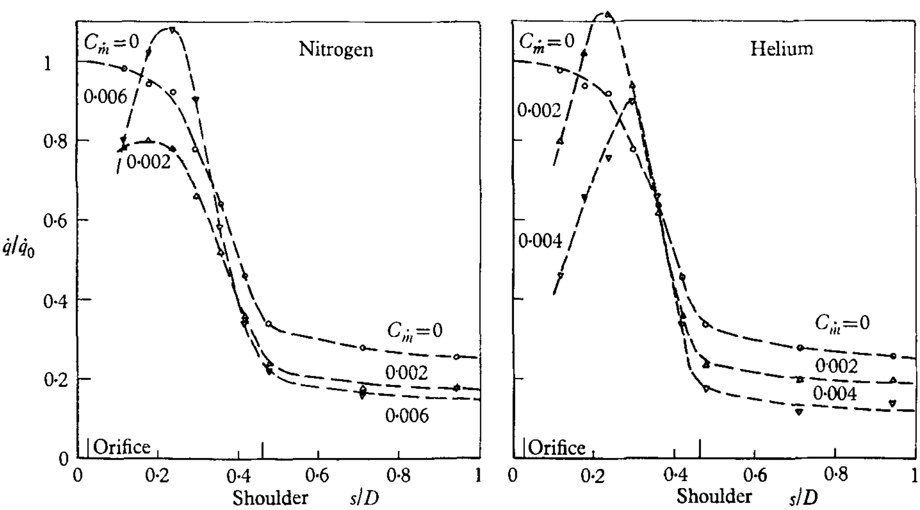

FIGURE 15. Distributions of heat flux at zero incidence ($\alpha = 0°$) for straight-out ejection.

The distribution of heat flux for straight-out ejection at zero incidence are shown in figure 15. The curve for nitrogen at a mass flow coefficient of 0·002 is of a markedly different shape from the curves for the other three cases. Moreover, it corresponds to a reduction in heat flux along the entire body profile. From the schlieren and pressure studies considered in §5 this case is one for which the coolant is introduced with sufficiently little momentum that it does not cause the bow shock wave to bulge out (see figure 8*b*, plate 1), or the pressure distribution to be markedly different from the case of no ejection (see figure 9). The other three cases (nitrogen at a mass flow coefficient of 0·006 and helium at mass flow coefficients of 0·002 and 0·004) all correspond to bulged bow shock waves (see figures 8*c*, *i*, plates 1, 2), and markedly different pressure distributions (see figure 9). In these cases although large reductions in heat flux are obtained in the vicinity of the nose, there is an increase further round the profile, where s/D is about 0·25. These results agree with those of McMahon (1958). He found large reductions in the average heat flux over the nose sector of a sphere of 60° included angle, but considerably smaller reductions over a sector of 120° included angle.

The explanation of these results is provided by considering the associated flow patterns. As shown in § 5, in these cases the ejected gas acts as a 'gas spike', causing the main air flow to separate ahead of the model thereby leaving a roughly conical 'dead-air' region in the vicinity of the nose. The flow external to the boundary layer, instead of having a stagnation point at the nose, now has a 'stagnation circle' where the incident flow meets the body, along which the heat flux is increased compared with the heat flux at the same station for no ejection. Inside the dead-air region the pressure is greatly reduced (see figure 9), and this reduction in pressure is largely responsible for the reduced heat flux in the vicinity of the nose.

It is of interest to consider the ratio of the reductions in total heat transfer to the 'heat capacity' of the ejected gas, taken as

$$\dot{m}c_p(T_s - T_p).$$

This expression represents the amount of heat that the gas can absorb when its temperature is raised from that in the plenum chamber, T_p, to the stagnation temperature of the main air flow, T_s; c_p is the specific heat of the gas at constant pressure. For nitrogen ejected straight out at a mass flow coefficient of 0·002, corresponding to an unbulged bow shock wave, the ratio of the reduction in total heat transfer up to the station $s/D = 1$ to the 'heat capacity' of the ejected gas is about 1·1. That this is greater than unity implies that the nitrogen is acting more than as a blanket; that is, a greater reduction in heat transfer is being achieved than would correspond to the absorption by the nitrogen of the heat that would otherwise have been transferred to the model. The ratio of the reduction in total heat transfer up to the shoulder ($s/D = 0{\cdot}459$) to the 'heat capacity' of the ejected gas is about 0·4, which is still remarkably high. These figures should be compared with those for helium for the same mass flow rate, remembering that in this case the shock wave is now bulged out (see figure 8*i*, plate 2). The ratio of the reduction in total heat transfer up to the station $s/D = 1$ to the 'heat capacity' of the ejected gas is about 0·1, which is less than one-tenth of the value with nitrogen: the ratio based on the total heat transfer up to the shoulder is roughly zero.

The implication of these results seems to be that if the gas can be ejected without causing the bow shock wave to bulge out, as is the case with nitrogen ejected at a mass flow coefficient of 0·002, then a steady reduction in heat flux with increase in flow rate should be achieved. This state of affairs can be achieved by arranging that the mass flow rate be increased without increasing the momentum flow rate, so that on impingement with the air the coolant is directed around the body without too much mixing and consequent reduction of its heat alleviation properties. The importance of this observation is brought out by the results for nitrogen and helium ejected at a mass flow coefficient of 0·002 already referred to. Although it has five times the heat capacity and is one-seventh of the density, implying a thicker layer for the same mass flow rate and velocity, helium is not as effective as nitrogen in reducing the heat flux at this flow rate simply because its heat alleviation properties are enormously reduced by mixing. It would obviously be extremely interesting to extend these experiments by varying the ejection pipe in such a way that the mass flow rate with a given gas could be varied independently of the momentum flow rate. In this way it should be possible to delay bulging the bow shock wave to higher mass flow rates, and substantial reductions in heat flux for quite small mass flow rates should thereby be achieved.

The effect of incidence on the distribution of heat flux for straight-out ejection is shown in figure 16 for nitrogen. Qualitatively the results are similar to those at zero incidence. At a mass flow coefficient of 0·002, corresponding to an unbulged bow shock wave, the heat flux is reduced less on the windward meridian than on the leeward meridian; and at an incidence of 8° ejection is having very little effect on the windward meridian. At a mass flow coefficient of 0·006, corresponding to a bulged bow shock wave, the heat flux is greater, over most of the model, than the heat flux at the lower flow rate, and on the windward meridian it is greater than with no ejection.

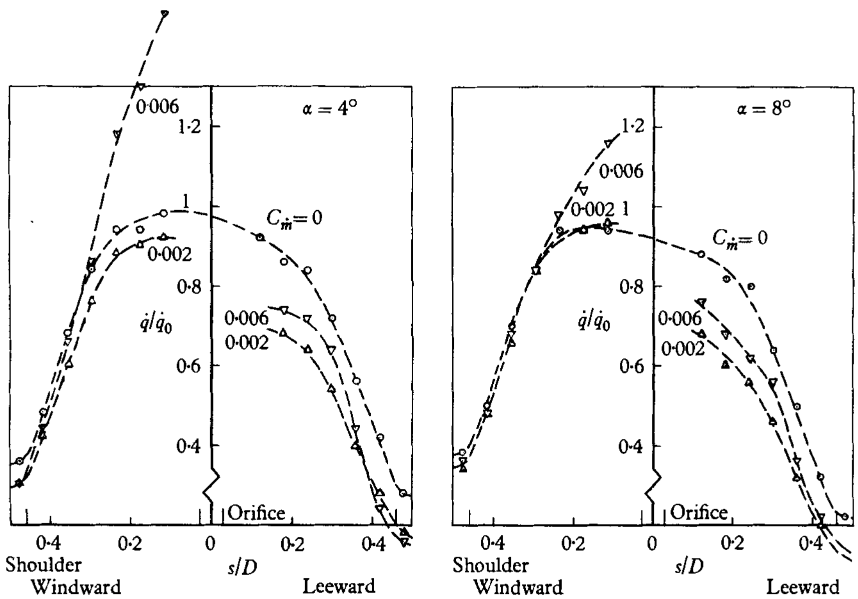

FIGURE 16. Distributions of heat flux in the plane of incidence for the straight-out ejection of nitrogen.

7. Conclusions

In the course of the investigation three ways of ejecting a coolant gas from the nose of a bluff body have become apparent, and something has been learned about the heat transfer rates associated with them.

The method that was tried initially was to encourage the coolant gas to flow tangentially to the model surface at ejection by giving it some swirl in the ejection pipe. The method was successful in the sense that, at the smaller flow rates, the coolant gas was ejected with very little disturbance to the flow external to the boundary layer, as witnessed by the pressure distributions and schlieren studies. However, this method of ejection is not satisfactory as a means of easing the heating problem. Although the cool layers of coolant gas reduce the driving temperature difference the high tangential velocity with which the coolant is injected into the boundary layer increases the surface shear considerably, and hence, by the Reynolds analogy, the heat flux. The results indicate that the effect of the increased shear predominates, at least for the conditions considered here. This method of ejection was therefore abandoned.

Attention was then centred on straight-out ejection, but here two flow régimes were found. Except at the smaller flow rates the coolant gas acts as a 'gas spike', causing the bow shock wave to bulge out and the main air flow to separate ahead of the model, thereby leaving a roughly conical 'dead-air' region in the vicinity of the nose. The flow external to the boundary layer, instead of having a stagnation point at the nose, now has a 'stagnation circle'. Inside the dead-air region the pressure is greatly reduced compared with the case of no ejection, and, associated with this reduced pressure, there is a greatly reduced heat flux. However, in the vicinity of the stagnation circle the pressure is somewhat above its value for the case of no ejection, and associated with this there is an increased heat flux. The nett result is that, although the region of severest heating is shifted, the overall heat transfer rate is not greatly reduced, at least not unless large flow rates are employed.

At the smaller flow rates the momentum of the ejected gas is not sufficient to disturb the external flow appreciably. The critical flow rate corresponds to a momentum flow coefficient of about 0·00035. With nitrogen this corresponds to a mass flow coefficient of 0·003, and with helium to a mass flow coefficient of 0·001. This method of ejection was investigated with nitrogen at a mass flow coefficient of 0·002, and under these conditions relatively large reductions in heat flux were obtained all over the model. The reductions in total heat transfer were of the order of the 'heat capacity' of the coolant nitrogen, where the 'heat capacity' is defined for this purpose as the amount of heat that the gas can absorb in having its temperature raised from that just before ejection (i.e. in the plenum chamber) to the stagnation temperature of the main air stream. In comparison, for the straight-out ejection of helium at the same mass flow coefficient of 0·002, but a case in which the bow shock wave is now bulged out, the reduction in total heat transfer over the model was no more than one-tenth of the 'heat capacity' of the coolant helium.

Clearly the method of ejecting straight out, but without sufficient momentum to cause the blow shock wave to bulge out, seems extremely promising as a means of alleviating the heating problem. It would form an obvious and interesting extension of the present experiments to be able to vary the momentum flow rates and mass flow rates of an ejected coolant independently. This could be done by varying the size of the ejection pipe.

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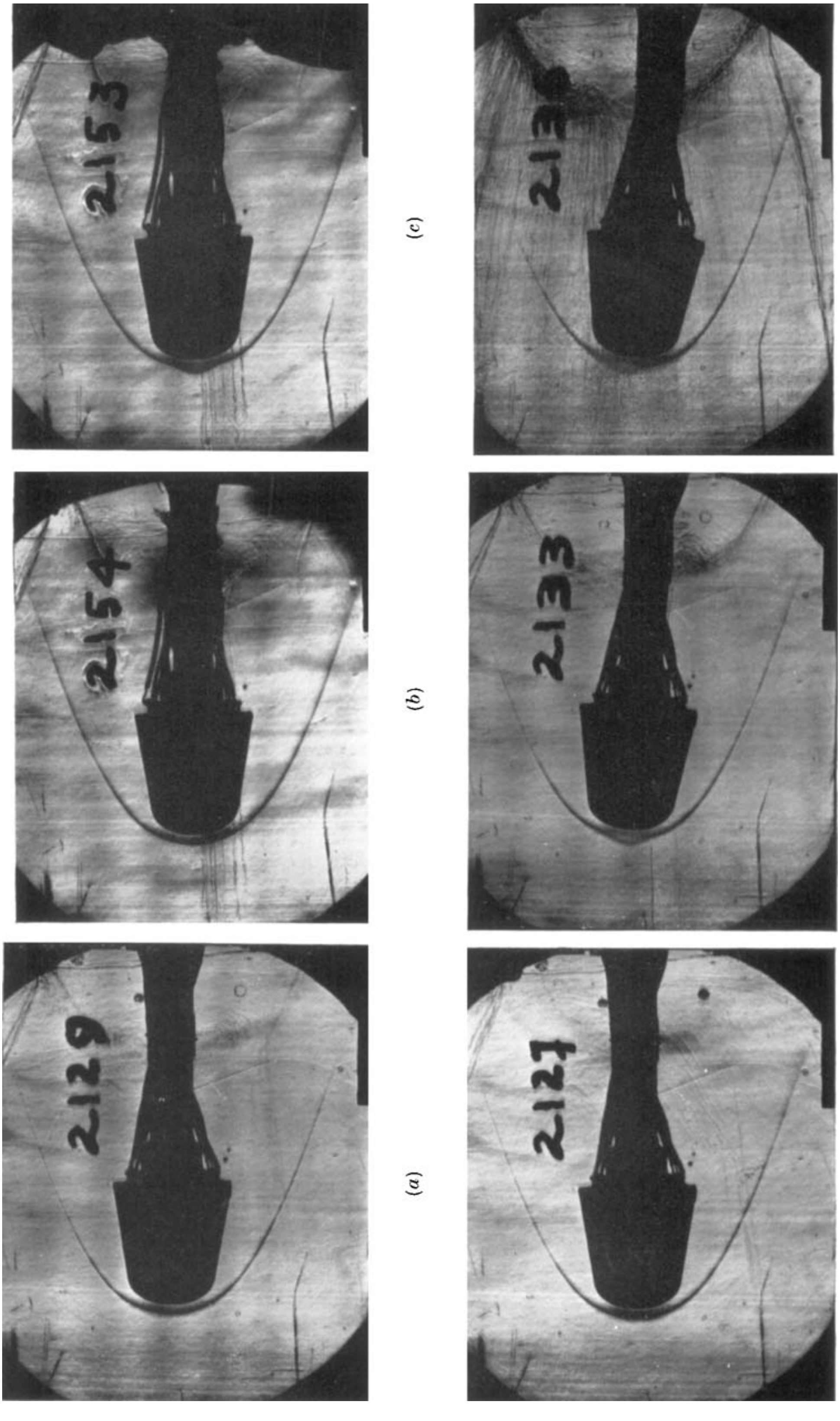
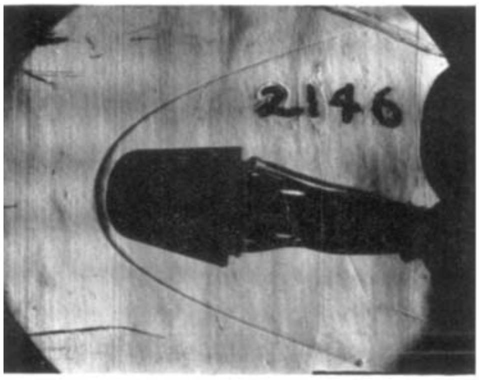
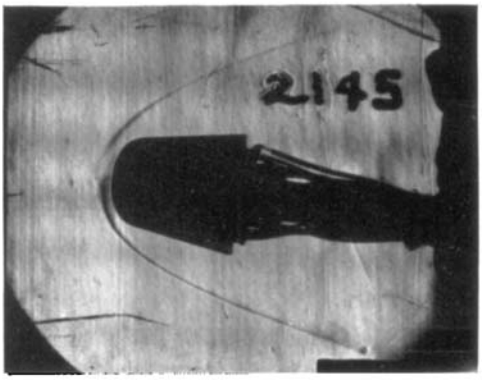


(c) (b) (a) (f) (e) (d)

Figure 8 (plate 1). Schlieren photographs. (*a*) No ejection, $C_{\dot{m}} = 0$; $\alpha = 0^\circ$. (*b*) Nitrogen ejected straight out, $C_{\dot{m}} = 0{\cdot}002$; $\alpha = 0^\circ$. (*c*) Nitrogen ejected straight out, $C_{\dot{m}} = 0{\cdot}004$; $\alpha = 0^\circ$. (*d*) Nitrogen ejected with swirl, $C_{\dot{m}} = 0{\cdot}006$; $\alpha = 0^\circ$. (*e*) Nitrogen ejected with swirl, $C_{\dot{m}} = 0{\cdot}006$; $\alpha = 4^\circ$. (*f*) Nitrogen ejected with swirl, $C_{\dot{m}} = 0{\cdot}006$; $\alpha = 8^\circ$.



(*g*)



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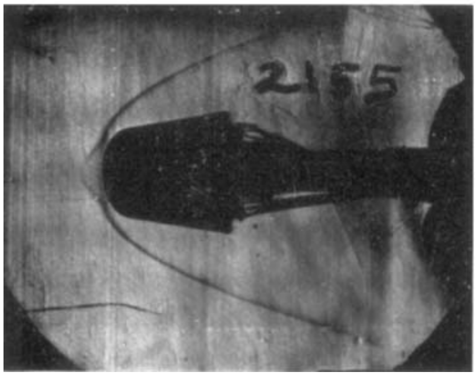
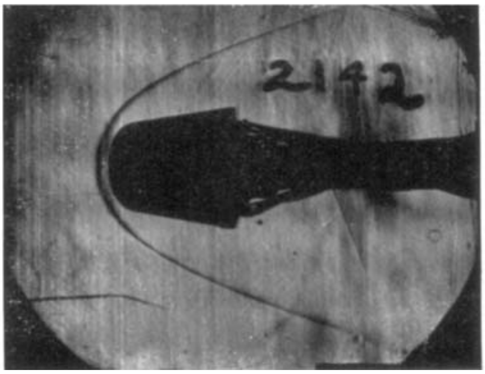


(*i*)



(*j*)

FIGURE 8 (plate 2). Schlieren photographs. (*g*) Nitrogen ejected straight out, $C_{\dot{m}} = 0{\cdot}004$; $\alpha = 8^\circ$. (*h*) Nitrogen ejected straight out, $C_{\dot{m}} = 0{\cdot}006$, $\alpha = 8^\circ$. (*i*) Helium ejected straight out, $C_{\dot{m}} = 0{\cdot}002$, $\alpha = 0^\circ$. (*j*) Helium ejected with swirl, $C_{\dot{m}} = 0{\cdot}002$; $\alpha = 0^\circ$.

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