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A Note on the Effects of Heat Transfer on the Separation of a Laminar Boundary Layer

By

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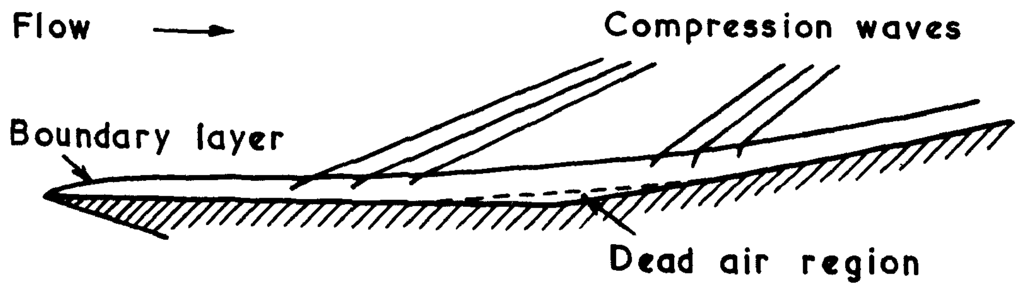
FIG. 1



Flow past a bent wall

FIG. 2

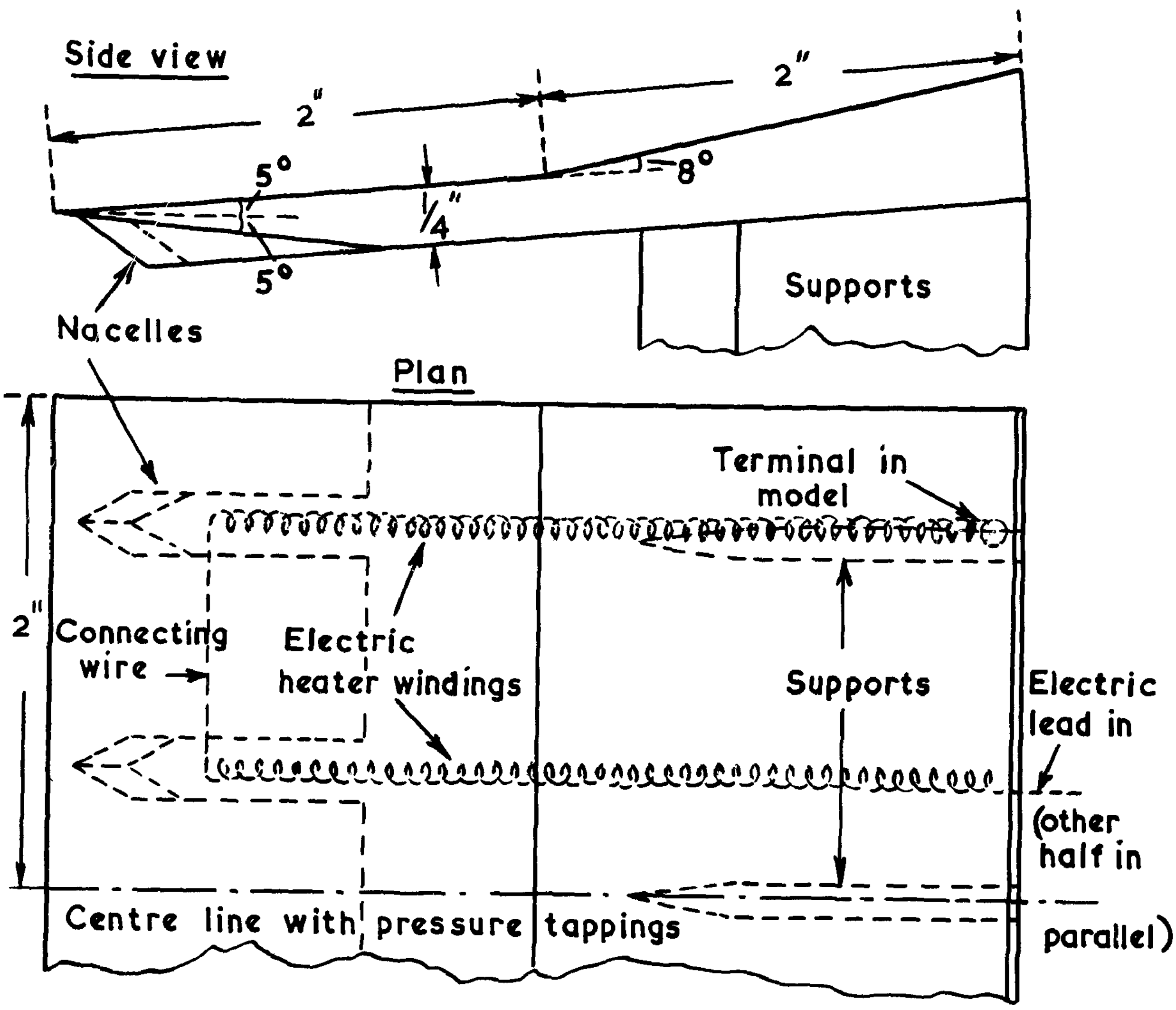
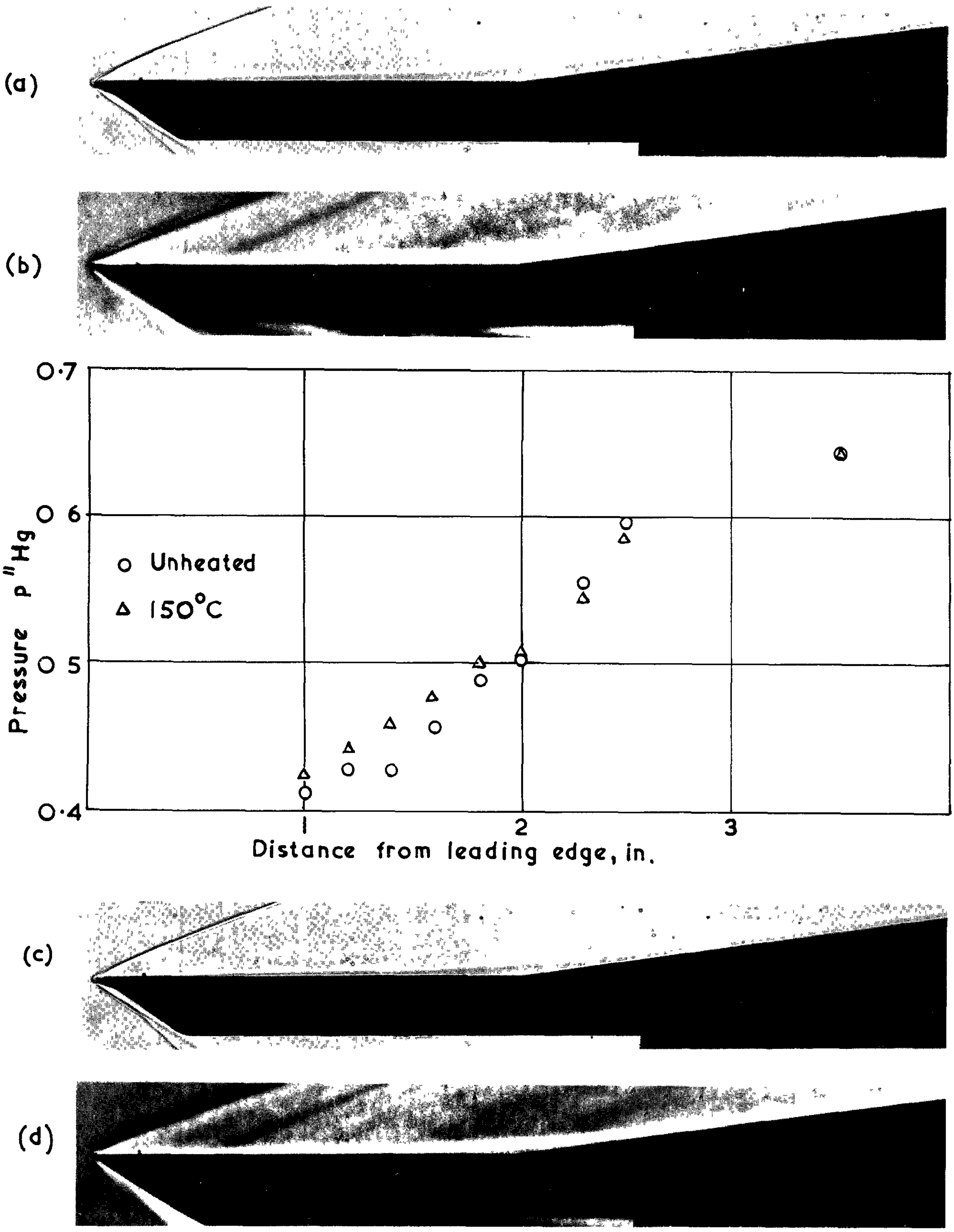


Diagram of electrically heated model

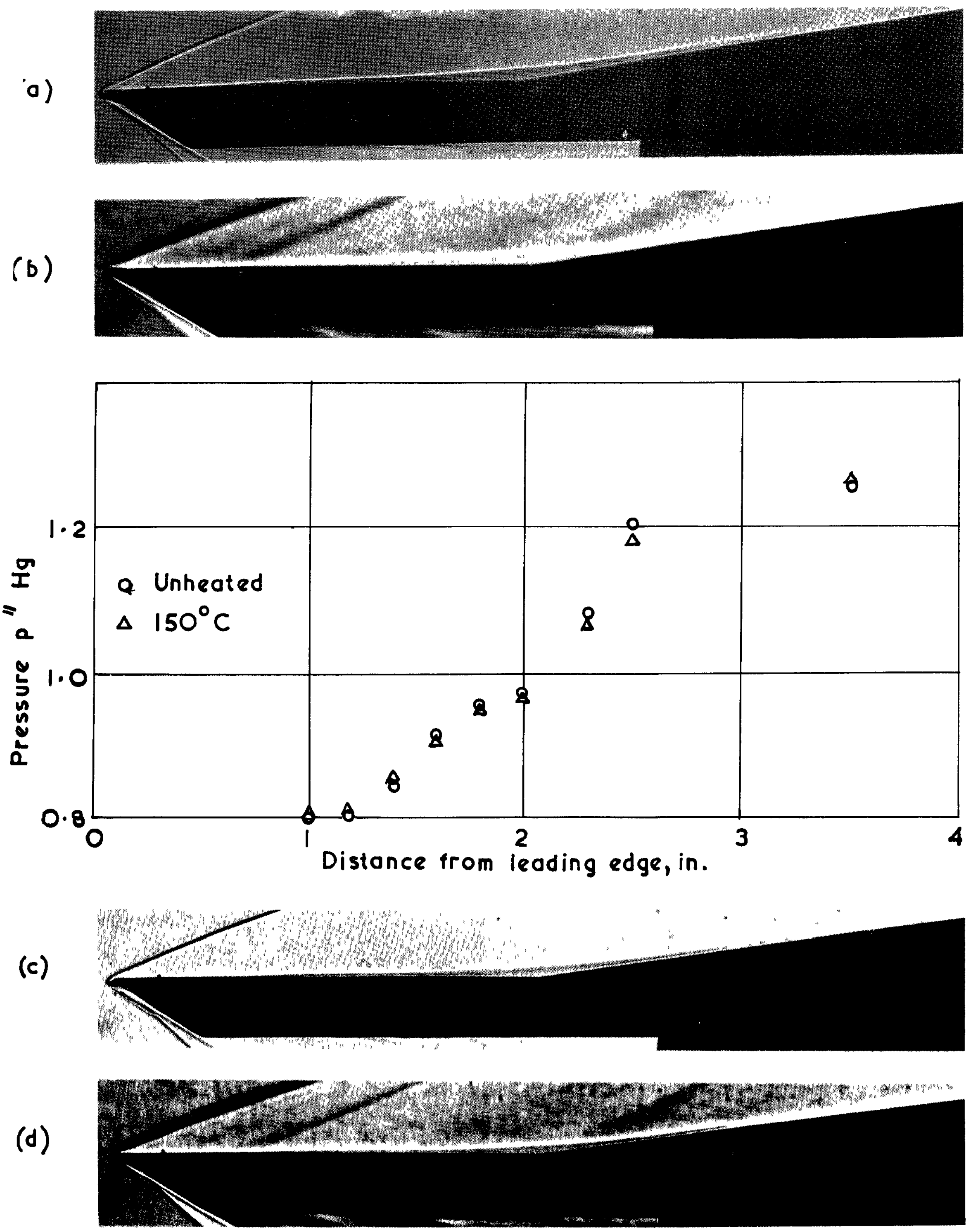
FIG. 3.



(a) Shadow 150° C
(b) Schlieren, 150° C
(c) shadow, unheated
(d) Schlieren, unheated

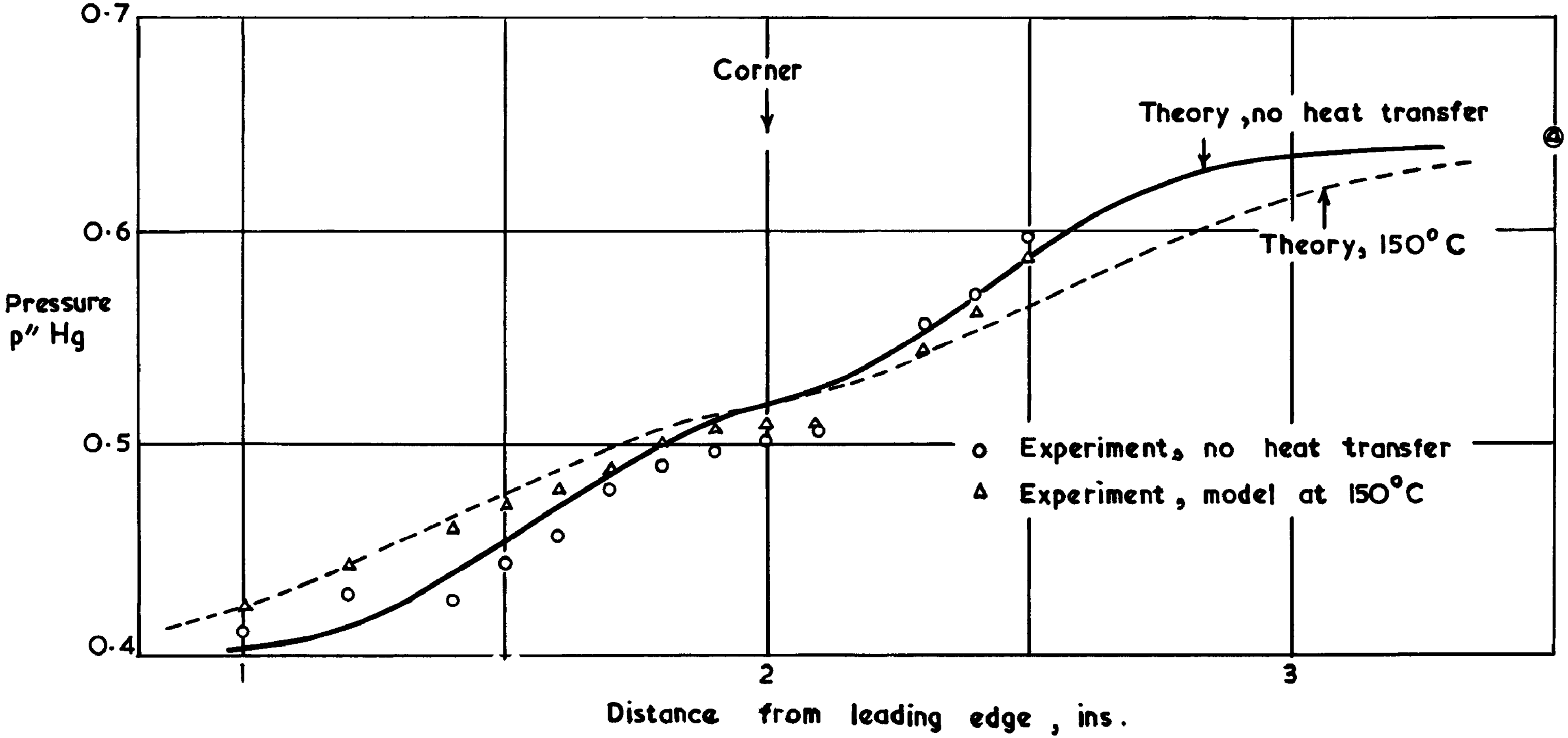
FIG. 3. Flow pictures and pressure distributions stagnation pressure 10" Hg abs.

FIG. 4.



(a) Shadow, 150°C
(b) Schlieren, 150°C
(c) Shadow, unheated
(d) Schlieren, unheated

FIG. 4. Flow pictures and pressure distributions, stagnation pressure 20" Hg abs



Theoretical and experimental pressure distributions.

FIG. 5.

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This short note is concerned with laminar separation in supersonic flow. Such separation may be provoked in a number of ways, for example by a discontinuity in the slope of the wall, as shown in Fig.1. When the discontinuity in slope is large enough, (i.e., greater than an angle of the order of 6° for a laminar layer) separation is provoked upstream of the corner. The boundary layer thickens, and this generates a band of compression waves. These are associated with the adverse pressure gradients which are the cause of boundary-layer thickening. Thus the flow must adjust itself so that the pressure gradients and boundary-layer thickening are in equilibrium. This process can be investigated theoretically, and such analyses[1,2,3] predict that heat transfer between the fluid and the wall affects the equilibrium process. When heat is extracted from the fluid, the boundary layer is predicted to be more difficult to separate, in the sense that the equilibrium pressure gradients in the vicinity of separation are steepened[1,2,3]; in addition, according to some theories, the ratio of the pressure at the separation point to its undisturbed free-stream value is increased[1]. When the wall is heated the opposite effects are predicted. If the boundary layer remains laminar over the entire region of interaction, the length of this region is predicted to increase as the wall temperature is raised.

Earlier experiments on separation with heat transfer either appeared to disagree with the theory[4], or were in some respects unsatisfactory[2]. A further experiment was therefore undertaken, using the configuration of Fig.1. The model used is sketched in Fig.2. Its width was 4 in. as compared with the $4\frac{1}{2}$ in. width of the $7 \times 4\frac{1}{2}$ blow-down tunnel in which the experiments were carried out. Thus there were gaps at the side of the model. This was because the model could be heated electrically, and the hot model could not be permitted to be in contact with the glass windows of the working section. The disturbances arising from the gaps should not greatly affect the measurements made on the tunnel centre line, since the total length of the model was 4 in. and the free-stream Mach number of the tests was 3. Thus even at the trailing edge, the Mach cones from the two ends of the leading edge should be about 0.6 in. away from the centre line, the central inch or so being free from disturbances. There were pressure tappings along the centre line of the model, and three thermocouples to measure its temperature. At the low stagnation pressures and correspondingly low heat-transfer rates at which the model was tested, it could be assumed that the surface temperature of the model was roughly uniform, due to heat conduction in the metal. The heating was effected by an electric element divided into four portions, as indicated in Fig.2. The element was wound on Pyrex glass rods which were placed in channels in the model.

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The insides of these channels were painted with Quigley Blue Cement, to insulate the element from the model. So that the channels could go as close as possible to the leading edge, thus ensuring adequate heating in this region, the channels were, as shown in Fig. 2, carried forward in nacelles where the thickness of the model would otherwise have been too small to accommodate the elements.

Runs were made at two stagnation pressures, 10 and 20 in. of mercury absolute, both with the model unheated, so that it was a little below room temperature, and with it heated to about 150°C. Flow photographs and pressure distributions are shown in Figs. 3 and 4. At the lower stagnation pressure, in Fig. 3, it can be seen from the direct-shadow photographs that the flow remains laminar throughout the region of interaction. Under these conditions heating the wall reduces the pressure gradients at the upstream end of the region of interaction, and increases the streamwise extent of the region. This is in accord with theory, as will be discussed further below. At the higher stagnation pressure, in Fig. 4, the flow turns turbulent at the downstream end of the interaction region, and then the interaction region does not extend any further upstream of the corner with heating than it does without heating. A single pressure-distribution curve could well be drawn through the experimental points with and without heating, so that it might appear that heat transfer has no effect on the pressure distribution through the region of interaction. This was also the conclusion of Ref. 4. However, in the upstream part of the interaction region, it is possible to discern in the experimental points of Fig. 4 a tendency for the pressure gradients to be steeper without heating than they are with heating. Thus in this respect there is probably no conflict with the theory, though the experimentally-determined pressure gradients cannot be relied on to be very accurate, since the slightest errors in the measured pressures make considerable errors in the gradients. The fact that the overall streamwise extent of the separated region is virtually unchanged by heat transfer may be due to the heated layer being more ready to turn turbulent, a process likely to counteract the tendency in the entirely laminar interaction for the upstream effect to be increased.

Returning to the entirely laminar interaction, Fig. 5 shows the experimental pressure distribution compared with the theoretical predictions of the simple method "A" of Ref. 1, Section 8. The theory has been worked out for a Mach number upstream of the interaction region of 2.7 and a Reynolds number of 1.5×10^5 based on the distance from the leading edge to the corner, with the upstream pressure 0.40 in. of mercury, and the downstream pressure 0.64 in. These conditions approximate to the experimental ones, the Mach number on the plate upstream of the interaction being a little less than the tunnel free-stream Mach number of about 3, due to the 5° inclination of the plate, shown in Fig. 2. The overall pressure ratio 0.64: 0.40 or 1.60, is rather less than the theoretical value of about 1.73 for an 8° discontinuity of wall slope at a Mach number of 2.7. The rate of thickening of the boundary layer upstream of the interaction region is insufficient to account for this discrepancy. Possibly it is due to the gaps at the side of the model. The effects which these give rise to must, outside the boundary layer, be confined behind the Mach cones from the two ends of the leading edge, but in the boundary layer they may perhaps spread inwards rather more rapidly, and hence may slightly reduce the peak pressures reached on the centre line.

It can be seen from Fig. 5 that qualitatively the theory agrees moderately well with the experiment. There is indeed a tendency for the interaction to extend further upstream in the heated-wall case, the pressure gradients being correspondingly reduced. Downstream of the corner the two experimental pressure distributions differ from each other much less than the predicted ones do. However the theory would be

expected/

expected to become progressively less accurate for the more downstream parts of the interaction regions. Thus it may be concluded that for entirely laminar interactions, theory and experiment are in reasonable harmony. The opposite conclusion reached in Ref.4 was probably due to the issue being obscured by the effects of transition.

References

No.	Author(s)	Title, etc.
1	K. N. C. Bray, G. E. Gadd and M. Woodger	Some calculations by the Crocco-Lees and other methods of interactions between shock waves and laminar boundary layers, including effects of heat transfer and suction. A.R.C. C.P.556. April, 1960.
2	G. E. Gadd	Boundary-layer separation in the presence of heat transfer. NPL/Aero/400. February, 1960.
3	N. Curle	The effects of heat transfer on laminar boundary layer separation in supersonic flow. A.R.C.21,986 May, 1960.
4	G. E. Gadd	An experimental investigation of heat transfer effects on boundary-layer separation in supersonic flow. J. Fluid Mech. Vol.2, p.105, 1957.

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