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An experimental study of the near wake of a slender cone at varying incidence at $M_\infty = 7$

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An extensive experimental study of the near wake of a 9° half-angle sharp cone at incidence at $M_\infty = 7$ has been conducted. The model was suspended by six thin wires. The flow field in the plane of symmetry was surveyed from 0 to 2·5 diameters downstream of the base in the axial direction, and to the bow shock in the transverse direction. For three values of incidence (0°, 5° and 15°), measurements were made of the static pressure, Pitot pressure and stagnation temperature, from which the streamline pattern was determined. In addition the $u = 0$ line was found independently. The results of the measurements were also used to trace lines of constant Pitot pressure showing the shock waves, and lines of constant stagnation temperature in the viscous wake.

1. Introduction

The near-wake problem has received a significant amount of interest owing to its importance in the development of hypersonic re-entry vehicles. A good knowledge of the configuration of the near wake is essential for the analysis of the far-wake problem. In addition, the configuration of the flow is useful from the viewpoint of detection. The theoretical aspect has been successfully investigated in the two-dimensional case but few studies have been devoted to the axisymmetric and three-dimensional problems. The work presented in this article is part of a continuing effort to provide experimental information that will help to describe the fluid mechanics of hypersonic wakes behind slender axisymmetric bodies at an angle of attack.

The model used in the tests is a sharp cone with a 9° half-angle supported by fine wires. The tests were performed at $M_\infty = 7$ in the hypersonic blowdown wind tunnel of the Institut de Mécanique des Fluides de Marseille. The Reynolds number Re_∞ could be varied from 0·25 to $1{\cdot}10 \times 10^5\,\mathrm{cm}^{-1}$, values for which the boundary layer at the model base was laminar for the zero-incidence case.

Systematic measurements of the static pressure, Pitot pressure, stagnation temperature and the $u = 0$ line have been obtained and transformed to streamlines.

2. Experimental techniques

The experimental work reported here was conducted in a $M_\infty = 7$ blowdown tunnel with a test section 200 mm in diameter. The stagnation pressure can be varied from 5 to 30 bars, corresponding to a Reynolds number change from 0·25 to $1{\cdot}40 \times 10^5\,\mathrm{cm}^{-1}$. The wall to stagnation temperature ratio is 0·49 with the model at the ambient temperature.

The model used in the tests is a sharp cone with a half-angle θ_c equal to 9° and a base diameter d equal to 50 mm. It was supported by six piano wires of diameter 0·3 mm. This suspension mode has been made a controversial issue chiefly by the researchers using magnetic suspension techniques. The conclusion of studies by Zakkay & Cresci (1966), Ragsdale & Darling (1966), Schmidt & Cresci (1967) and Softley & Graber (1967) concerning the use of support wires is that the effect of wires on the near-wake configuration is negligible if the ratio of wire diameter to model base diameter is less than about 0·008. The value of this ratio in the present tests was 0·006, so the eventual perturbations due to the presence of the wires may be considered to have a small effect on the near-wake profiles. To verify this assumption Pitot pressure measurements were made for a fixed value of y at $x/d = 1{\cdot}0$ and 2·3. Following the result of this study, it was concluded that the Pitot pressure measurements were not affected by the wires.

The diagnostic tools for the present study consisted of Pitot pressure, static pressure, total temperature and null velocity ($u = 0$) probes. The Pitot pressure probe was a cylindrical tube of external diameter 1 mm. The effects of displacement of the streamlines were evaluated using the results of Dewey (1965) and Batt (1967) and found to be small. The effect of misalignment of the probe with the local flow was investigated and found to be smaller than 1 % up to 10° incidence and less than 4 % up to 20° incidence.

The static pressure probe was constructed following the method of Behrens (1963) and Batt (1967). A small 10° half-angle cone is followed by a 1 mm diameter cylinder with four lateral holes for wall pressure measurements. The distance from these holes to the probe tip is 13·5 mm, a sufficient value for the recovery of the static pressure, according to Behrens (1963). The estimated viscous effect for the present probe is always less than 5 %. On the other hand, the incidence effect is important when the misalignment of the probe becomes higher than 10°.

A thermocouple junction obtained by butt welding together two wires of diameter 0·1 mm was used to measure the total temperature T_0. This junction was midway between the supports, which were 2·8 mm apart (figure 1). The probe was placed in the free stream at a total temperature of 600 °K; the temperature measured by the probe was 96 % of the free-stream value, which is in good agreement with the recovery factor for a cylinder under these conditions. The loop shape of the probe was particularly designed to study the near wake without noticeable perturbation.

A differential pressure probe was constructed using the method suggested by Batt (1967), to determine the location of the $u = 0$ line, along which the longitudinal component of the velocity is zero. This probe consists of pressure leads shaped like half-loops sealed together at their ends at the centre-line. Pressure orifices, one facing downstream and the other upstream, are located on either side of the centre cap. When the probe is moved through the recirculation region, the two pressures balance each other at the $u = 0$ point.

More details of these experimental techniques are given by Marcillat (1970).

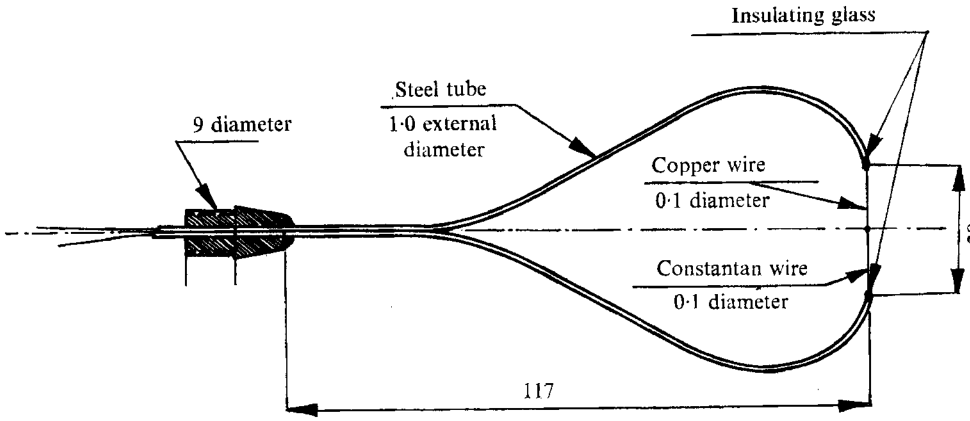


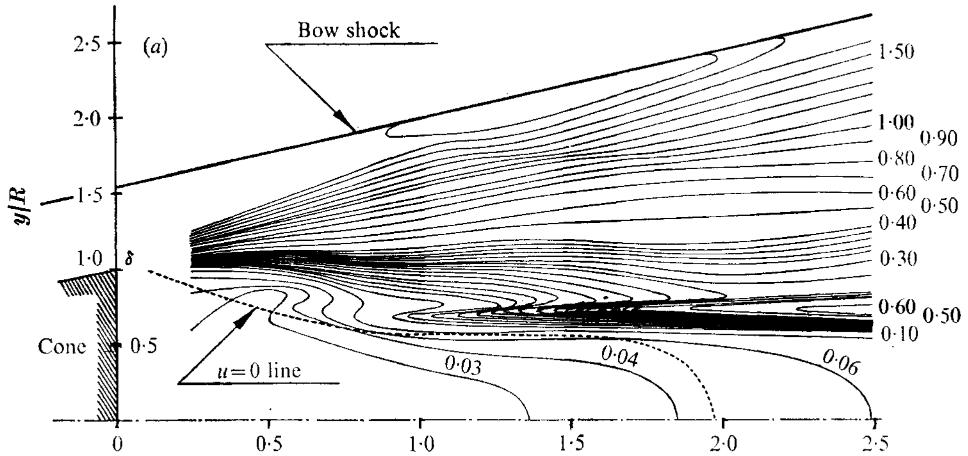
FIGURE 1. Sketch of total temperature probe. Dimensions in mm.

3. Presentation and discussion of results

3.1. *Zero-incidence tests*

The results of a detailed study of the flow near the base of a cone (Marcillat 1970) have been used to establish the initial conditions of the near wake. The boundary layer at the base of the cone is laminar with a thickness of 0·12 cm at the lowest available Reynolds number. The measured wall static pressure and edge Pitot pressure were in good agreement with the inviscid calculations of Jones (1968). No effort was made to detect transition in the near wake. Previous studies (Wen 1964; Pallone, Erdos & Eckerman 1964; Birkhoff, Eckerman & McKay 1966) have indicated a possibility of transition occurring at about 4 or 5 base diameters for the present test conditions.

The flow characteristics of the near wake were determined from a systematic Pitot pressure study. A map of constant Pitot pressure lines between the abscissa $x = 0$ and $x = 2{\cdot}5d$ is presented in figure 2 (a) for a free-stream Reynolds number of $2{\cdot}5 \times 10^4\,\mathrm{cm}^{-1}$ and in figure 2 (b) for $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$. From these figures one can locate the bow, lip and trailing shocks and the zero-velocity line. Over a major portion of the body and in the near wake, the bow shock is linear (confirmed by schlieren photographs) and agrees with the theoretical value (12·89° for $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$ and $M_\infty = 6{\cdot}85$ and 12·75° for $Re_\infty = 2{\cdot}5 \times 10^4\,\mathrm{cm}^{-1}$ and $M_\infty = 6{\cdot}67$). At the higher Reynolds number, the boundary-layer thickness near the base is 0·18 cm, rather than 0·12 cm, which consequently affects the shock-layer thickness. The trailing shock appears on the figure as an accumulation of constant Pitot pressure lines. The lip shock can also be located by this means but with a lower degree of accuracy as it is weaker. In addition, as the Pitot pressure is nearly constant between the boundary-layer edge on the cone and the bow shock, the continuation of this inviscid region lies between the bow shock and the line $P'_0/P'_{0\infty} = 1{\cdot}70$. According to its inclination, the small disturbance affecting the constant P'_0 lines in the low Reynolds number case is probably due to a nozzle failure which is transmitted by the thicker boundary layer closer to



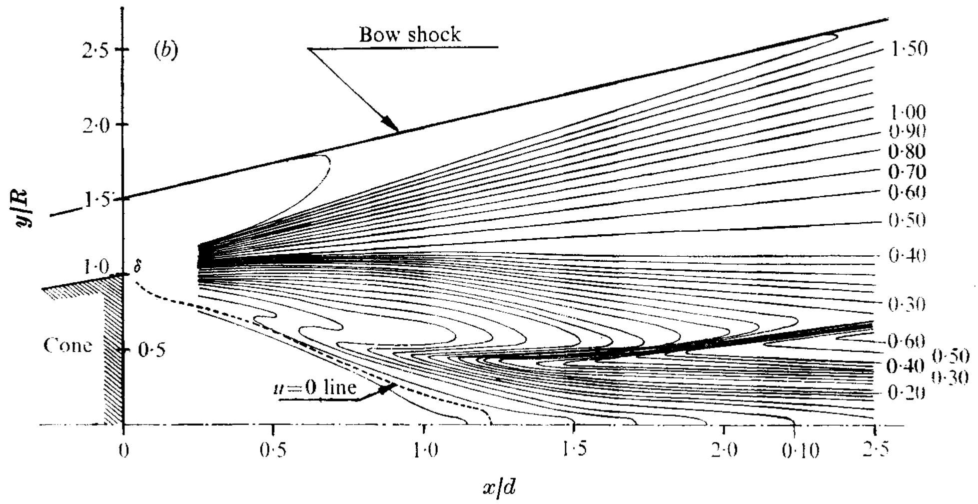


FIGURE 2. Maps of constant Pitot pressure ($i = 0$). (a) $Re^h_\infty = 2{\cdot}5 \times 10^4\ \mathrm{cm}^{-1}$. (b) $Re_\infty = 1{\cdot}1 \times 10^5\ \mathrm{cm}^{-1}$.

the wind-tunnel axis than in the high Reynolds number case. The expansion fan begins at this isobar but one needs static pressure data to define the other edge of the expansion fan.

These flow characteristics of the wake are shown in figure 3, including the $u = 0$ line for the two values of the free-stream Reynolds number. The contour $u = 0$, which was independently determined, is similar to adjacent Pitot pressure contours as shown in figure 2. The location of the $u = 0$ line is considerably affected by changing the Reynolds number as shown in figure 3. At the high Reynolds number ($Re_{\infty d} = 5{\cdot}5 \times 10^5$, based on d) the stagnation point is about $1{\cdot}2d$ from the base, and moves to about $2d$ at the lower Reynolds number ($Re_{\infty d} = 1{\cdot}25 \times 10^5$). The shape of the $u = 0$ line downstream of the base is in good agreement with the prediction of Weiss & Weinbaum (1966). The lip and trailing

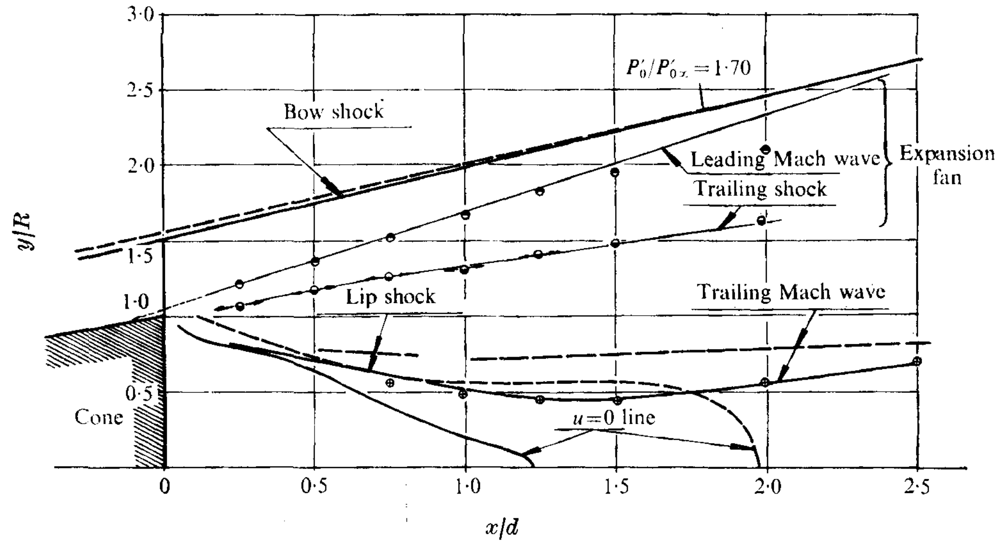


FIGURE 3. Flow characteristics of the near wake ($i = 0$). ———, $Re_\infty = 2{\cdot}5 \times 10^4\,\mathrm{cm}^{-1}$; ——, $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$. Data obtained from static pressure profiles: ◓, leading Mach wave; ◒, trailing Mach wave; ○, trailing shock.

shocks move away from the axis of the wake with decreasing Reynolds number (figure 3). It is interesting to note that these two shock waves appear to form a continuous shock structure as found by Hama (1966) and Batt (1967) in their experiments behind wedges for high free-stream Mach numbers.

The detailed exploration of the near wake by a static pressure probe confirmed some of the trends obtained by the Pitot measurements. The expansion fan is clearly indicated by the static pressure profiles; the leading and trailing waves determined by this means are shown in figure 3 and are in good agreement with the data deduced from the Pitot measurements. The same comment is applicable to the trailing shock wave.

In the near-wake region ($x < 2d$), as the trailing shock exists within the viscous core, the hypothesis of constant pressure throughout the core cannot be used to determine its width. However, the viscous wake can be identified by detailed measurements of the stagnation temperature. The edge of the viscous wake is defined as the location where the stagnation temperature reaches the value of the free-stream stagnation temperature.

For $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$, the radial distributions of total temperature at eight locations between $x = 0$ and $2{\cdot}5d$ have been used to establish constant total temperature lines (figure 4*a*). In presenting these measurements the edge of the viscous core has been arbitrarily taken to be at $T_0 = 0{\cdot}99T_0$. An unusual result which is clearly shown in these profiles is a cold inner core within the viscous core which appears downstream of $x = d$, i.e. the recirculation region. Such a phenomenon has been mentioned by Rom (1969) for the case of a wedge. The results of Zakkay & Cresci (1966) and Todisco & Pallone (1965) for cones show profiles which also indicate a cold inner core.

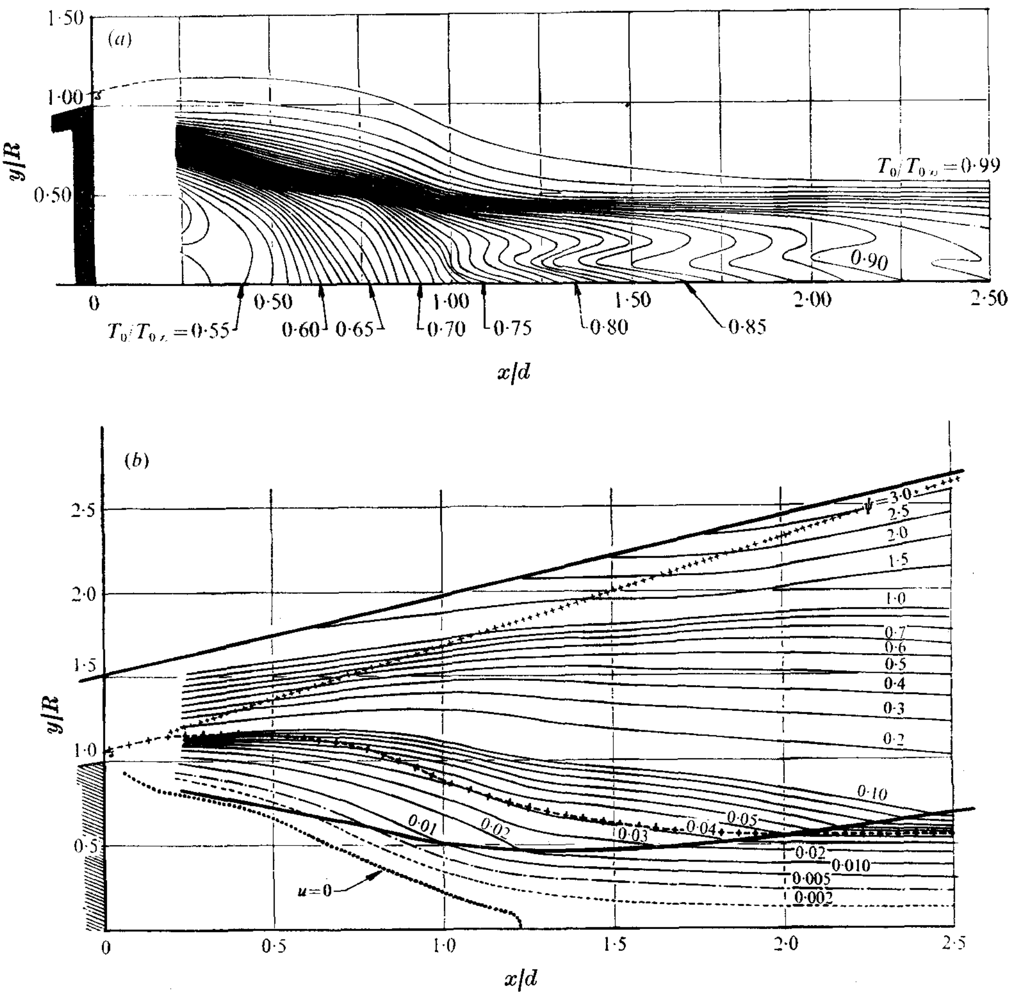


FIGURE 4. (*a*) Map of constant total temperature and (*b*) near-wake streamlines ($i = 0$, $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$). In (*b*): + + +, $P_0'/P_{0\infty}' = 1{\cdot}70$; + − + − +, $T_0/T_{0\infty} = 0{\cdot}99$.

The centre-line distribution of stagnation temperature is similar to previous results. At $x/d = 0{\cdot}25$ the temperature measured is slightly above the wall value ($T_w/T_{0\infty} = 0{\cdot}5$). In going downstream the temperature gradually increases, to $x/d = 0{\cdot}6$, after which a rapid increase occurs within the recirculation region. Downstream of the recirculation region, the temperature continues to increase to within 10% of the free-stream stagnation temperature at $x/d = 2{\cdot}5$ (see figure 7*b*).

The results of these measurements have been used to calculate other flow properties such as the Mach number M, velocity u, static temperature T and density ρ. From the cross-sectional data, the mass flow ρu was calculated and after integration,

$$\psi = \int_0^y \frac{u}{\rho_\infty u_\infty} y d(y),$$

streamlines obtained in the near wake between the axis and the bow shock (figure 4*b*).

The streamline map was used to correct the measured values of the static and Pitot pressures (which were made with the probe aligned with the free stream). Using a calibration of the static and Pitot probes (Marcillat 1970), the maximum error in the quantity ρu was found to be 3 %. This correction has been taken into account in figure 4(*a*). Also shown in figure 4(*b*) is the zero-velocity line ($u = 0$) given by the null probe. Good agreement is noted between these measurements and those obtained from the integrated quantity. Turning of the streamlines is consistent with the shock position obtained by the Pitot measurements; the stronger the shock the larger the deflexion of the streamline across the shock. Also shown in the figure is the leading wave given by the Pitot pressure measurements ($P'_0/P'_{0\infty} = 1{\cdot}70$) and the edge of the viscous layer ($T_0/T_{0e} = 0{\cdot}99$). The neck may be defined as the location where the stream tubes have become parallel to the centre-line, or as the location corresponding to the minimum thickness of the viscous wake. The location of the wake neck is about $2d$ using both definitions. For these conditions, the stagnation point is located at $x/d = 1{\cdot}20$.

3.2. 5° *incidence tests*

The methods of investigation used in the zero-incidence case were applied to the present case. From surface heat transfer, oil visualization and boundary-layer Pitot pressure measurements, it was shown that, at the base of the model, the boundary layer was laminar on the windward side and turbulent on the leeward side. A small separation bubble was found on the leeward side near the apex, downstream of which transition occurred. The onset of transition in the leeward plane ($\phi = 180°$) was observed 16 cm from the base. The transition region decreased as one went away from the leeward plane, so that in the interval $180° + 95° < \phi < 180° - 95°$ no transition was observed on the cone.

Pitot pressure measurements made in the symmetry and normal planes led to the location of the shock waves. It is interesting to note the same effect of the Reynolds number on the trailing shock as was observed in the zero-incidence case: a decreasing Reynolds number causes a widening of the trailing shock in the plane of symmetry. Lines of constant Pitot pressure show the inner core (indicated by the minimum Pitot pressure) displaced towards the windward side. This result agrees with that of Browand, Finston & McLaughin (1967), which was obtained for a 7° half-angle cone at small incidence ($i = 1{\cdot}5°$, 3° and 4·5°). On the other hand, for large incidence, the results of Schmidt & Cresci (1967) and Schlessinger & Martellucci (1966) show a displacement of the minimum Pitot pressure towards the leeward side as is also shown in the present study for $i = 15°$.

The Pitot pressure survey made in the normal plane shows a decrease from the plane of symmetry to a minimum value, followed by an increase up to the trailing shock wave. This result was also observed by Browand *et al.* (1967) and interpreted as a recirculation region with two symmetrical cells with respect to the plane of symmetry. This idea is consistent with the measurements of the $u = 0$ line in the normal plane for $Re_\infty = 2{\cdot}5 \times 10^4\,\mathrm{cm}^{-1}$ only. It is interesting to note that in the normal plane the Pitot pressure measurements clearly indicate a lip shock, which is not observed in the symmetry half-plane. The shape of the trailing shock in the plane of symmetry is asymmetric with respect to the axis with the mean line displaced towards the leeward side of the cone. This wave configuration was also observed by Schlessinger & Martellucci (1966) for a 10° half-angle cone at 10° incidence.

Constant stagnation temperature lines in the plane of symmetry are shown in figure 5 (*a*). The thickness of the boundary layer on the leeward side of the cone is five times larger than on the windward side. One also observes that the entire wake has been shifted towards the leeward side. It is interesting to note a sudden change in the radial position of the stagnation temperature minima downstream of station $x = d$. Such a configuration may be due either to the incidence effect, or to transition which has occurred on the leeward side of the cone.

From the experimental measurements of static pressure, Pitot pressure and stagnation temperature, one can calculate the other flow properties. In particular, the mass flow has been used for tracing streamlines in the plane of symmetry (figure 5 *b*). In order to show the streamlines, it is necessary to integrate the mass flux. The minimum value of this mass flux is used as a reference in determining the streamlines. This minimum lies below the centre-line downstream of $x/d = 1{\cdot}5$. All the characteristics of the near wake are shown in figure 5 (*b*): the bow shock, expansion fan, viscous wake edge, trailing shock and $u = 0$ line. It is interesting to note the consistency of all these results particularly with respect to the $u = 0$ line, which was obtained independently. The expansion fan is stronger on the windward side than on the opposite side. A considerably larger viscous region appears within the expansion fan on the leeward side than on the windward side. A more important quantity to consider is the mass flow, within the shear region, which is considerably higher ($\psi_{\min} > 0{\cdot}10$) on the leeward side than on the windward side ($\psi_{\max} < 0{\cdot}10$).

3.3. 15° *incidence tests*

The flow over the cone has been determined for a high incidence case ($i = 15°$). The most important characteristic of this flow is the separation region lying on the leeward side with vortices starting from the apex. These vortices were indicated by surface visualizations and Pitot probe surveys (Marcillat 1970). Lines of constant total temperature (figure 6 *a*) show that the wake has moved towards the leeward side with the temperature minima located a constant height above the free-stream centre-line. In the leeward region where separated flow has been shown to exist, the stagnation temperature is relatively constant.

As for the two other incidences, the streamlines have been calculated and are shown in figure 6 (*b*). Owing to the higher inclination of the support wires on the windward side of the cone, the measurements of pressure are incorrect, resulting in a loss of information on the windward side. Indeed to obtain good stability of the model placed at high incidence, it was necessary to change the wire inclination. As a result, two of the three downstream wires, located on both sides of the windward plane of symmetry, are less inclined in the free-stream direction and, thus, cause more disturbance.

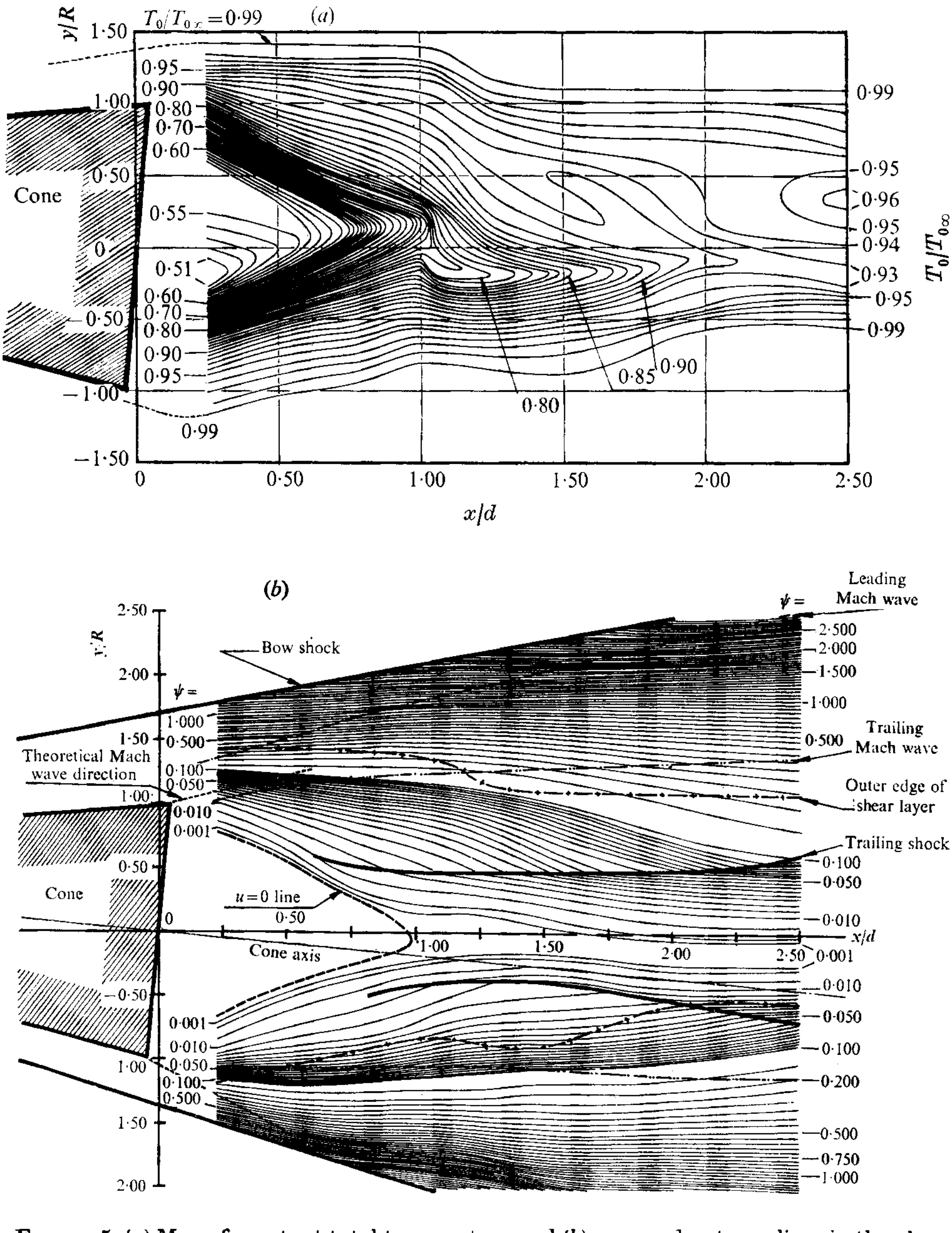
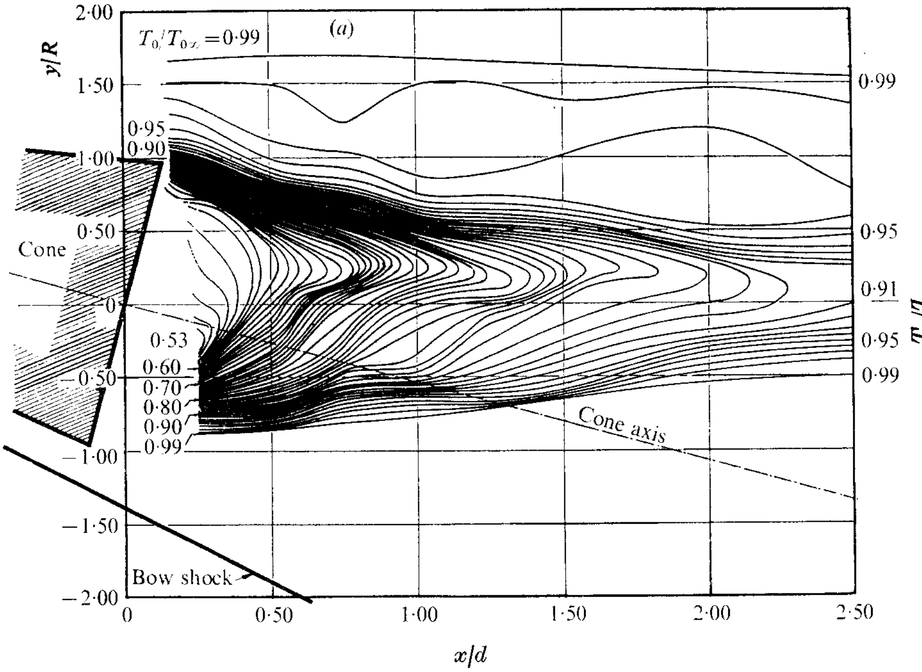


FIGURE 5. (a) Map of constant total temperature and (b) near-wake streamlines in the plane of symmetry ($i = 5°$, $Re^h_\infty = 1{\cdot}1 \times 10^5\ \text{cm}^{-1}$).



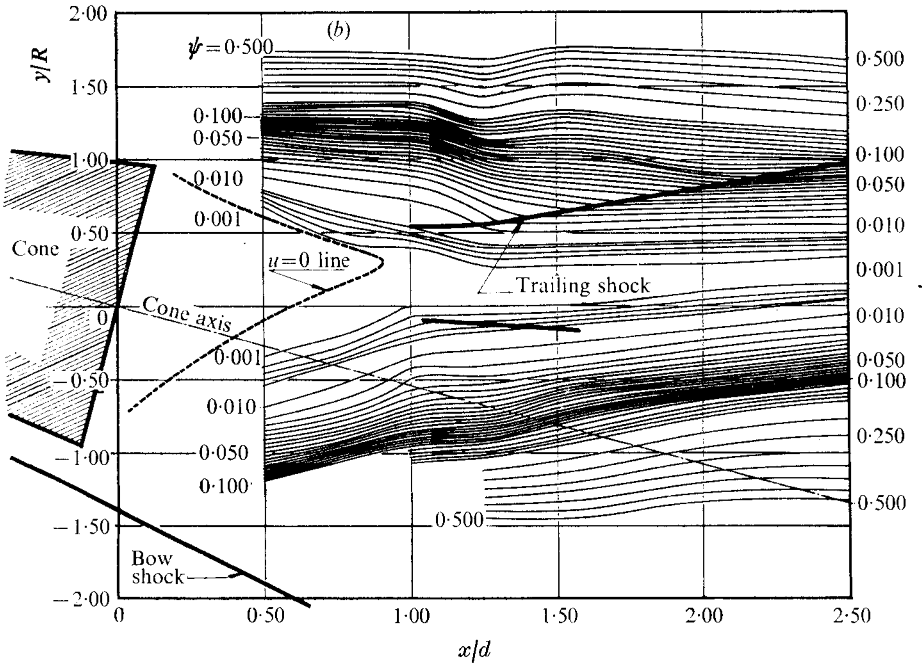


FIGURE 6. (a) Map of constant total temperature and (b) near-wake streamlines in the plane of symmetry ($i = 15°$, $Re_\infty = 1{\cdot}1 \times 10^5\ \text{cm}^{-1}$).

3.4. *Comments on incidence effects*

The static pressure and stagnation temperature are shown for the minimum value of ρu in figures 7 (*a*) and (*b*). Two effects may influence the measurements: the incidence effect and transition occurring on the body. For zero incidence no transition was observed on the cone, at $i = 5^\circ$ large transition was observed on the leeward side and at $i = 15^\circ$ a large separated region existed on the leeward side. The effect of transition at $i = 5^\circ$ may be the cause of the pressure increase over the $i = 0$ case (figure 7 *a*). This is borne out again by the fact that the stagnation temperature along the ρu minimum line is higher for $i = 5^\circ$ than for $i = 0$.

The edge of the viscous wake given by the $T_0/T_{0\infty} = 0{\cdot}99$ line is shown in figure 8. The width of the viscous wake increased with the incidence angle by a factor of two at $x/d = 2{\cdot}5$. On the windward side, the location of the edge of the viscous wake was unaffected by incidence; significant changes however occurred on the opposite side.

4. Conclusion

An experimental investigation has been conducted at $M_\infty = 7$ to determine mean flow properties of the near wake of a sharp 9° half-angle cone at an angle of attack. The variation of flow characteristics of the near wake with the Reynolds number ($0{\cdot}25$ and $1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$) and angle of attack ($0^\circ$, 5° and 15°) have been obtained by measuring the Pitot pressure, static pressure, stagnation temperature and $u = 0$ location. From the measurements the streamline patterns in the plane of symmetry of the near wake were derived and may be used for the construction of fluid mechanical models. The main results which have been obtained from this investigation are as follows.

(i) The location of the rear stagnation point was determined from the null-probe measurements. At zero incidence, the stagnation point is located at $x/d = 1{\cdot}23$ and $x/d = 1{\cdot}96$, measured from the model base, respectively for $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$ and $Re_\infty\, 2{\cdot}5 \times 10^4\,\mathrm{cm}^{-1}$. With increasing incidence the stagnation point moves upstream. The recirculation region is reduced with increasing incidence and increasing Reynolds number.

(ii) The neck of the wake structure is located at $x/d = 2{\cdot}0$ for $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$.

(iii) The lip shock and trailing shock waves appear to form a continuous structure as was found also by Batt (1967) and Hama (1966). Downstream of the neck the trailing shock becomes straight and makes an angle of $7{\cdot}5^\circ$ with the free-stream direction for $Re_\infty = 1{\cdot}1 \times 10^5\,\mathrm{cm}^{-1}$ in the zero-incidence case. At incidence the strength of the trailing shock in the plane of symmetry is less than its value for zero incidence, however, in the normal plane, no change in the shock strength was observed owing to incidence.

(iv) The complete stagnation temperature distribution has been determined between the model base and $x/d = 2{\cdot}5$. The outer edge of the viscous wake is strongly affected by incidence on the leeward side but essentially unmodified on the opposite side.

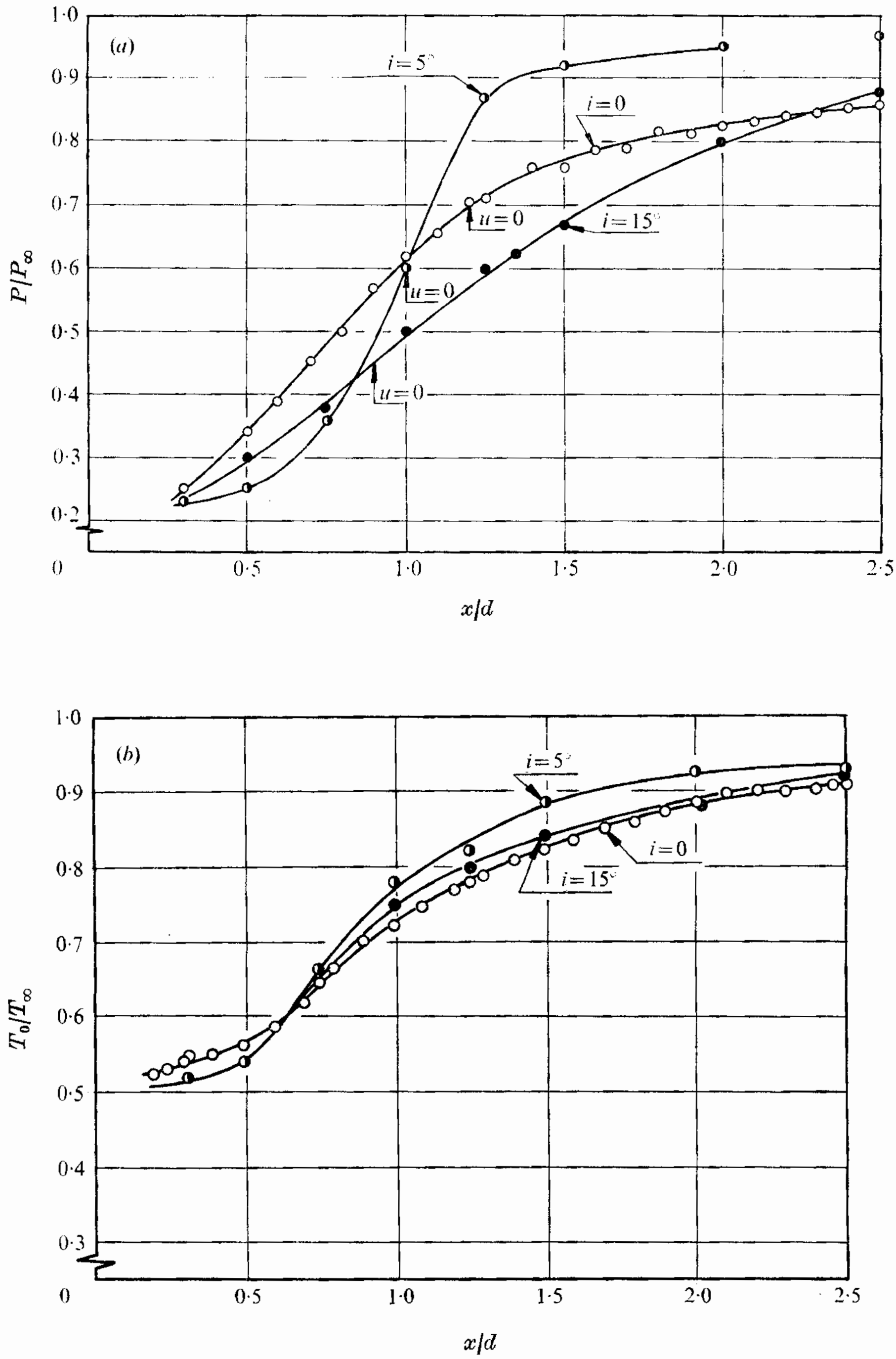


FIGURE 7. Centre-line evolution of (a) static pressure and (b) total temperature ($Re_\infty = 1{\cdot}1 \times 10^5\ \mathrm{cm}^{-1}$).

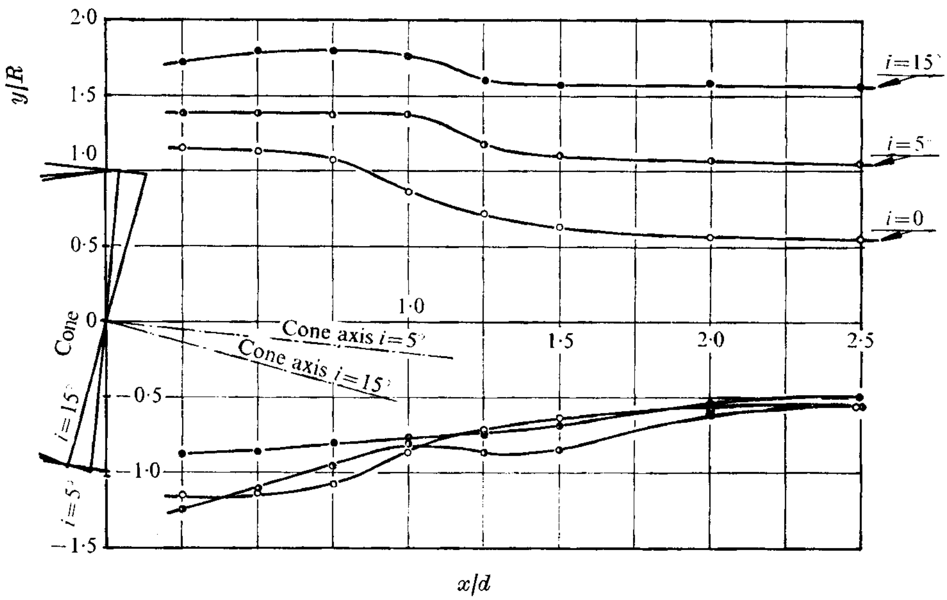


FIGURE 8. Viscous wake edge as a function of the angle of attack.

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