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An experimental study of turbulent separating and reattaching flows at a high Mach number

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Separating and reattaching flows in a two-dimensional compression corner were investigated experimentally at a Mach number of 7·0 and Reynolds numbers (based on the distance from the leading edge to the corner) of $4\cdot75 \times 10^6$, $9\cdot51 \times 10^6$ and $1\cdot55 \times 10^7$. Heat-transfer measurements and Pitot traverses in the upstream boundary layer showed that the boundary layer had become fully turbulent at the start of the interactions. Increases in the Reynolds number gave increases in the length of separated shear layers and decreases in the corner angle required for incipient separation. The reattachment pressure coefficients gave good agreement with the criterion of Batham (1969).

1. Introduction

Separated flows at supersonic speeds have been the subject of considerable theoretical and experimental effort, but little information is available on fully turbulent flows at a high Mach number. This lack of data is mainly due to the difficulty in obtaining natural transition in most relatively small hypersonic facilities. The hypersonic gun tunnel has the advantage that the high Reynolds numbers can be obtained with a running time long enough for accurate static pressure measurements to be made, and is therefore suitable for the study of turbulent separated flows.

It was therefore decided to undertake an investigation in the Oxford University Hypersonic Gun Tunnel aimed at isolating, as far as possible, the various parameters affecting a shock interaction. A two-dimensional compression-corner configuration was chosen as it was felt that this relatively simple flow field should be understood before investigating more complex flows. As it is not yet possible to correlate transition data obtained in different facilities reliably, measurements of the boundary layer upstream of the interaction were made to ensure that the boundary layer had become fully turbulent and to provide information on the thickness parameters at the start of the interactions. Precautions were taken to ensure that a two-dimensional flow existed in the corner; surface flow visualization and spanwise pressure measurements confirmed that this had been achieved.

2. Experimental arrangement and precautions

The Oxford University Hypersonic Gun Tunnel consists of a free-piston compression heater supplying a conventional hypersonic blow-down tunnel and has a running time of approximately 40 ms. It has a contoured open jet nozzle designed to produce an exit-plane Mach number of 7·0. The total pressure was measured with a Kistler type 601 H piezo-electric transducer located at the end of the barrel near the nozzle; a typical pressure–time record is shown in figure 1. It can be seen that the shock waves reflecting between the piston and the end of the barrel weaken rapidly owing to the small piston mass and expansion through the nozzle giving a reasonably steady pressure after 25 ms. A total temperature of 720 ± 10 °K was used for all tests described in the present paper unless stated otherwise. A shielded thermocouple probe of the type described by East & Perry (1967) was kindly loaned to us by Dr R. A. East of Southampton University, and was used to determine the tunnel total temperature. Measurements of total temperature were also made by means of a platinum thin film operated at constant temperature and located at the forward stagnation point of a blunt body, as outlined by La Graff, Batham & Owen (1969). These measurements gave agreement to within 1 % of those from the shielded thermocouple probe. A full description of the design and calibration of the facility is given by La Graff (1969).

Static pressure measurements were made with Kistler type 7031 piezo-electric transducers in conjunction with Kistler type 566 charge amplifiers. The transducers were connected to holes in the model surface by means of 0·100 cm diameter plastic tubes and it was found that the readings were independent of tube length if the total length of tube used was less than 7·5 cm. The transducers were isolated from the vibration of the model by rubber bands, so that it was unnecessary to filter the signals. When the outputs from the charge amplifiers were displayed on Tektronix oscilloscopes an overall accuracy of 4 % could be obtained for flat-plate static pressure measurements at all Reynolds numbers employed. Heat-transfer measurements were made with platinum thin-film resistance thermometers operated at constant current in conjunction with analog circuits of the type described by Meyer (1963). An overall accuracy of $\pm$ 10 % is generally accepted for heat-transfer measurements of this type and is justified by the scatter of the experimental results.

The flat-plate model used in the investigation had a length of 28 cm, a breadth of 8·55 cm and a flap length of 6·85 cm. The leading edge was honed to a sharp edge and was found by examination with a microscope to be approximately semicircular, with a diameter of $0{\cdot}0015 \pm 0{\cdot}0005$ cm. Schlieren glass side plates with sharp steel leading edges were fitted. These were triangular and had dimensions slightly larger than the largest region of separated flow investigated. The Pitot probe used in the investigation of flat-plate boundary layers had a sharp honed inlet of breadth 0·160 cm and height 0·226 cm.

Pressure measurements were taken across the span both upstream and downstream of the corner. A systematic drop in pressure towards the edges greater than the quoted experimental accuracy was found when the model was run without side plates, indicating an outflow in the region of the corner. When side plates

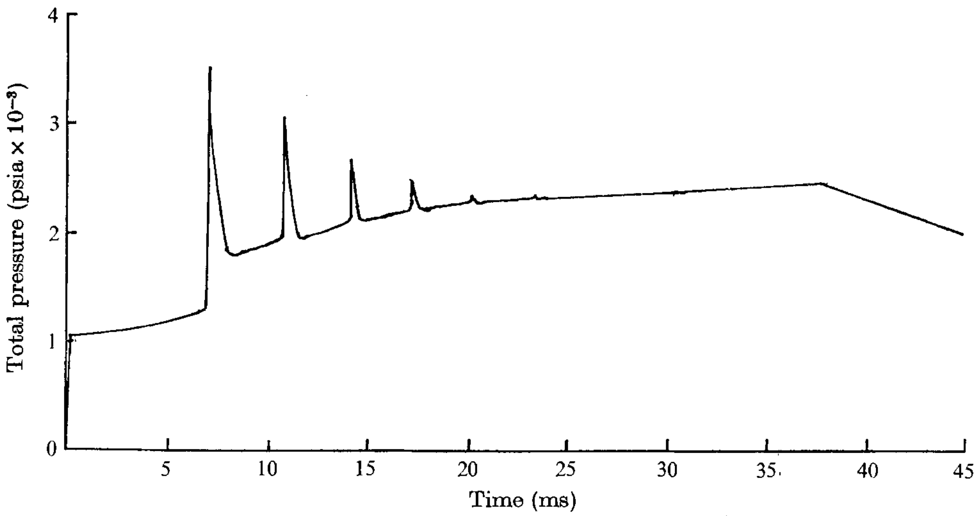

FIGURE 1. Typical gun tunnel total pressure record. Driving pressure = 2015 psia, barrel pressure = 100 psia.

were fitted, the pressure was found to be constant across the middle 50 % of the span, with a rise towards the edges slightly greater than 4 %. This slight rise at the edges is probably due to the separation of the three-dimensional laminar boundary layer on the side plates, however, the effect appeared to be very small compared with the strong turbulent interaction on the flat plate. Surface oil flow photographs also confirmed that a two-dimensional flow was obtained on the flat plate and ramp. It was found that the total length of separated flow was reduced by about 70 % when the side plates were removed, and highly curved separation and reattachment shocks were observed. The satisfactory use of small side plates to produce a two-dimensional flow has already been demonstrated for laminar separated flows by Lewis, Kubota & Lees (1968).

As turbulent separated flows had not previously been studied in a facility of such a short running time, it was felt necessary to take a high-speed cine-film of the flow to ensure that the flow had become fully established and that no gross unsteadiness existed. A 16 mm Hycam camera was used to obtain focused shadowgraph photographs of the flow at a Reynolds number of $1{\cdot}55 \times 10^7$ and a ramp angle of $36^\circ 30'$. A frame rate of 6300 frames/s was used and the 270 frames covering the run were enlarged. The length from the separation shock to the ramp corner was measured and is shown in figure 2.

Although the accuracy of the cine-film was not high (about $\pm$ 7 %), the lengths measured were adequate to determine the length of separation sufficiently accurately to relate it to the changes in free-stream flow properties. At the start of the run a small separated flow was observed in the fourth frame and the length of separation increased until it became reasonably steady after 20 frames, with a slight increase in length up to 50 frames. This corresponds to the almost steady conditions behind the first reflected shock in the barrel. The small increase in length between 20 and 50 frames was due to the increase in the Reynolds number

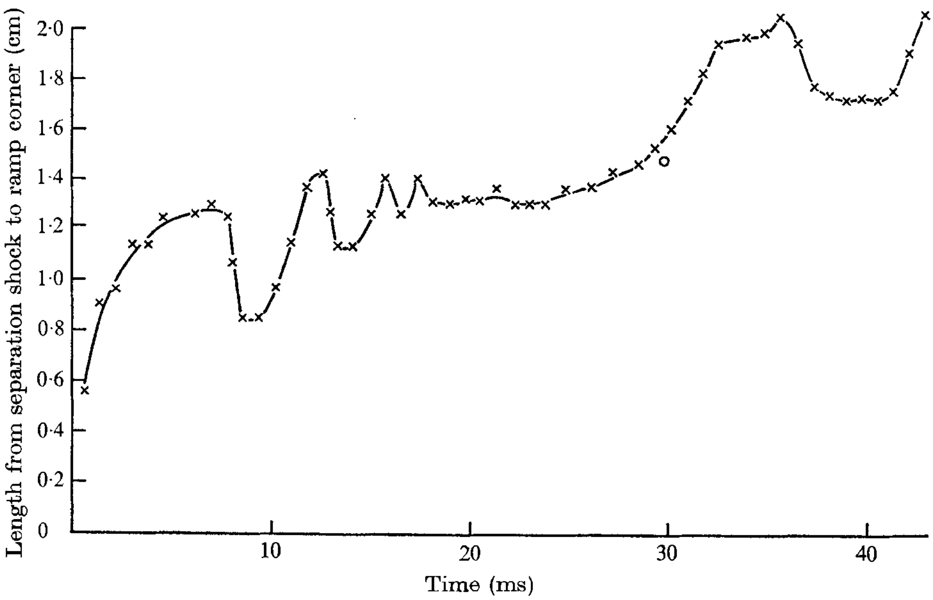

FIGURE 2. Length from separation shock to ramp corner measured from cine film. $Re = 1{\cdot}55\times10^5$; $\alpha = 36°30'$; ○, spark; ×, photograph.

owing to the small rise in total pressure and fall in total temperature over this period. Fluctuations in the separated length were caused by the arrival of subsequent shocks, gradually becoming weaker as the shocks become weaker, and only small fluctuations were observed after 25 ms. The separated length started to increase at about 30 ms owing to the gradual rise in total pressure and drop in total temperature caused by heat transfer to the walls of the barrel. All measurements in the present investigation were taken 30 ms from the start of the runs to give the maximum filling of transducer cavities. A decrease in length was observed after 36 ms, and was caused by the drop in total pressure at that point. Flow breakdown occurred at 43 ms, when the shock in the corner was observed to move upstream and be followed by a highly unsteady subsonic flow in the working section. It is concluded from the above observations that no gross unsteadiness existed in the flow, and that turbulent separated flows could be successfully studied in a shock tunnel with a running time of the order of 3 ms.

3. Results and discussion

Although a large amount of experimental data is available on boundary-layer transition at supersonic and hypersonic speeds, the phenomenon is still poorly understood. The transition region can be considered as a collection of turbulent spots which grow as they move downstream, finally merging to form a fully turbulent boundary layer. Evidence of the passage of turbulent spots was found in the transition region on the flat plate by the spiky appearance of the heat-transfer records compared with those for laminar or fully turbulent records.

It is not possible at present to correlate transition data obtained in different

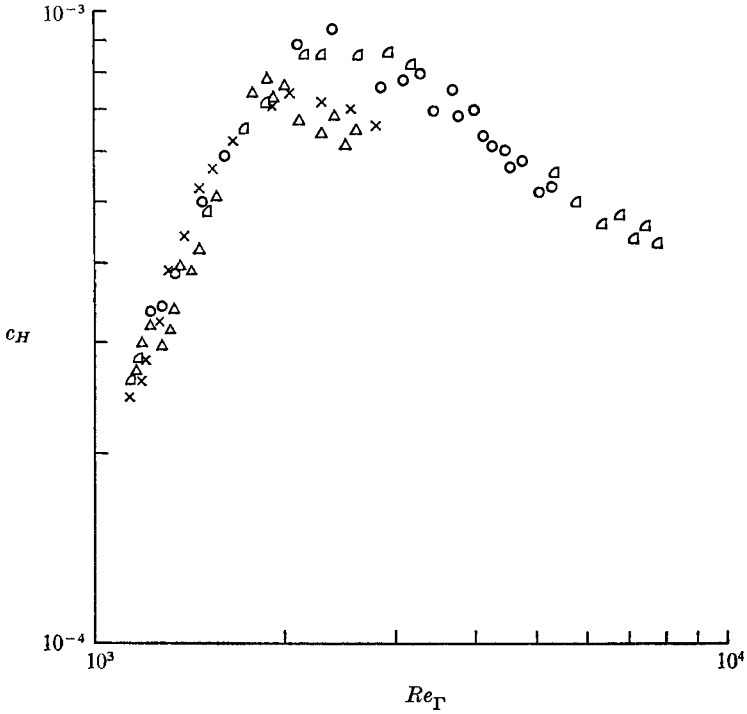

FIGURE 3. Heat transfer to flat plate. △, Re/cm = $1{\cdot}70 \times 10^5$; ○, Re/cm = $3{\cdot}41 \times 10^5$; □, Re/cm = $5{\cdot}55 \times 10^5$; ×, Hopkins *et al.* (1969).

facilities reliably because of the large effect of the ambient noise level and free-stream disturbances. In the present investigation it was found that the location of transition was also a function of the position of the model relative to the nozzle. All measurements were therefore taken with the model in the same position. This variation can be attributed to the variation of the ambient noise level throughout the nozzle sound field.

Measurements of heat transfer to a flat plate are shown in figure 3, where the Stanton number is plotted against the local energy thickness Reynolds number obtained by numerical integration in the transitional and turbulent regions. Good agreement is shown with the data of Hopkins *et al.* (1969) at the lowest Reynolds number, but a higher peak heat transfer is shown at the two highest Reynolds numbers.

Pitot profiles were taken through the turbulent boundary layer at the Reynolds numbers of $1{\cdot}37 \times 10^7$, $8{\cdot}39 \times 10^6$ and $4{\cdot}18 \times 10^6$, based on the distance from the leading edge, and the resulting Mach number profiles are shown in figure 4. As no probe has yet been developed which is capable of measuring total temperature in the small thickness of boundary layer encountered, velocity profiles were calculated from the profiles of Walz (1961) and the square-law relation

$$(u/u_\infty)^2 = (T_0 - T_w)/(T_{0\infty} - T_w).$$

Thickness parameters were calculated from the Mach number profiles and compared with parameters calculated from the heat-transfer measurements.

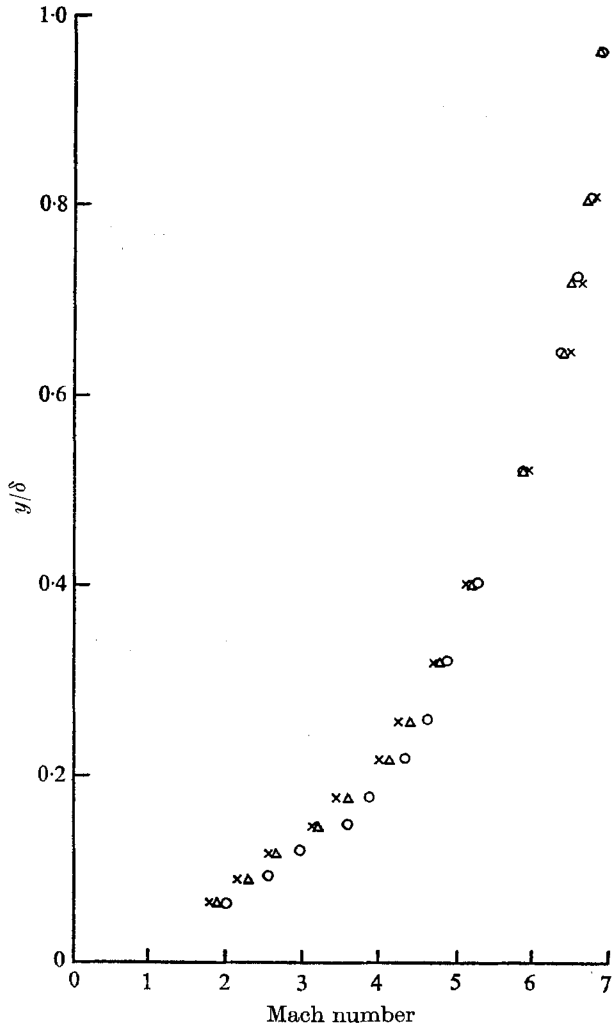

FIGURE 4. Turbulent boundary layer Mach number profiles. ○, $Re = 4{\cdot}18 \times 10^6$; △, $Re = 8{\cdot}39 \times 10^6$; ×, $Re = 1{\cdot}37 \times 10^7$.

Agreement within 15 % was obtained for all parameters, using the Walz (1961) relation, which also gave agreement within 10 % for the form factor at the wall temperature ratio employed with values published by Danberg (1964). Poor agreement with errors of over 100 % was obtained in all cases from the square-law relation, as would be expected from the data correlation of Bushnell *et al.* (1969), who show that the square-law relation is only applicable to nozzle wall data with a history of upstream favourable pressure gradient.

Pressure distributions in compression-corner flows are shown in figure 5, together with the reattachment points located with a surface Pitot tube. Attached flows are seen to exhibit a slight pressure rise ahead of the corner and a steep pressure gradient downstream. A single point of inflexion is shown and the pressure continues to rise to a peak corresponding closely to the inviscid wedge

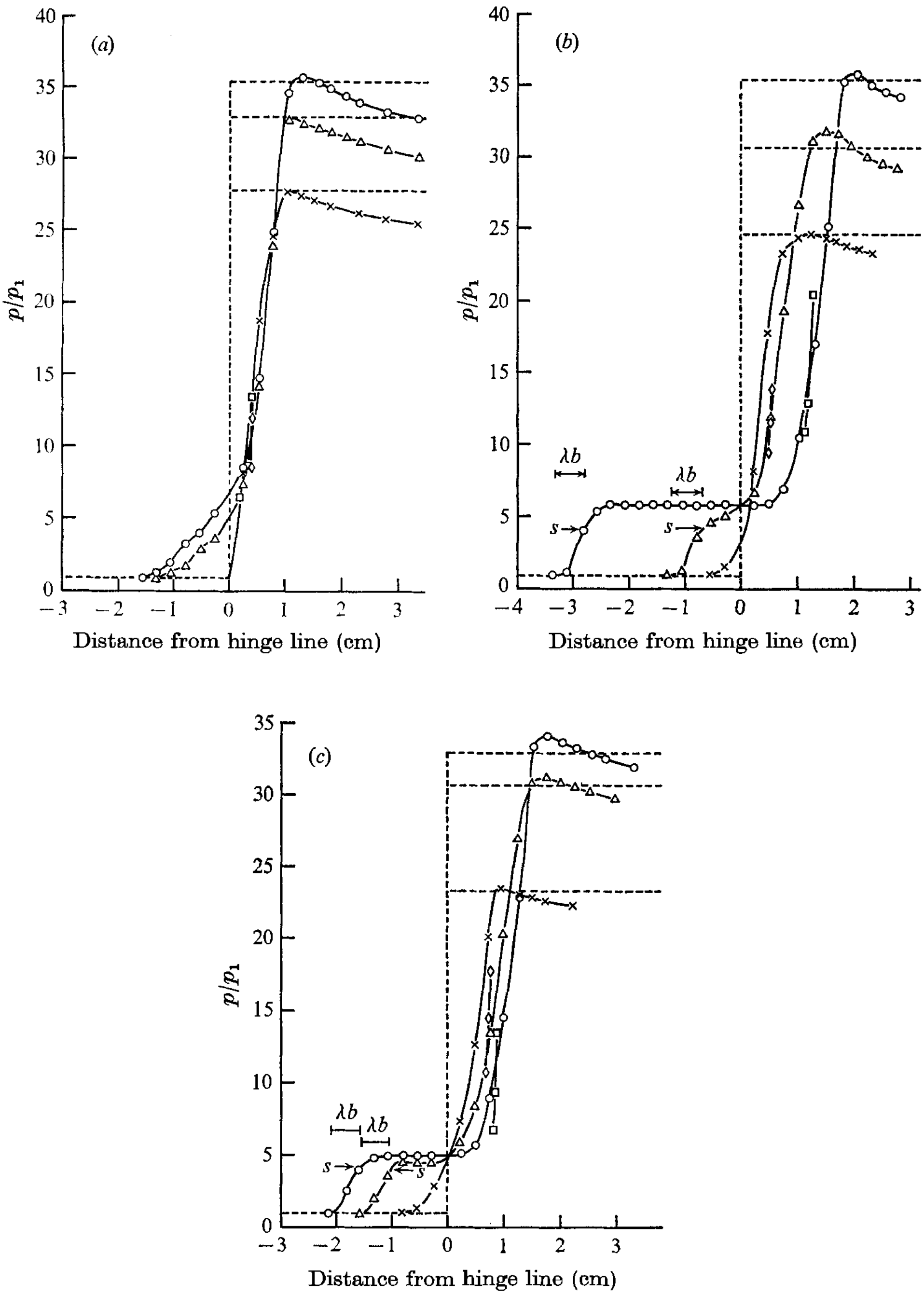

FIGURE 5. Compression corner pressure distributions. - - - - - -, inviscid pressure distribution. (*a*) $Re = 4{\cdot}75 \times 10^6$; ×, $\alpha = 33°0'$; △, $\alpha = 36°30'$; ○, $\alpha = 38°0'$; □, surface Pitot pressures, $\alpha = 38°0'$; ◇, surface Pitot pressures, $\alpha = 36°30'$; (*b*) $Re = 9{\cdot}51 \times 10^6$; ×, $\alpha = 31°0'$; △, $\alpha = 36°30'$; ○, $\alpha = 38°0'$; □, surface Pitot pressures, $\alpha = 38°0'$; ◇, surface Pitot pressures, $\alpha = 36°30'$; (*c*) $Re = 1{\cdot}55 \times 10^7$; ×, $\alpha = 30°0'$; △, $\alpha = 35°0'$; ○, $\alpha = 36°30'$; □, surface Pitot pressures, $\alpha = 36°30'$; ◇, surface Pitot pressure, $\alpha = 35°0'$.

pressure. A single oblique shock was observed on schlieren photographs and moved forward as the range angle was increased, penetrating the boundary layer ahead of the corner. As the ramp angle was increased further, two shocks became visible, and for large regions of separation the dividing streamline could be seen clearly on schlieren photographs. A graded filter schlieren photograph of the flow at a ramp angle of 38° and a Reynolds number of $9{\cdot}51 \times 10^6$ is shown in figure 6 (plate 1) and a direct shadowgraph photograph of the same flow is shown in figure 7 (plate 1).

When the ramp angle for incipient separation was exceeded, the pressure distribution developed a 'knee' or kink just ahead of the corner which broadened into a plateau as the angle was increased further. The plateau pressure was seen to increase slightly as the ramp angle was increased at a fixed Reynolds number. An increase in the Reynolds number at a given ramp angle produced a large increase in the length of separation and a small increase in the plateau pressure. No change could be detected in the length of separation when a total temperature of 900 °K was employed at the Reynolds numbers of $4{\cdot}75 \times 10^6$ and $9{\cdot}51 \times 10^6$.

The values of momentum thickness at the start of the interactions were all within 20 % of each other with no consistent trend with the Reynolds number. Thus the large variation in lengths of separation with varying Reynolds number does not appear to be explained by variations in thickness parameters at the start of the interactions. The fluid on the dividing streamline would then have been accelerated by the shear stress gradient until the correct velocity was achieved to satisfy reattachment conditions. Thus it was expected that an increase in the unit Reynolds number would lead to an increase in the length of separation because of the decrease in shear stress produced. This trend is seen in the present experimental results and also in the results of Coleman, Elfstrom & Stollery (1971).

Incipient separation data from the present study are shown with previous data in figure 8. The present results show the same trend as the results of Coleman *et al.* (1971) as the Reynolds number based on boundary-layer thickness at the hinge line is increased. The steeper slope and greater angles for incipient separation shown by the present data may be explained by the interactions in the present study being closer to the transition region. The larger flat plate used by Coleman *et al.* (1971) may have enabled the turbulent boundary layers to be more fully developed at the hinge line.

The pressure distributions up to the separation points were compared with the data of Sterrett & Emery (1962) by means of the free interaction theory of Erdos & Pallone (1962). Values of separation pressure rise and length to separation calculated from the data of Sterrett & Emery (1962) at $M = 4{\cdot}8$, following natural transition, are shown in figure 5. The calculated separation points are located just as the pressure distributions begin to flatten, as was found also in the comparison data. The lengths (denoted by λb) are predicted to within the accuracy of the data in all cases. Overpredictions of the lengths to separation by factors of up to 3 were obtained when comparison was made with the data of Sterrett & Emery (1962) and Holloway, Sterrett & Creekmore (1965) following tripped boundary layers. From the curves of momentum thickness distributions given

FIGURE 6. Schlieren photograph, $Re = 9{\cdot}51 \times 10^6$, $\alpha = 38^\circ 0'$.

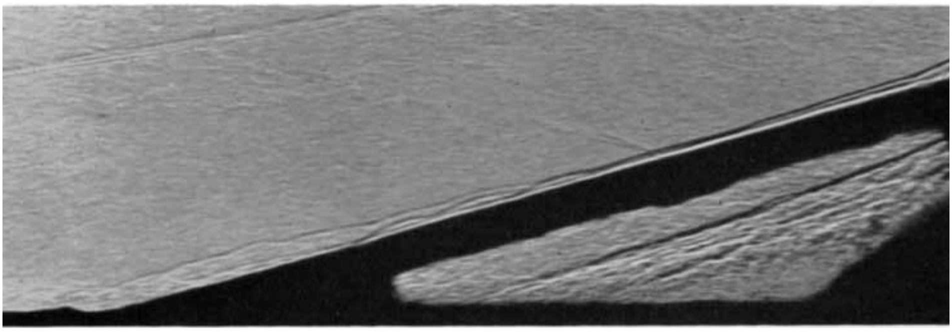

FIGURE 7. Direct shadowgraph, $Re = 9{\cdot}51 \times 10^6$, $\alpha = 38^\circ 0'$.

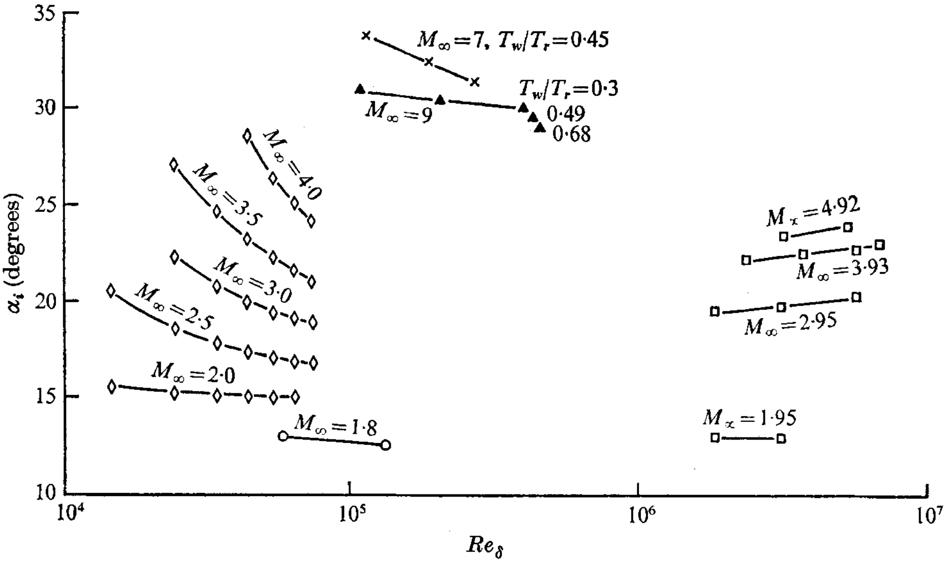

FIGURE 8. Incipient separation. ×, present data; ▲, Coleman *et al.* (1971); ◇, Kuehn (1959); □, Roshko & Thomke (1969); ○, Drougge (1953).

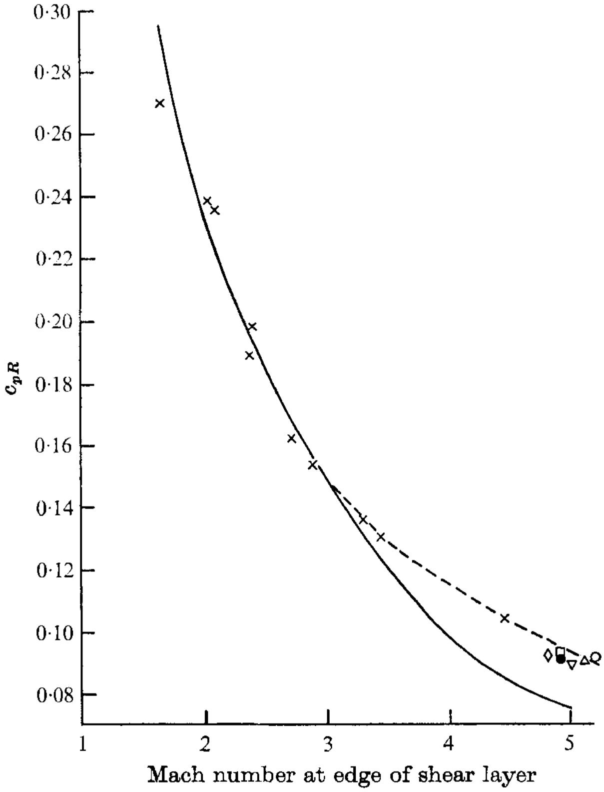

FIGURE 9. Reattachment correlation. ×, data given by Batham (1969); ○, $Re = 4{\cdot}75 \times 10^6$, $\alpha = 36°30'$; △, $Re = 4{\cdot}75 \times 10^6$, $\alpha = 38°0'$; ▽, $Re = 9{\cdot}51 \times 10^6$, $\alpha = 36°30'$; □, $Re = 9{\cdot}51 \times 10^6$, $\alpha = 38°0'$; ●, $Re = 1{\cdot}55 \times 10^7$, $\alpha = 35°0'$; ◇, $Re = 1{\cdot}55 \times 10^7$, $\alpha = 36°30'$; —, $c_{pR} \sim [c_{fi}/(M_2^2 - 1)^{\frac{1}{2}}]^{\frac{1}{2}}$ (linearized theory); - - - -, empirical curve for higher Mach numbers.

by Sterrett & Emery (1962) it would appear that the boundary layers were transitional at the separation points when tripped boundary layers were employed.

Reattachment points were located by means of a very small surface Pitot tube and the probe pressure measurements are shown with the wall static pressure measurements in figure 5, the intersection of the curves giving the reattachment points. No evidence of probe interference could be found on schlieren photographs and the position of reattachment points coincided with those measured from schlieren photographs; see, for example, figure 6 (plate 1). The pressure coefficients at reattachment are plotted in figure 9 as was suggested by Batham (1969), and a good correlation with existing data is shown.

4. Conclusions

It has been shown that turbulent separated flows can be successfully studied in short duration facilities. The flow establishment time was found to be an order of magnitude shorter than the running time of the tunnel and unsteadiness observed could be explained by treating the flow on a quasi-steady basis.

Comparison of the present incipient separation data with that of Coleman *et al.* (1971) suggests that although the boundary layers upstream of the interactions had become fully turbulent, they had probably not reached asymptotic behaviour. The results suggest that the state of the turbulent boundary layer at the interaction can have a first-order effect on the pressure rise for incipient separation. The trend of increasing length of separation with increasing Reynolds number would appear to be explained by the effect of unit Reynolds number on the shear stress in the shear layers rather than the upstream boundary layer. The reattachment pressure data is seen to collapse onto one curve with existing data when plotted as suggested by Batham (1969).

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REFERENCES

Batham, J. P. 1969 *A.I.A.A. J.* 7, 154.

Bushnell, D. M., Johnson, C. B., Harvey, W. D. & Fellor, W. V. 1969 *N.A.S.A. Tech. Note*, no. D-5433.

Coleman, G. T., Elfstrom, G. M. & Stollery, J. L. 1971 *AGARD Conf. Preprint*, no. 93.

Danberg, J. E. 1964 *Nov. Ord. Lab. Tech. Rep.* no. 64–99.

Drougge, G. 1953 *F.F.A. Sweden Rep.* no. 46.

East, R. A. & Perry, J. H. 1967 *Aero. Res. Counc. Current Paper*, no. 909.

Erdos, J. & Pallone, A. 1962 *Proc.* 1962 *Heat Transfer and Fluid Mechanics Inst.*

Holloway, P. F., Sterrett, J. R. & Creekmore, H. S. 1965 *N.A.S.A. Tech. Note*, no. D-3074.

Hopkins, E. J., Rubesin, M. W., Inouye, M., Keener, E. R., Mateer, G. C. & Polek, T. E. 1969 *N.A.S.A. Tech. Note*, no. D-5089.

KUEHN, D. M. 1959 *N.A.S.A. Memo.* no. 1–21-59 W.

LA GRAFF, J. E. 1969 *Dept. of Eng. Sci., Oxford University. Rep.* no. 109469.

LA GRAFF, J. E., BATHAM, J. P. & OWEN, F. K. 1969 *Aero. Res. Counc.* 31, 246 Hyp. 757.

LEWIS, J. E., KUBOTA, T. & LEES, L. 1968 *A.I.A.A. J.* **6**, 7.

MEYER, R. F. 1963 *Nat. Aeron. Establishment of Canada Rep.* no. LR-375.

ROSHKO, A. & THOMKE, G. J. 1969 *Proc. Symposium on Viscous Interaction Phenomena in Supersonic and Hypersonic Flow.* U.S.A.F. A.R.L., Ohio.

STERRETT, J. R. & EMERY, J. C. 1962 *N.A.S.A. Tech. Note*, no. D-1014.

WALZ, A. 1961 *Proc. Symposium on the Mechanics of Turbulence*, C.R.N.S. Marseille.