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A Review of Research on Two-Dimensional Base Flow

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Summary.

A descriptive review is made of recent work on base flow with particular reference to blunt-trailing-edge wings. The main factors which influence base pressure through subsonic and supersonic speeds are discussed in the light of existing experimental data and current theory. Attention is drawn to areas requiring further elucidation either by the acquisition of more data or by the development of the theory.

1. *Introduction.*

1.1. *Historical Note.*

Interest in the flow over bluff bodies dates back to the very earliest days of fluid dynamics. It was known that the pressure on the downstream face of a plate held normal to the incident stream, or on the leeward side of a cylinder, could not be predicted from classical potential-flow theory. Prandtl and others observed that the streamlines did not in general follow the surface of a bluff body round to a rear stagnation point but separated away from the surface somewhere earlier, leaving in some cases an extensive region of low-pressure eddying fluid adjacent to the body. In particular the flow over two-dimensional bluff bodies was characterized at Reynolds numbers above about 50 by the periodic shedding of eddies into the wake. Von Kármán's vortex-street hypothesis was able to shed some light on the periodic motion but the problem as a whole was to be regarded as of no more than academic interest in aeronautics. The large-scale energy dissipation in the wake gave rise to a very considerable drag penalty and bluff shapes were consequently to be avoided in the design of bodies moving in a fluid.

1.2. *Ballistic Research.*

In more recent years ballistic research gave a new impetus to the study of base flow. The trajectories of bullets and shells could not be estimated without some knowledge of the pressure acting on their blunt bases and indeed it was recognized that the base pressure made an important contribution to the total drag of the body. The correlation of measurements made in wind tunnels and in firing trials was found difficult and it soon became clear that body shape, Reynolds number and compressibility effects all played their part in determining the base pressure. Moreover the speed range of projectiles penetrated into the supersonic régime where there was a scarcity of aerodynamic data in general, and new problems were met. The more recent development of large rocket vehicles

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has aroused interest in the problem of predicting their base pressures both before and after fuel burn-out, and the high speeds and extreme altitudes at which these rockets operate has created the need for aerodynamic data including base pressures over a very wide range of Mach number and Reynolds number.

1.3. *Blunt-Trailing-edged Wings.*

Interest in the practical use of aerofoil sections with a trailing edge of finite thickness was not aroused until much later. Hoerner[1, 2] discussed the effect of blunt trailing edges on the lift and drag of a low-speed section, comparing the increment in lift obtained with that given by a split flap. Hoerner also referred to some work of German origin drawing attention to the increase in lift/drag ratio which could be obtained on thick sections by the use of a blunt trailing edge, and suggested that it might have an application in propeller design.

The advent of the supersonic aircraft gave recognition to the advantages that could be obtained by the design of wing sections with rearward positions of maximum thickness and blunt trailing edges. With reduced surface slopes over the front of the section the decrease in forebody wave drag was sufficient to off-set the base-drag penalty[3] and a definite performance advantage began to show. Moreover the relaxation of the restriction of zero trailing-edge thickness meant that a more efficient structure could be designed resulting in a significant saving on structure weight. Thirdly there was always the prospect that the potential gains to be derived from blunt trailing edges could be exploited still further if some means could be found of minimising the base drag.

More recently it has been suggested that the use of blunt-trailing-edged wings has attractions at high subsonic speeds[40]. Pearcey[4] has shown that provided the base-drag penalty can be kept to a minimum advantages would accrue from the use of sections with blunt trailing edges for aircraft operating at high subsonic speeds or at supersonic speeds with the wings swept sufficiently to maintain subsonic-type flow. These advantages would result from the lower super-velocities on the forebody, and hence from the delay in the onset of the wave drag due to shock waves on the wings and the delay in the onset of shock-induced separation. In certain cases it seems possible that a substantial reduction in sweep-back angle could be achieved for a given cruise Mach number with a resultant saving in structure weight. Blunt-trailing-edged ailerons have already been used on certain high-speed aircraft where the favourable delay in shock-induced separation could be exploited to alleviate loss of control effectiveness and aileron buzz. In all such cases where there is normally no wave drag at the cruise condition the emphasis on methods for reducing the base drag would appear to be even stronger than for those in which some of the base drag can be off-set by the reduction in forebody wave drag.

2. *Experiment.*

2.1. *Experiments at Subsonic Speeds.*

During the 2nd World War a number of low-speed experiments were carried out in Germany to investigate the effects on aerofoil characteristics of cutting away the trailing edge to give various degrees of bluntness. The results of some of these tests have been collected by Hoerner[2] who found that the base-drag data could be correlated in terms of the skin-friction drag of the aerofoil upstream of the trailing edge, or in equivalent terms that the base pressure was a function of the ratio of the boundary-layer thickness to the trailing-edge thickness. Hoerner also analysed measurements of the drag of sheet-metal joints which presented a small backward-facing step to the stream and found that the drag depended on the ratio of the thickness of the metal skin to the boundary-layer thickness. However it was found that the two sets of data remained distinct from one another, the base pressure on a blunt-trailing-edged aerofoil being rather less than that on a sheet-metal joint for the same ratio of 'base height' to boundary-layer thickness.

Hoerner attributed the discrepancy to the existence of a Kármán vortex street in the wake of the aerofoil, whereas in the case of the sheet-metal joint the presence of the wall downstream of the 'base' inhibited the formation of any such vortex system. To support this argument he referred to some tests which he had carried out in a water tunnel[5]. It had been found that if the vortex street behind a plate normal to the stream was suppressed by means of a splitter plate, i.e., a thin two-dimensional flat plate placed in the plane of symmetry of the wake, the base-pressure coefficient could be increased from $-1\cdot3$ to $-0\cdot8$. The use of a splitter plate to reduce the base drag of bluff cylinders was later demonstrated by Roshko[6,7] who was able to show that as the splitter plate was moved downstream from the body the base pressure rose and the shedding frequency of the periodic vortices decreased. If a long splitter plate was used (five diameters) the flow reattached to the plate effectively suppressing the periodicity, and in this case the base drag was reduced to about a half its normal value. Roshko found from an analysis of all his results that a unique relation existed between the base pressure, C_{p_b}, the width of the wake, h', and the shedding frequency, n. A universal Strouhal number S^* could then be defined by

$$S^* = \frac{nh'}{u_s} = S\frac{1}{k}\frac{h'}{h} = 0\cdot16$$

where

$$u_s = ku_\infty = \sqrt{(1-C_{p_b})}\,.$$

Thomann[8] conducted some tests on a single-wedge section at $M = 0\cdot556$ to show that as the length of a splitter plate was increased the point at which the vortices formed was pushed further downstream and their strength reduced. Thomann suggested that the likelihood of the wake breaking down into strong vortices was greatest when the shear layers springing from the body surface were thin compared with the distance between them. Thus the action of the splitter plate was to allow the shear layers to diffuse to some extent before they were free to engage, thereby reducing the severity of any possible instability. The concept that wake instability is attenuated by the reduction or cancellation of the large transverse velocity gradients was in accordance with the conclusions of Hoerner who pointed out that the base pressure on wings with only a small degree of trailing-edge thickness, where the velocity gradients are quickly cancelled by the merging of the shear layers from the two surfaces, tended towards the values for the sheet-metal joints. It has since been shown[9] however that the periodicity is still present on sections with a very small base height but presumably the strength of the vortices is then greatly reduced.

Chapman *et al*[10] suggested that if the periodic vortex formation is suppressed the subsonic base flow is quite similar to the steady base flow at supersonic speeds. Indeed it was shown that the residual base drag measured by Roshko on bluff bodies with a splitter plate could be predicted by extrapolating the theory of supersonic laminar base flow to $M = 0$. Thus we may suppose that the steady base flow is fundamental and can exist throughout the Mach number range but that this flow is in general unstable at subsonic speeds so long as large transverse velocity gradients are allowed to persist at the trailing edge.

The break-up of the wake behind bluff sections into a vortex street has been observed in some cases to be associated with a periodic circulation round the section which gives rise to unsteady lift and drag components. In fact it has been suggested[69] that it is the periodic circulation round the section which causes the shedding of eddies into the wake. As yet there appear to have been no tests to investigate these effects on aerofoil sections but reference can be made to various tests on circular cylinders. McGregor[11] reports measurements of the fluctuations of surface pressure round the circumference of a circular cylinder, and integrations of the pressure distributions showed a sizeable lift force alternating at the shedding frequency and a rather smaller fluctuating drag force alternating at twice this frequency.

It would be expected that the magnitude of the fluctuations of the overall force on a body would depend to a large extent on the two-dimensionality of the flow in the wake. It has been shown[12] that over no part of the Reynolds number range is the vortex street strictly two-dimensional. In the range 40 to 150, over which the flow is everywhere laminar, there is strong evidence of a spanwise periodic structure, and for higher Reynolds numbers the onset of turbulent flow in the wake gives rise to an increasingly random pattern. However the existence of well-defined overall force fluctuations on a cylinder extends to considerably higher Reynolds numbers. Macovsky[13] has reported measurements of total lift and drag forces in the range 10^4 to 10^5, which indicate that in the lower part of this range the cylinder experiences a fluctuating lift coefficient with an amplitude of the same order as the steady drag coefficient, in this case approximately 1·0. At the higher Reynolds numbers the spanwise structure of the vortex street was observed to deteriorate and the amplitude of the lift coefficient decreased steadily.

Tests by Fung[14] on cylinders at supercritical Reynolds numbers have shown that when turbulent flow is well established the force components tend once again to constant values. Above 4×10^5 the lift coefficient is given as 0·13 r.m.s. peaking to 0·30 and the drag coefficient 0·04 r.m.s.

It is fairly clear that overall force fluctuations of this order would not be experienced by a blunt-trailing-edged aerofoil. The circular cylinder is probably a particularly bad example because the separation points are free to move in sympathy with the shedding of the eddies. Presumably this could also occur on sections with rounded trailing edges and for this reason it would seem desirable to design blunt aerofoils with sharp corners at the rear to fix the separation points on each surface. Pressure disturbances are then still observed to travel forward over the section[38] but it is doubtful whether they contribute to significant unsteady lift and drag components. A few tests are needed to check this.

2.2. *Experiments at Supersonic Speeds.*

Large numbers of tests have been conducted chiefly in the U.S. to measure the base pressure under different flow conditions on a variety of body shapes* ranging from simple wedge sections to typical aerofoils for high-speed flight (Refs. 15 to 18). The effects of wing planform and sweepback have also been investigated by Goin[19]. These experiments have shown that the principal variables affecting base pressure in the supersonic régime are:

(1) Mach number.

(2) Reynolds number.

  (*a*) The boundary-layer thickness at the trailing edge.

  (*b*) The position of the transition point.

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* The word 'body' is taken in its general sense and is not meant to specify a body of revolution.

(3) Body geometry.
   (*a*) The ratio of base height to chord.
   (*b*) Boattail angle.
   (*c*) Incidence.

In supersonic base-flow, conditions are determined by the flow in the initial part of the wake. The shear flows originating in the boundary layers on the body surface are deflected by centred expansions at the trailing edge to converge to a narrow 'waist' a short distance downstream of the base. It is clear that the base pressure depends on the ability of the shear layers to negotiate the sharp pressure rise through the region of confluence: the low-velocity fluid in the shear layers is reversed to form a slowly circulating vortical flow in the cavity, while the higher-velocity fluid is able to overcome the pressure rise and escape into the downstream wake. The final recovery pressure far downstream is not greatly different from the free-stream pressure for thin sections and hence the base pressure falls as the shear layers are able to withstand larger pressure rises. It is because the turbulent shear layer can overcome larger pressure rises than the laminar layer that the onset of turbulence in the initial part of the wake is associated with a significant fall in base pressure[10, 20]. Disturbances introduced into the wake downstream of the recompression region appear to have no influence on the base pressure and hence a base flow can be considered laminar if the transition point is delayed to a position downstream of this region.

Such are the stability characteristics of free-shear layers that the passage from the laminar to the turbulent state, accompanied by the sharp fall in base pressure, is rapid and occurs over only a small Reynolds number range[20]. Nor is the transition phenomenon a function of the Reynolds number alone, the familiar factors of free-stream turbulence, past history of the shear layers, etc., make their appearance in the same way as they affect transition in the attached boundary layer. The outcome of these considerations is that the correlation of base-pressure measurements in this range becomes exceedingly difficult and design predictions even more so. It soon became apparent that data from various sources did not reduce to a single function of Reynolds number based on body chord or again of the Reynolds number based on trailing-edge thickness. An attempt to make some allowance for the probability of instability in the shear layers has been made by Lehnert[21]. The base pressures measured on bodies of revolution were plotted against the Reynolds number based on the momentum thickness of the boundary layer on the body, and some correlation was claimed. The same degree of success was not obtained however by Dahl[22] who examined additional data. More recently Potter *et al*[23] have got to grips with the problem by making direct reference to the actual position of the transition point in the wake. An encouraging degree of correlation was obtained among measurements of base pressure on bodies of revolution and this method could no doubt be applied with equal success to two-dimensional results. This work was of considerable importance in drawing attention to the critical dependence of base pressure on transition but it is unlikely to be of very much help to designers.

When the flow in the early part of the wake is entirely laminar or entirely turbulent the problem is simplified and the dependence on other parameters can be examined in more detail. The tests have shown that the base pressure is a function of the thickness of the boundary layer on the body surface just upstream of the trailing edge. At a given Mach number the base pressure increases with the ratio, θ/h, of the boundary-layer momentum thickness to the base height[15, 16, 24], although in only two cases[25, 26] has this ratio actually been measured. As yet there is insufficient data to predict accurately the base pressure on a wing given the conditions of the boundary layer on its surface.

As the ratio of boundary-layer thickness to base height is extrapolated to zero the base pressure appears to tend to a minimum value which may be termed the 'limiting base pressure' (*see* Fig. 2). In both the laminar and turbulent cases the limiting base pressure is a function of Mach number only, without further dependence on Reynolds number, and body geometry has only a secondary effect at least for sections with a reasonably small thickness/chord ratio. Values of limiting base pressure inferred from a large number of measurements of turbulent base flow* are plotted in Fig. 3. Experiments on laminar base flow have been carried out almost exclusively by Chapman *et al* and data on limiting base pressures in the laminar case are presented in Ref. 10. For the turbulent case Fig. 3 demonstrates the agreement obtained between measurements on a variety of models, even including the base pressure on the rear of a spoiler[27]. Through the range in which supersonic base flow is established the ratio of base pressure to free-stream static pressure for these models, falls from around $0 \cdot 5$ at $M = 1 \cdot 5$ to $0 \cdot 1$ at $M = 4$. Above $M = 4$ there is little data but some experiments (Ref. 17, e.g.) suggest that the base pressure may tend to rise again in the hypersonic range although this could possibly be attributed to the reappearance of laminar flow.

In certain cases base pressures below the limiting value have been measured but these with a few exceptions can be attributed to three-dimensional effects. The interaction of the base flow with the boundary layer on the tunnel wall gives rise to small three-dimensional vortices which entrain fluid from the dead-air region in this way inducing negative bleed. The base pressure measured on the model in the centre of the test section appears to be influenced by this effect when the ratio of base height to span is greater than about $\frac{1}{6}$ (Refs. 18, 26, e.g.). Another type of three-dimensional effect arises chiefly in cases where the boundary layer on the model is laminar[24, 28, 29]. Small disturbances upstream tend to provoke streamwise vortices in the shear layers; the increased momentum exchange enables the flow to negotiate a greater recompression and the wake can support a lower base pressure. A third type of three-dimensional effect is found near the tips of finite-aspect-ratio wings and models, and here again the base pressure can fall below its limiting value[16].

Geometrical parameters such as body shape and incidence appear to influence the base pressure on two-dimensional sections mainly in the way they control the effect of the boundary layers on the base flow. Numbers of experiments have been made to measure the base pressure on wing models over a range of incidence[19, 30] but any effect was very slight so long as the flow remained attached to both surfaces and in different cases an increase or a decrease in base pressure was observed. Section boattailing appears to have a rather larger effect than angle of attack[25, 30]. Slight positive boattailing, i.e., with the section thickness decreasing towards the trailing edge, gives a small increase in base pressure until the boundary layer separates from the afterbody. Conversely, negative boattailing leads to a lower base pressure and in severe cases such as single-wedge sections the base pressure may tend to its limiting value.

2.3. *Transonic Base Flow.*

Apart from a very few measurements of base pressure through this speed range (Refs. 31 to 34) little advance in our knowledge of transonic base flow has been made until the last two or three

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* For sections of large trailing-edge thickness the base-pressure data were taken directly; for other sections where the boundary-layer thickness was comparable to the base height the results were extrapolated to the limiting value. (*See* Fig. 2, e.g.)

years. Recently a research programme has been initiated at the N.P.L. to investigate this most complicated class of base flows and the preliminary results of these tests, as yet unpublished, have been of considerable assistance to the author in preparing this section of the review.

At both subsonic and supersonic speeds we have seen that for a given Mach number the base pressure is a function of the ratio of the boundary-layer thickness to the thickness of the trailing edge. This was alternatively expressed by Chapman *et al*[16] in the convenient form

$$\frac{c}{hR_e^{1/2}} \quad \text{or} \quad \frac{c}{hR_c^{1/5}}$$

according to whether the boundary layer was laminar or turbulent. Now especially in the latter case the Reynolds number term is relatively weak and base-pressure data obtained over a moderate Reynolds number range can be correlated quite well against h/c, the ratio of the trailing-edge thickness to the section chord, (*see* Fig. 4), for Mach numbers at least up to $1 \cdot 0$. It is quite possible of course that the ratio h/c itself has more significance in subsonic flow than it appeared to have in the supersonic range since below $M = 1$ the base flow cannot be considered in isolation from the flow over the section upstream of the base, and the external potential flow will depend on the ratio of the physical dimensions of the section. The variation of the base-pressure coefficient with Mach number for a selection of models is shown in Fig. 5. It is important to note that whereas at Mach numbers below about $0 \cdot 85$ the curves for different values of h/c are well spread out, the curves converge near $M = 1$ to a value of C_{p_b} around $-0 \cdot 7$ and the base pressures for sections of very small h/c are forced to decrease sharply over this short Mach number range. This fact is also brought out by the flattening of the curves in Fig. 4 where it is seen that increase of h/c above about 2% has very little effect on the base pressure. Rogers[71] has shown that the transonic fall in base pressure can be delayed by trailing-edge sweep according to the simple sweep analogy, and that the results correlate well in terms of the velocity component normal to the trailing edge.

The breakdown of the wake into periodic vortices which dominated the flow picture at low subsonic speeds (Fig. 1) extends through the transonic range also, and values of the base pressure on models with a severe degree of trailing-edge bluntness are found to be considerably lower than could be estimated from tentative steady-flow calculations using for example an extrapolation to subsonic speeds of the theory of Chapman, Kuehn and Larson[10].

With increase of Mach number from low subsonic speeds shock waves develop on the body surface and the movement of these back to the trailing edge appears to be associated in some cases by the small rises and falls in base pressure near $M = 0 \cdot 8$ or $0 \cdot 9$. Further increase of Mach number causes the shocks to trail behind the section at the end of short well-defined shear layers extending almost parallel to each other downstream of the trailing edge (Fig. 6a). In this condition there is a complicated interplay between movements of the trailing shock system and the formation of the vortices. Measurements[38] have shown that the Strouhal number (non-dimensional vortex-shedding frequency $S = nh/u_\infty$) increases through this short Mach number range and the wake downstream of the trailing shocks spreads out accompanied by the fall of the base-pressure coefficient to its absolute minimum. There is some evidence that the minimum base pressure is reached first in terms of increasing Mach number on sections with a high h/c ratio, but this may possibly be influenced by wind-tunnel interference effects.

A small increase of Mach number from this condition causes an abrupt change in flow pattern (Fig. 6b). The shear layers from the body surface now turn sharply at the trailing edge and converge to a narrow waist approximately two base heights downstream. There is a short Mach number range in which the trailing shocks are bifurcated but very shortly the more familiar supersonic-type base flow with a simple trailing shock system is established (Fig. 6c) and further increase of Mach number does not produce any significant change in the flow picture. At Mach numbers from 1·0 to about 1·4 the base pressures are still below the values computed from steady-flow considerations[50] (*see* Fig. 5) but it is not clear whether this is due to the effect of periodicity in the wake or to a deficiency of the theory. The shedding frequency has been measured for the section shown in Fig. 1 at Mach numbers up to 1·1. In this range the intensity of the vortices does not appear to be very great but there is no evidence that the periodicity entirely dies out at higher Mach numbers. Indeed certain Schlieren photographs[18] suggest that discrete eddies may persist in the wake behind blunt-trailing-edge sections even up to $M = 4$. (*See* also Ref. 67.) Above a Mach number of about 1·4 however the base pressures agree more closely with steady-flow theory and it can be safely concluded that any instability which persists will no longer have a significant effect on the base flow.

At transonic speeds there is little data to indicate the effect of different aerofoil section shapes on base pressures, and it is noted that most of the available results refer to simple symmetric models. There is some evidence[32] that at the lower Mach numbers the effect of increasing incidence is to increase the base pressure on two-dimensional sections, near $M = 1$ however, any regular pattern in the variations is not easy to detect.

2.4. *Methods of Reducing Base Drag.*

Some research has been carried out on methods of reducing the base-drag penalty of sections with blunt trailing edges. It was seen that at low speeds the base pressure on bluff sections could be raised by the suppression of the vortex street by a splitter plate projecting from the trailing edge. To the author's knowledge no measurements of base pressure on more typical aerofoil sections with splitter plates have been made although Thomann[8] demonstrated their effect on vortex-shedding frequency and recovery temperature using a 16% single-wedge section.

At supersonic speeds tests have shown that significant increases in base pressure can be achieved by the continuous injection of low-velocity air into the base region[25, 26, 42, 43]. It is found that the base pressure is particularly sensitive to small bleed rates, a point which lends considerable encouragement to the practical application of base bleed. However as an attempt is made to introduce greater quantities of bleed air the injection velocity must in general rise, and a stage is reached when the injection velocity becomes excessive. Further increase of the bleed quantity causes appreciable momentum addition to the wake and the base pressure falls again. Wimbrow[43] found that the optimum effect was attained when the blowing pressure was between 75% and 95% of ambient static pressure. Thus with a limitation on injection velocity the mass-flow rate can be raised only by increasing the area of the vent through which bleed air exhausts into the wake. Fuller and Reid[25], and Wimbrow found that reductions in base drag of order 50% could be achieved with the area of the vent equal to half the base area.

Thus base bleed has been shown to be an important technique in controlling the base flow at supersonic speeds and giving a useful reduction in base drag, and under normal flight conditions it could have an important application. In flight at extreme altitudes however laminar flow might persist even into the wake. In these circumstances the operation of base bleed might disturb the flow bringing about an earlier transition and the fall in base pressure due to the onset of turbulence in the wake might not be off-set by the increase due to the bleed.

More recently the effects of base bleed at subsonic speeds have been investigated by Holder[40] who was able to show significant reductions in the drag of an aerofoil for small injection quantities. Tests on the same model by Moulden[44] have shown that there is no apparent relation between the fall in base drag at the optimum blowing condition and the vortex-shedding frequency which remained almost constant through the range of bleed quantities considered. There was some evidence from Schlieren photographs however that the strength of the eddies was reduced near the optimum condition.

3. *Theory.*

Many years ago simple theories were advanced in an attempt to predict the base pressure on bodies of revolution moving at speeds up into the supersonic range. In that they lacked any detailed appreciation of the flow mechanisms at work however, they were of little use and the results they gave were widely different (*see* Ref. 15, e.g.). Especially difficult to analyse has been the subsonic base flow when the vortex street is formed and only in incompressible flow has any progress been made. At supersonic speeds the position is much more satisfactory and the stable base flow of this range has shown itself more amenable to theoretical treatment.

3.1. *Supersonic Base Flow.*

Cope[45] devised a semi-empirical method for estimating the base pressure on projectiles moving at supersonic velocity, a theory which took account of the boundary layer developed on their surfaces. Numerous assumptions and approximations were made and the final result depended on a geometrical flow parameter which was assessed from shadow photographs of actual projectiles in flight. Cope's method was of some use in interpolating test data but it was never intended to be anything more than a first approximation. Prior to the more detailed analysis discussed below, Chapman[15] proposed another semi-empirical method based on the correlation of a large number of base-pressure measurements. More fundamental, though again of limited significance, was an 'heuristic' approach to base flows by Kurzweg[46], who supposed a relationship to exist between the base pressure and the momentum defect in the boundary layer approaching the base. As formulated Kurzweg's analysis predicted a decrease in base pressure with increasing boundary-layer momentum thickness.

An important step in the understanding of base flows came with the theory of Crocco and Lees[47]. The investigators recognized base flow as one of a class of problems in which the governing mechanism was the interaction between an external quasi-inviscid flow and a dissipative highly viscous region. The theory, which could be regarded as an extension of the integral method for the solution of the boundary layer on a plate, considered a general but highly simplified flow picture which nevertheless preserved the essential non-linear feature of the real flows. Applied to base flow the Crocco-Lees method proved valuable in that it was able to treat the problem in a general way, indicating the relevant parameters and describing the trend of the base-pressure variation with Mach number and Reynolds number even through the difficult Reynolds number range in which wake transition occurs. The behaviour of certain empirical functions which appear in the analysis is not known in sufficient detail, especially in the turbulent case, to permit the arrival at quantitative results. Moreover the theory itself has been shown to be subject to certain ambiguities both in the treatment of base flows[10] and shock-wave boundary-layer interaction[48], and it is now regarded by some investigators to be of less direct importance than was at first supposed.

More success in the analysis of base flow at supersonic speeds has been realised by methods based on the simplified flow model proposed by Chapman[15]. This model considered four flow regions: (*See* Fig. 7.)

(1) The flow approaching the trailing edge of the body.

(2) The centred expansions at the trailing edge.

(3) Constant-pressure flow along the edge of the wake separated from a region of semi-dead air by a free-mixing layer.

(4) Recompression at the 'waist' in the wake where the shear layers merge. (The region of confluence.)

Considering only the inviscid flow outside the wake Chapman was faced with an infinite number of solutions all of which satisfied the necessary boundary conditions. He concluded that the inviscid flow by itself did not represent the essential mechanism of the base flow and that the solution would be made unique only if the viscous effects could be satisfactorily accounted for. It was recognised that the shear layers springing from the two surfaces at the trailing edge entrain fluid from the dead-air region and the cavity would collapse were it not for the reversal of a certain amount of this air by the subsequent recompression where the shear layers converge. The solution could then be closed by allowing the pressure rise across the region of confluence to adjust itself such that the correct amount of fluid in the shear layers be reversed to preserve the mass balance in the cavity, and the remaining fluid with a higher velocity be able to negotiate the pressure rise and escape into the downstream wake. In this way the problem was reduced to one of finding the pressure rise which the fluid on a particular streamline, selected by continuity requirements, could just overcome before being brought to rest. On two-dimensional sections of small thickness/chord ratio the final recovery pressure far downstream in the wake was known to be almost equal to the free-stream pressure and hence once the pressure rise through the region of confluence was found the base pressure was automatically determined.

While the problem was formally solved by these arguments, an analysis of the free-shear layers was necessary to find the velocity on the dividing streamline. This of course depends on the mixing process and it was noted that here the difference between laminar and turbulent flow would be manifest.

Chapman later derived an exact solution of the asymptotic laminar mixing layer[49], and the results were used to obtain the solution of the laminar base flow in the limiting case when the thickness of the boundary layers on the body surface was vanishingly small. This theory then yielded values of the limiting minimum base pressure and these were shown to agree well with measurements made in experiments carefully devised to satisfy the requirement of zero boundary-layer thickness at separation[10].

The corresponding problem in turbulent base flow has been tackled independently by Korst[50] and Kirk[51]. For the analysis of the turbulent mixing layer no exact solution could be found as in the case of laminar flow, and while Kirk made reference to the low-speed results of Tollmien[52] and Abramovich[53], Korst[54] developed a simple approximate solution to the momentum equation which led to velocity profiles of the same form as those given by Görtler's 1st approximation in incompressible flow. The variation of limiting base pressure with Mach number computed from Korst's theory is seen from Fig. 3 to be in good agreement with measurements on models with fairly thick trailing edges, through the supersonic range.

Korst and Kirk have also considered the problem of base flow when the mass balance in the dead-air region is disturbed by the continuous removal or addition of fluid, i.e., low-velocity base bleed. Korst presented in his paper some computations of the increase in base pressure achieved by permitting air to bleed into the wake. At one Mach number the results were compared with a few measurements and the agreement is satisfactory. Sirieix[26] has also carried out experiments on base bleed which have shown a good measure of agreement with the theory. The unfavourable developments experienced in practice when the injection velocity becomes excessive are not represented in this simple theory which specifies that the bleed air has zero momentum. More recently Korst's analysis has been extended by Chow[55] to investigate the effects of a finite bleed velocity. Chow's theory predicts the changes in base pressure occurring as the bleed velocity is increased from zero up to sonic speed, and the results are shown to be in fair agreement with tests of Fuller and Reid[25]. A further extension of Korst's basic analysis has been to the case of a non-adiabatic base flow. Page and Korst[56] were able to show that increases in base pressure over and above that obtained by a normal base bleed could be achieved by the injection of air at a temperature in excess of the wake recovery temperature. The results of some measurements employing the bleed of hot air were submitted to support the theory.

The original analysis of the turbulent mixing layer by Korst, Page and Childs[54] included the effects of an initial boundary-layer profile and calculations of the velocity profiles close to the separation point were shown to be in good agreement with low-speed measurements[57]. However the results were not in a form which could readily be fed into the base-flow solution to yield data on the effect of an oncoming boundary layer on base pressures. Kirk discussed modifications to his analysis to take account of the presence of the boundary layer at separation. Kirk's approach to the problem of computing the development of the shear layers under the influence of an initial boundary layer was much less involved than that of Korst *et al* but it has since been shown to yield closely similar results[58]. Kirk formulated his general analysis in detail and showed that it would lead to qualitatively correct data but no calculations were performed.

Recently three methods have been proposed independently for extending the theory to cover the case when a boundary layer develops on the body surface upstream of the trailing edge[59, 60, 61]. It is noted that the theories which are essentially similar in approach, give results which agree well with the measurements of Chapman *et al*[16] for the case when the flow in the boundary layer is laminar[60]. This of course is not a valid test on the theory since the requirement of fully-developed turbulent flow over the length of the shear layers is hardly realised. No such agreement appears to be obtained when the transition point is well ahead of the trailing edge[59].

Extensive use has been made of the simple base-flow model originally proposed by Chapman and theories using it have yielded base-pressure data which, on the whole, have been in good agreement with measurements. Nevertheless it must not be forgotten that in any simplification of this nature some features of the flow may conceivably be obscured. Indeed Charwat and Yakura[24] have shown that at the higher Mach numbers certain interactions between the constituent parts of the flow field begin to be significant and the apparent validity of the flow-model concept becomes increasingly fortuitous.

3.2. *The Incompressible Flow over Bluff Bodies.*

The problem of devising an adequate mathematical model to represent the subsonic flow over bluff sections has fascinated only a few investigators in recent years. It was recognised from the earliest days that the flow field was dominated by the early separation of the boundary layer leaving a wide wake behind the section, and it was known that the departure of the real flow from the inviscid potential-flow model had a not insignificant influence on the whole pressure distribution even over the front of the body where the boundary layer remained attached.

Experiments[62] showed that the free-shear layers springing from the separation points could be traced at least for some distance downstream and the knowledge of this lent credence to the Helmholtz-Kirchoff flow models. The theory proposed that the shear layers in the real flow could be replaced by free streamlines extending from the body to infinity downstream. The flow was then divided into an external inviscid flow and a wake of dead air which was defined as being at ambient static pressure. The theory was a great step forward from classical potential-flow theory since it allowed the computation of a pressure distribution over the front of the body which resembled the measured distribution at least qualitatively and it gave a finite value for the drag. The shortcomings of course were the fact that the base pressure was fixed at free-stream static pressure when it was known that the real base-pressure coefficient was around $-1 \cdot 0$ for a bluff section, and that the computed drag coefficient was too small. More recently Roshko[63] has demonstrated that if instead of restricting the pressure in the dead-air region to ambient static pressure it is left as a disposable parameter a family of solutions can be obtained for the flow field over the front of the body. Selection of the particular solution representing the correct experimental value of the base pressure enables the pressure distribution over the front of the body to be predicted satisfactorily and reliable drag values can be computed. However the solution is not made unique until the base pressure is specified and hence some other relation is sought connecting the base pressure with the external flow parameters.

Not very far downstream of the body the wake was known to become unstable and break up into periodic vortices. The well-known Kármán vortex street was an idealised model of the periodic motion and it showed that there was a unique relation between the velocities in the wake, the width of the wake and the drag which it could support. Heisenberg[64] was the first to recognise that some representation of the flow past bluff bodies could be obtained by joining the Kirchoff free-streamline model to the Kármán vortex street. However Prandtl pointed out that the basic assumptions made by Heisenberg were incorrect (*see* Ref. 70), and in retaining the Kirchoff value of the base pressure ($C_{p_b} = 0$) the solution was redundant and could not lead to more realistic description of the pressure field over the body. Roshko[6] has since demonstrated that by joining his generalised free-streamline hypothesis to the Kármán vortex street (Fig. 8) an almost complete solution could be achieved. The free-streamline theory had one free parameter, the base pressure, and the complete solution has another; but this does not mean that the understanding of the general problem has not advanced. The remaining parameter represents the proportion of the vorticity shed in the boundary layers at separation which appears as discrete eddies in the wake. From experiments by Fage and Johansen[65] it was known that only about half the available vorticity finds its way into the vortices and using this information Roshko was able to compute fairly accurate base-pressure and base-drag values. It seems probable that no significant advance from the present position of the theory of incompressible flow over bluff bodies and indeed of blunt aerofoils at subsonic speeds can be made until there is a better understanding of the basic mechanism behind the formation of eddies and of the factors which provoke instability in the wake. In this respect tentative theories such as those of Shaw[68] and Spence[69] would seem to deserve a greater measure of attention than they have hitherto enjoyed.

3.3. *Subsonic Flow over Blunt-Trailing-Edged Aerofoils.*

So far it is not clear whether the theory of Roshko can be applied as it stands to describe the flow over blunt-trailing-edged aerofoils at subsonic speeds, but certain conclusions of Roshko's work would appear to be of direct interest in the understanding of the class of subsonic base flows.

The Kármán vortex-street model defines an equation connecting the drag with the width of the wake and the velocities in it, and it has been shown that this is equivalent to a relation between the drag, the wake width and the shedding frequency of the eddies. Roshko has shown experimentally that a universal Strouhal number could be found which was approximately constant for all the tests he conducted:

$$S^* = \frac{nh'}{u_s} = 0 \cdot 16$$

where

n is the shedding frequency

h' is the width of the wake

u_s is the velocity at separation

$$= u_\infty \sqrt{(1 - C_{p_b})} .$$

Thus it is clear that variations of base pressure are not necessarily accompanied by sympathetic variations of the shedding frequency since the wake width must also be taken into account.

Most of Roshko's calculations have been concerned with relatively bluff shapes such as circular cylinders and flat plates normal to the stream but he has reported that the method has also been applied to an $11\frac{1}{4}°$ single wedge. However as Bauer[9] points out, the effect of the boundary layer on thin sections may have a fairly large influence. Bauer suggests that the drag computed for the Kármán vortex street should be equated to the sum of the base drag and the skin-friction drag of the section, and that the width of the wake should be identified with the trailing-edge thickness plus the displacement thickness of the boundary layer on each surface.

The only conclusion to be drawn from this section is that there is a scarcity of the data that are needed to assist our understanding of the fundamental aspects of subsonic base flows. In particular there appears to be a need for experiments to measure the vortex-shedding frequency and the width of the wake behind sections with a trailing-edge thickness of comparable order to the thickness of the boundary layer on the surface.

4. *Concluding Remarks.*

At subsonic speeds it is observed that the flow in the wake of a blunt-trailing-edged section is dominated at Reynolds numbers above about 50 by the formation of periodic vortices. This phenomenon is known to exist when the transition point in the boundary layer on the surface is well forward of the trailing edge and there would seem to be no reason why it should not extend to flight Reynolds numbers. From tests on fairly bluff sections it appears that a relation exists between the base pressure, the width of the wake and the shedding frequency. Further tests are required to investigate the effects of the boundary layer on the vortex-shedding characteristics of thin sections.

Measurements of base pressure on blunt-trailing-edge aerofoils relating mostly to low-speed sections appear to be correlated in terms of the ratio of the boundary-layer thickness to the trailing-edge thickness. A few tests have shown that significant reductions in total drag can be achieved by base bleed.

At transonic speeds the development of shock waves on the aerofoil and the interplay between the shocks and the formation of the vortices lead to a complex succession of flow patterns. The base-pressure coefficient falls to a minimum at or near $M = 1$ for two-dimensional sections and at corresponding Mach numbers resolved normal to the trailing edge for swept sections. Available data on base pressure appear to correlate successfully in terms of the ratio of trailing-edge thickness to chord. Near $M = 1$ the base pressure appears to be insensitive to variations of this ratio above about 2%.

In the supersonic range the wake periodicity is observed to become less strong and for Mach numbers above about 1·4 does not appear to have any further effect on the base pressure. At a given Mach number the base pressure falls as the transition point in the wake moves upstream towards the trailing edge, i.e., a turbulent base flow can support a lower base pressure than a laminar base flow. Base-pressure data relating to the Reynolds number range in which wake transition occurs are particularly difficult to correlate.

At a given supersonic Mach number the base pressure rises with increase of the ratio, θ/h, of the boundary-layer momentum thickness to the thickness of the trailing edge. However reliable quantitative data which would assist the accurate prediction of the base pressure in terms of the boundary-layer conditions on the aerofoil surface are not in abundance. Attempts to compute the variation of base pressure with boundary-layer thickness from theory have met with limited success particularly in the case where the transition point is well forward of the trailing edge.

For small values of the ratio θ/h, the base pressure tends to a minimum in two-dimensional flow—the limiting base pressure. For both laminar and turbulent base flow the variation of the limiting base pressure with Mach number would appear to be predicted successfully by theory.

Incidence and section boattailing are shown to affect the base pressure at supersonic speeds chiefly through their effects on the boundary layer. Large numbers of experiments indicate that the effect of angle of attack on base pressure is small and can be of either sign. Positive boattailing can induce a slight increase in base pressure so long as the boundary layer remains attached to the afterbody. Boattailing of two-dimensional bodies has not been examined in great detail.

At supersonic speeds it is well known that the base pressure can be increased significantly if air is allowed to bleed at low velocity into the wake. The degree to which the base pressure can be increased appears to be limited only by excessive increase of the injection velocity, but decreases in base drag of order 50% have been achieved. For turbulent base flow the increase in base pressure due to low-velocity bleed can be predicted accurately from theory.

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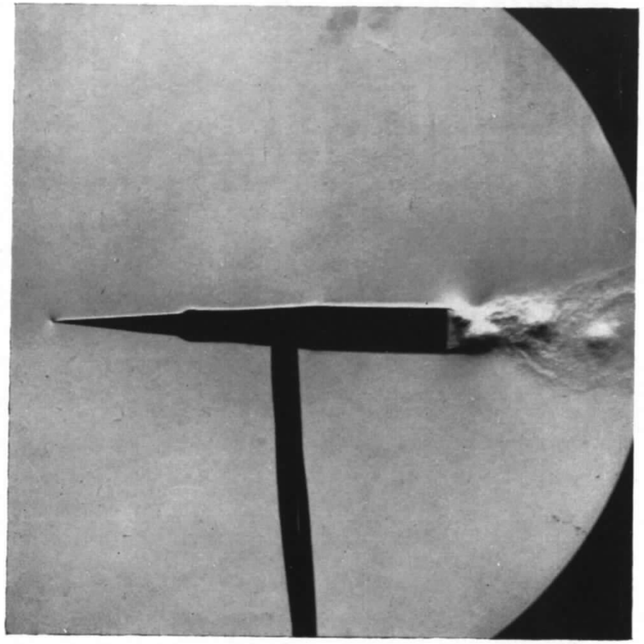


FIG. 1. The flow past a blunt-trailing-edged section at $M = 0{\cdot}4$ (Ref. 38).

$$C_{p_b} = -\,0{\cdot}625,\ s = 0{\cdot}250$$

$$\frac{h}{c} = 0{\cdot}10$$

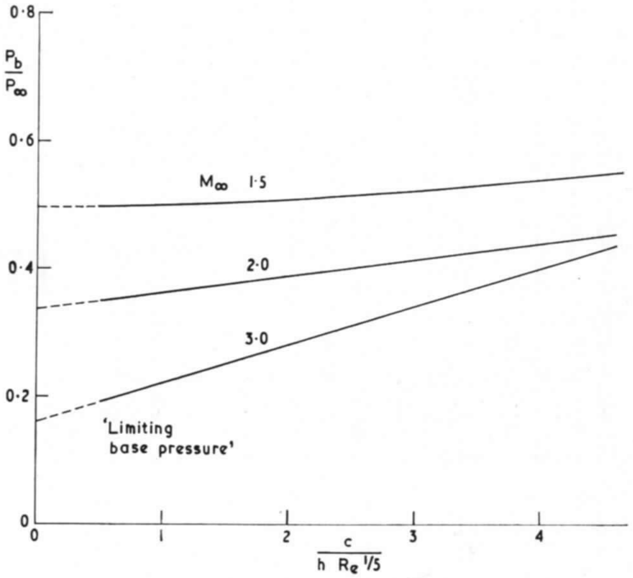


FIG. 2. Variation of base pressure with boundary-layer thickness at supersonic speeds. Chapman's results for turbulent boundary layer (Ref. 16).

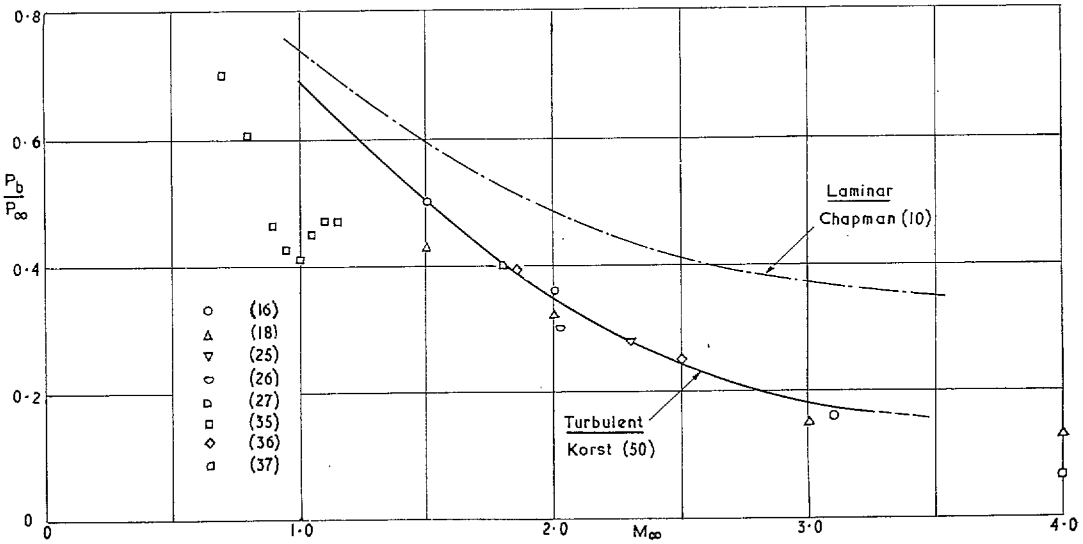


FIG. 3. Limiting base pressure for turbulent base flow.

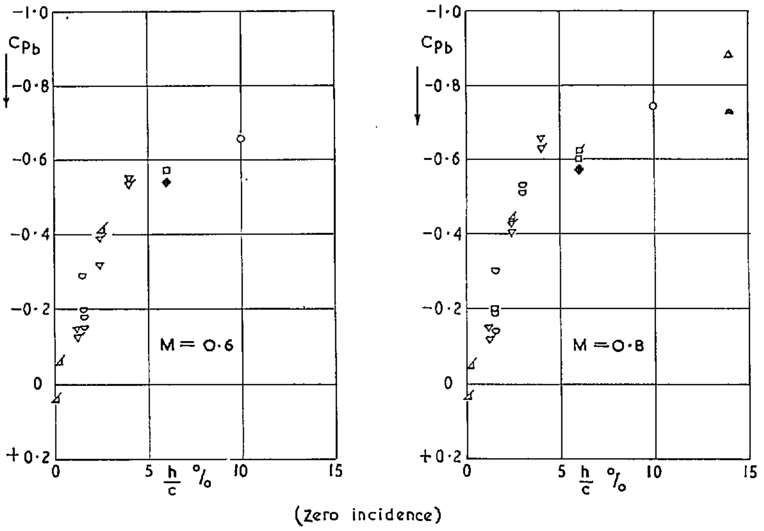


FIG. 4. The variation of base-pressure coefficient with trailing-edge thickness at transonic speeds.

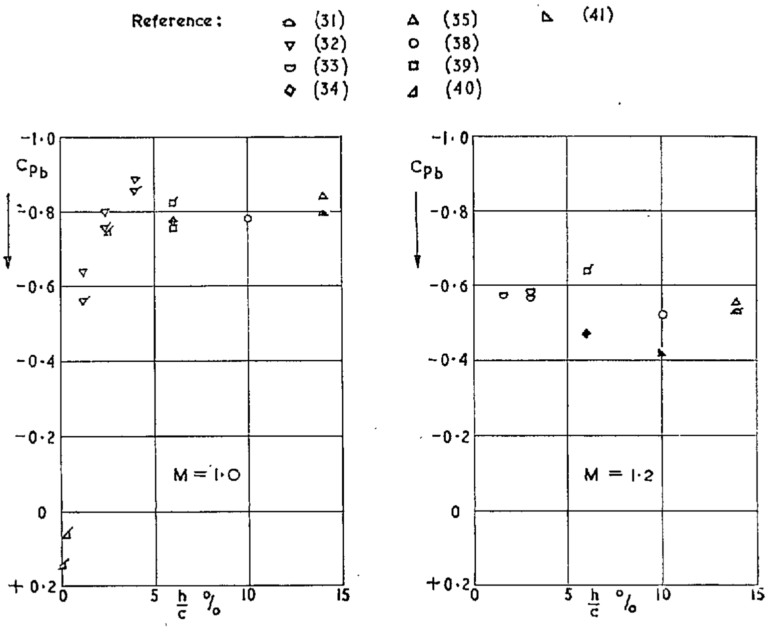


FIG. 4 (*continued*). The filled symbols denote free-flight tests. The flagged symbols denote tests on models with a roughness band.

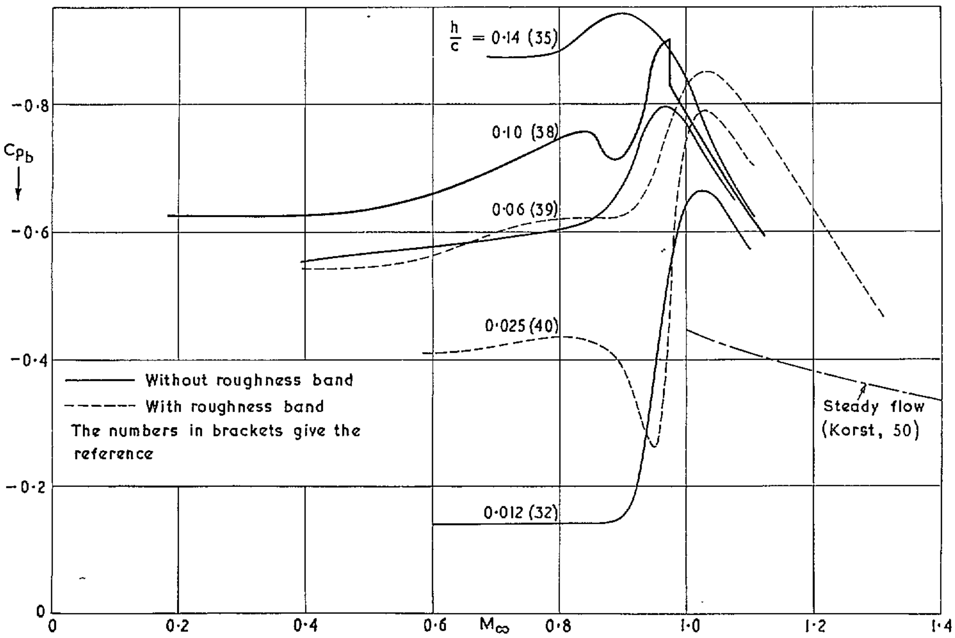
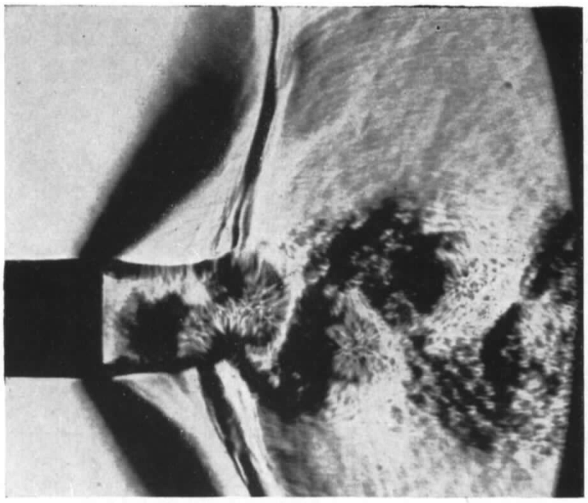
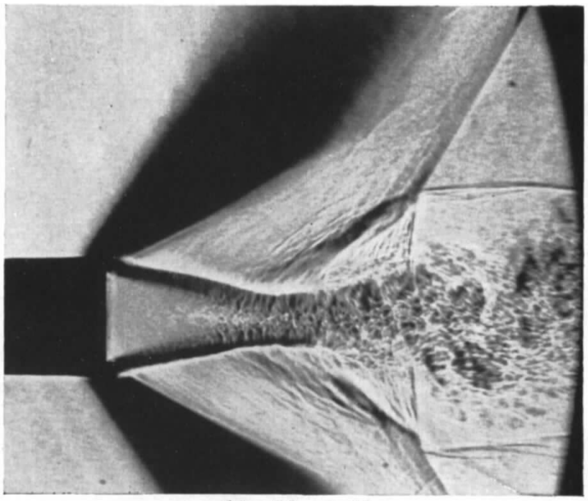


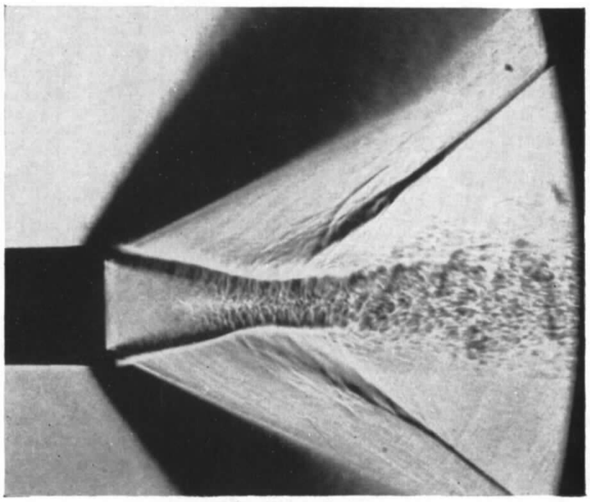
FIG. 5. Variation of base-pressure coefficient with Mach number.



(a) $M = 0{\cdot}925$



(b) $M = 1{\cdot}00$



(c) $M = 1{\cdot}05$

FIG. 6. Phases in the base flow behind the section in Fig. 1 at transonic speeds (Ref. 38).

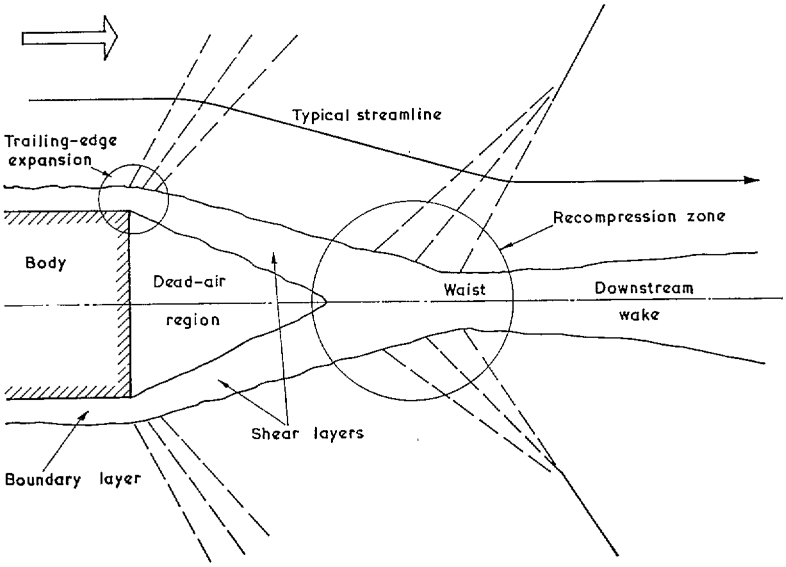


FIG. 7. Chapman's model of supersonic base flow.

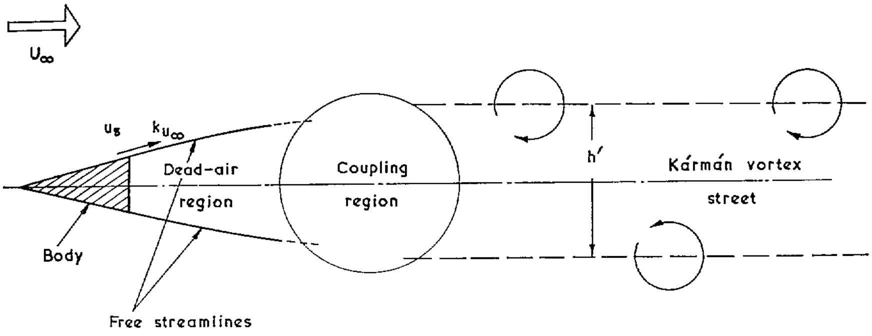


FIG. 8. Roshko's model of subsonic base flow.

(87114) Wt. 64/1857 K5 6/63 Hw.

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