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Summary.—Tests have been made in the National Physical Laboratory 9-in. × 3-in. High-Speed Tunnel to investigate the use of sonic throats downstream from the working-section of a slotted-wall high-speed tunnel employing diffuser suction. It was found that such throats behaved at subsonic speeds in a manner similar to their behaviour in a solid-wall tunnel. The Mach number in the working-section was approximately that to be expected from the ratio of the area between walls, at the beginning of the slots, to the area at the throat.

Tests were made with various configurations, including the conditions which could be expected on the 18-in. × 14-in. and 36-in. × 14-in. High-Speed Tunnels at the N.P.L. It was found that the throat mechanisms at present used with the subsonic liners on these tunnels should work satisfactorily, and that the power required should be of the same order as that required to run the unchoked slotted walls at unit Mach number.

Information has also been obtained on the beneficial effects to be obtained from (*a*) an improvement in the pressure recovery downstream from the parallel slotted length of the working-section and (*b*) a reduction in the slope of the upstream face of the sonic throat.

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1. *Introduction.*—Difficulty has sometimes been experienced in obtaining steady flow past aerofoils in the working-section of an induction-type high-speed wind tunnel fitted with slotted walls, particularly when boundary-layer separation is present on the aerofoil. This unsteadiness may arise from, or at least be aggravated by, an interaction between the separated flow and disturbances propagated upstream. Such disturbances can come either from the injector and diffuser, or from the region where the air in the working-section mixes with the air that is re-entering the tunnel circuit from the plenum chamber.

Disturbances from the first source are well known in subsonic wind-tunnel operation, and are normally cured by introducing a sonic throat between the working-section and the injector slots. Such a throat, if adjustable, has the added advantage of providing a method for controlling the Mach number in the working-section, and has been found to be essential for the control of large and pressurised induction tunnels. No published information is available, however, on the use of sonic throats in the subsonic operation of tunnels fitted with slotted-wall liners, although it is known that they are in use in Sweden[1].

It is much more difficult to prevent the upstream propagation of disturbances arising from the mixing region, since a sonic condition would have to exist upstream from the mixing region. It is known that such a condition would adversely affect the supersonic operation of the tunnel[2].

This report describes tests made with sonic throats downstream from a slotted working-section to remove disturbances of the first type. It also describes some tests made to improve the efficiency of the tunnel by varying the conditions downstream from the working-section in the absence of a sonic throat.

2. *Description of the Slotted Liners.*—The liners were bolted to the upper and lower rails of the working-section of the N.P.L. 9-in. × 3-in. High-Speed Tunnel[3]. The slotted length of each liner was made from seven strips of $\frac{1}{16}$-in. thick brass and had a ratio of open to total area of 0·125. The strips were mounted between two wooden blocks, the upstream block being faired smoothly into the 16 : 1 contraction and the downstream block into the tunnel circuit just upstream from the injector slots (Fig. 1). The tunnel height at the beginning of the slots was 7·34 in., and this increased by 0·016 in. per inch to allow for the boundary-layer growth along the four walls of the tunnel. At a distance of 18·54 in. from the beginning of the slots, the walls began to diverge at a total included angle of $12\frac{1}{2}$ deg, until they blended into the tunnel circuit at the downstream wooden blocks. These blocks had a length of approximately one tunnel height between the end of the slots and the plane in which they blended into the tunnel circuit. Space was thus available for the introduction of additional blocks in order to form a sonic throat downstream from the ends of the slots as shown in Figs. 1 and 2. Two supports of the comb type were introduced under each set of slots to prevent vibration of the strips comprising the walls.

Static pressure holes were provided at intervals along the slotted walls. The pressure leads from the holes passed outside the tunnel to a multitube mercury manometer.

The walls were later modified to represent the arrangements that would need to be used in two of the larger N.P.L. tunnels. These modifications are described in the appropriate sections (4 and 5) of this report.

Schlieren photographs were taken of the flow in the downstream region of the working-section ; two 12-in. diameter spherical mirrors and a spark-light source of 1 microsecond duration were used*.

3. *Tests with the Unmodified Liners.*—The unmodified liners, as described in the preceding section, were bolted in position, and the static pressure at the various holes observed for the top speed of the tunnel and for five other speeds. The variation of this pressure, expressed as a fraction of the total pressure H of the main stream, along the slotted walls is shown in Fig. 3. The pressure H is approximately atmospheric. The pressures plotted are a mean of the readings obtained for the two walls ; the difference between these readings did not exceed a value of $p/H = 0 \cdot 003$. A slight positive pressure gradient existed along the walls at subsonic speeds ; the gradient represented a decrease of about 1 per cent in Mach number for each tunnel height downstream from the beginning of the slots. The supersonic distribution exhibited the characteristic over-expansion associated with square entry-shape slots, but after one tunnel height settled down to a variation of about $\pm 1\frac{1}{4}$ per cent in Mach number.

An indication of the relative power requirements for the various tests reported here was obtained by measuring the total pressure of the inducing air needed to drive to the tunnel at each particular free-stream Mach number. This Mach number is taken as that corresponding to the static pressure on the centre strip of the slotted walls at a point 1·3 tunnel heights downstream from the beginning of the slots.

Pairs of wooden blocks, which spanned the tunnel, were mounted in both top and bottom liners downstream from the end of the slots (Fig. 2). The blocks mounted in this position were designated Series A. Their heights were such that, in a similar position in a solid-wall tunnel of height equal to that of the parallel slotted length, they would give free-stream Mach numbers of approximately 0·5, 0·7 and 0·9. The cross-section of the part of each block which projected

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*Owing to the limited working space that existed near the tunnel, it was not possible to arrange the optical components in the conventional Z pattern. The photographs may therefore contain some lateral distortion.

into the airstream was approximately triangular, with a base of 5 in. The apex of the triangle was flattened to allow for any small error in lining up each pair of blocks, the flat being $\frac{1}{4}$ in. long. Generally each block was symmetrical about this flat, but two pairs of asymmetric blocks, A2 and A3, were made ; their heights corresponded to the lowest Mach number, 0·5.

It was found that in every case a sonic throat could be established downstream from the slots, and that, once this condition existed, further increase in the total pressure of the inducing air produced no further increase of the Mach number between the slotted walls. The free-stream Mach number was approximately that to be expected from the ratio of the height of the tunnel at the beginning of the slots to the distance between the blocks.

The distributions of static pressure along the slotted walls, obtained with the sonic throats, are shown in Fig. 4.

The three pairs of blocks designed for a free-stream Mach number of 0·5 gave distributions of the same general shape, which was similar to that obtained with the unmodified tunnel (Fig. 3). The mean Mach number in each case was different. Examination of the schlieren photographs showed that the boundary layer on the upstream face of each block was separating at the apex and that the separated layers continued to converge. Thus the effective throat was occurring downstream from the apex of the block and outside the region covered by the photograph. This condition is illustrated in Fig. 5, where the flow round the blocks A1 ($M_0 = 0 \cdot 5$) is shown. The severity of the separation, and hence the minimum area reached across the separated layers, varied with the slope of the forward face of the blocks. The steepest slope, A2, produced the lowest Mach number ; the highest was produced by the shallowest slope, A3, even though this involved a vertical discontinuity between the working-section and the tunnel circuit just upstream from the injector slots.

The pressure distributions obtained with the blocks A4 and A5, corresponding to free-stream Mach numbers of 0·7 and 0·9, are also shown in Fig. 4, and the flow round the blocks A5 is shown in Fig. 6. The pressure distributions are, again, almost identical in shape to those obtained without blocks (Fig. 3). The photographs showed that sonic conditions existed around the blocks (*e.g.*, Fig. 6).

It is interesting to compare Fig. 6 with Fig. 7, which shows the flow in the same region at approximately the same free-stream Mach number in the absence of the blocks. The pattern of wavelets in Fig. 7, which must be formed by disturbances travelling upstream, is totally absent in Fig. 6. This shows that the sonic throat extended right across the tunnel and prevented such disturbances travelling upstream. It will also be seen that the blocks A5 lie wholly within the turbulence created by the mixing of the air from the main stream and the plenum chamber, and that they seem to cause little, if any, disturbance to the inner boundary (*i.e.*, that nearer the centre-line of the tunnel) of this region. Fig. 5, however, shows that where the larger blocks extend beyond the normal inner boundary of the turbulent mixing region, this boundary is deflected round the block and the mixing region is apparently made thinner.

The minimum total pressure of the inducing air required to maintain the pressure distributions of Fig. 4 was measured in each case. Fig. 8 shows the variation of this total pressure P (expressed as a fraction of the total pressure of the main stream H) with free-stream Mach number. Fig. 8 also shows the corresponding variation for the unmodified tunnel. It will be seen that considerably higher pressures were required to drive the tunnel when the sonic throats were used.

The values given were obtained with an injector-slot width of 0·119 in. In an induction-type tunnel the blowing pressure is a function of the ratio of injector-slot area to tunnel working-section area, 0·135 in the present tests. This value, used throughout the tests reported here, is a typical value.

With the symmetrical blocks A1, at a free-stream Mach number of 0·51, the ratio of the excess pressure to the pressure required for the unmodified tunnel was about 2·2. This ratio fell off rapidly as the Mach number increased and at $M_0 = 0 \cdot 88$ (A5), it had fallen to 0·40.

At an approximate free-stream Mach number of $0 \cdot 5$ the change in shape of the blocks A1 to A3 had a marked effect on the pressure required to run the tunnel, as well as on the Mach number produced (*see* above). The blocks with the shallowest slope of the foward faces, A3, not only gave the highest Mach number but also required the lowest pressure to run the tunnel.

4. *Tests with an Arrangement Suitable for the Existing Throat Mechanism and Slotted Walls of the N.P.L.* 18-*in.* × 14-*in. High-Speed Tunnel.* (*Blocks* B).—4.1. 9 *per cent Slotted Expansion.*—The run out of the expansion of the slotted walls of the 18-in. × 14-in. High-Speed Tunnel is so near to the injector slots that there is no possibility of forming a second throat of the type dealt with in the previous section. However, the existing throat mechanism could be used if the expansion were cut off in the plane of the forward vertical face of this throat.

The 9-in. × 3-in. Tunnel walls were therefore modified to represent the conditions that would, in the above case, be present in the 18-in. × 14-in. Tunnel. Tests were then made to obtain some idea of how these modifications would affect the performance of the tunnel.

The modifications made are shown in Fig. 9. The walls were cut off $3 \cdot 94$ in. (*i.e.*, $0 \cdot 53_5$ tunnel heights) downstream from the beginning of the expansion and the divergence was reduced to make the distance between the walls $8 \cdot 02$ in. (*i.e.*, $1 \cdot 09$ tunnel heights) in this plane. Two blocks B1 were attached to the base of the liners to represent the existing throat mechanism of the 18-in. × 14-in. Tunnel in its fully withdrawn position. These blocks were parallel for $11 \cdot 38$ in. (*i.e.*, $1 \cdot 55$ tunnel heights), the distance between them was $9 \cdot 57$ in. (*i.e.*, $1 \cdot 30_5$ tunnel heights), and their upstream faces were in the same plane as the end of the slotted expansion.

Four pairs of blocks (B2 to B5), were made to represent approximately the contour of the sonic throat in positions which would give free-stream Mach numbers of approximately $0 \cdot 5$, $0 \cdot 6$, $0 \cdot 7$, and $0 \cdot 9$. These were of the shape shown in Fig. 9, the flattened apex being $\frac{1}{4}$ in. long. The centre of this flat was $5 \cdot 69$ in. (*i.e.*, $0 \cdot 77_5$ tunnel heights) from the upstream end of each block, and a straight taper was made from the downstream end of the flat to meet the tunnel circuit just upstream from the injector slots.

Pressure distributions along the slotted walls with the blocks B1 in position, were measured for approximately the same values of the total pressure of the inducing air as were used in obtaining the distributions with the unmodified walls. These distributions are shown in Fig. 10. It will be seen that over the parallel length of the walls the variation of pressure was almost identical with that obtained in the unmodified walls (Fig. 3). However, the fall in pressure associated with the wall divergence in the unmodified case was considerably reduced during both subsonic and supersonic operation of the tunnel.

The variation of the total pressure of the inducing air with free-stream Mach number is shown in Fig. 12. This shows very little change from the results obtained with the unmodified walls, although the modified ones reveal a slightly unfavourable trend at supersonic speeds.

The slotted-wall pressure distributions obtained with the blocks B2 to B5 are shown in Fig. 11. These appear to be identical in form with those obtained using the blocks B1. The flow in the region of the throats is shown in Fig. 13. It will be seen that at $M_0 = 0 \cdot 53$ and $0 \cdot 64$ steady supersonic flow was not established behind the blocks. However, the expansion to supersonic speeds at the forward lip of the throat evidently extended right across the tunnel, since none of the large unsteady disturbances visible downstream were propagated upstream from the blocks.

By increasing the blowing pressure still further a stable supersonic régime, terminating in a shock wave symmetrical about the centre-line of the tunnel, could be established. This produced no change in the tunnel-wall pressure distributions.

The variation with free-stream Mach number of the minimum total pressure of the inducing air, required to obtain the distributions of Fig. 11, is shown in Fig. 12. The presence of the blocks again increased the value of the pressure required to run the tunnel at any given Mach number. This value was approximately the same as that needed to run the tunnel at unit free-stream

Mach number in an unchoked condition. However, the amount of the increase was much less than that needed with blocks A1 to A5 (Fig. 8). The ratio of the increase of blowing pressure at a given Mach number to that required using the parallel blocks B1, varied from 1·12 at $M_0 = 0{\cdot}53$ to as little as 0·03 at $M_0 = 0{\cdot}92$.

The series B blocks had a base length which was more than twice that of the series A blocks and therefore the slopes of their upstream faces were considerably smaller. Moreover, the throats of the series B blocks were further upstream from the injector slots. The losses due to separation between the throats and the injector slots would therefore be smaller and the efficiency of the tunnel would be improved.

4.2. *No Slotted Expansion.*—The slotted expansions were cut off in a plane $\frac{3}{16}$-in. upstream from the end of the parallel length of the working-section, as shown in Fig. 9. The tunnel in this plane had a height of 7·64 in. The experiments with blocks B1 to B5 were repeated.

Fig. 14 shows the pressure distributions obtained with the blocks B1, Fig. 15 those obtained with the blocks B2 to B5 and Fig. 16 the corresponding curves of the total pressure of the inducing air against free-stream Mach number. The removal of the slotted expansion caused no deterioration of the distribution of pressure along the parallel walls of the tunnel, but the curves of Fig. 16 show that the efficiency of the tunnel was improved, both when the sonic throat was present and when it was absent.

Fig. 17a shows a comparison of the flow over the blocks B1 at the rear of the working-section, with and without the slotted expansion, at a free-stream Mach number of approximately 0·9. Fig. 17b shows the similar comparison using blocks B5.

The region of turbulent mixing of the air from the main stream and from the plenum chamber spreads due to the mixing. It also deflects outward from the tunnel centre-line due to the expanding stream tubes ; these expand because of the rising pressure brought about by the mixing. The outer boundary of the mixing region therefore bends towards the outer wall of the working-section. The absence of the slotted expansion allowed this process to start further upstream. The mixing region was therefore attached to the block B1 from a point further upstream than it was when the slotted expansion was present. This is more clearly seen in the upper half of the photographs of Fig. 17a. The pressure recovery upstream from the injector slots was thus improved and this increased the efficiency of the tunnel.

The same tendency is visible in the photographs of Fig. 17b. In the absence of the slotted expansion the flow appears to have been attached over most of the upstream face of each block, whereas with the slotted expansion it appears to have been attached from a point approximately half way along the upstream face. This change in the position of flow attachment was accompanied by a decrease in the blowing pressure required to run the tunnel. This result is discussed at some length in section 6.

The overall improvement of the efficiency of the tunnel when the slotted expansion was removed would appear to contradict some results reported in Ref. 2. However, in those experiments the removal of the slotted expansion was accompanied by the introduction of a large step inwards towards the tunnel centre-line, and just upstream from the injector slots. Separation caused by this step probably masked the beneficial effects of an increased pressure recovery further upstream.

5. *Tests with an Arrangement suitable for the Existing Throat Mechanism and Slotted Walls of the N.P.L.* 36-*in.* × 14-*in. High-Speed Tunnel.* (*Blocks* C1 *to* C4 *and* D1 *and* D2).—The second throat mechanism in the 36-in. × 14-in. High-Speed Tunnel extends downstream from the plane of the end of the parallel slotted length of the working-section. In this tunnel the upstream extremity of the throat mechanism, as well as the join between the leaves, can be moved towards the centre-line of the tunnel. Tests were therefore made with two types of blocks. Series C

(Fig. 18) represented the conditions with the forward jacks fully retracted, and series D (Fig. 19) the conditions with them extended so that the leading edges of the upstream leaves were level with the slotted walls.

The throat mechanism in the 36-in. × 14-in. Tunnel extends for 2·74 tunnel heights downstream from the ends of the slots; the distance between the end of the parallel slotted length and the end of the working-section in the 9-in. × 3-in. Tunnel is only 2·15 tunnel heights. It was therefore impossible to test a complete scaled-down representation of the 36-in. × 14-in. Tunnel throat mechanism. Since the experiments with blocks A1 to A3 (section 3) had suggested that the slope of the upstream face was more important than that downstream, it was decided to represent to scale the upstream face of the 36-in. × 14-in. throat and to provide a straight taper from the throat to the tunnel circuit at the downstream end of the working-section. Thus the distance from the beginning of the blocks to the centre of the throat was made 8·60 in. (*i.e.*, 1·17 tunnel heights).

It had been intended that the upstream faces of the blocks representing the throat mechanism should be in the same plane as the end of the parallel slotted length, but after the blocks were made it was found mechanically impossible to do this. The slotted expansion had to be cut off in a plane $\frac{3}{16}$ in. upstream from the beginning of the blocks. The experience already gained suggested that this probably would not appreciably affect the tunnel performance with blocks C but might with the series D. These latter therefore had $\frac{3}{16}$ in. attached to their upstream faces but the distance between the throat and the end of the slots was kept the same, *i.e.*, 8·60 in.

The blocks C1 (Fig. 18), represented the adjustable throat with all its jacks withdrawn; they had a 45-deg bevel at their downstream end to fair into the tunnel circuit. The distance between the parallel faces was 9·31 in. (*i.e.*, 1·27 tunnel heights).

The heights of the blocks C2 to C4 were such that the approximate free-stream Mach numbers would be 0·5, 0·7 and 0·9 respectively; once again the blocks were approximately of triangular shape with a $\frac{1}{4}$-in. flat at the apex. The blocks D1 and D2 (Fig. 19), were of the same maximum height as C2 and C3 but their upstream edges were level with the ends of the slots.

The pressure variations along the slotted walls with the blocks C1 in position are shown in Fig. 20; Fig. 21 shows the corresponding distributions with blocks C2 to C4, and Fig. 22 those obtained using blocks D1 and D2. It will be seen that only in the presence of the blocks D2 did a deterioration in the pressure distributions occur, and this was confined to a small region at the downstream end of the slotted section where a sudden fall in pressure was measured.

The curves of total pressure of the inducing air against free-stream Mach number are shown in Fig. 23, and the values are listed in Appendix I. The performance using the blocks C1 showed a greater improvement over the basic wall than that obtained with blocks B1 and no slotted expansion (Fig. 16). This improvement can be attributed to the decrease of tunnel width, from 9·57 in. to 9·31 in., that occurred when the blocks C1 were substituted for the blocks B1. Earlier attachment of the turbulent mixing thus occurred on the blocks C1 and the pressure recovery upstream of the injector slots was thus improved.

A further examination of Appendix I, and also Figs. 16 and 23, shows that an improvement in tunnel performance also occurred at the higher Mach numbers when the sonic throats were formed by the blocks C instead of the blocks B. However, at a free-stream Mach number of approximately 0·5 the performance of the blocks C was slightly worse. Photographs taken of the flow over the blocks C (Fig. 24), show that, at a free-stream Mach number of 0·53, the presence of the blocks C2 caused the boundary of the mixing region to be deflected inwards towards the tunnel centre-line at the beginning of the blocks. A comparable photograph for the blocks B2 is not available, but Fig. 25 shows the flow at the end of the slotted length with the blocks C1 in position; the position of the blocks B2 is marked in white ink. From this photograph it is reasonable to assume that the mixing region would have spread outwards away from the tunnel centre-line before meeting the blocks B2. Fig. 26 shows a sketch of the suggested flows of the mixing region over the two blocks superimposed on each other. The flow over B2, shown dotted, was attached from a point which is further from the tunnel centre-line than the region of attachment on C2; from the results discussed in section 3, the performance would therefore have been expected to be inferior in the latter case. However, the slope of any block in series C is smaller than the slope of the corresponding block in series B. Any favourable effect caused by this reduction in slope was insufficient to nullify the adverse effects of the smaller amount of attached flow on C2.

The photographs of Fig. 24 show that, as the free-stream Mach number was raised by increasing the width of the throat, the inward deflection of the mixing region was reduced. The amount of attached flow on the blocks was thus increased, so that the beneficial effects of the reduction in slope of the forward face predominated and caused an overall increase in the efficiency of the tunnel.

The blocks D did not give as good a performance as the blocks C (Fig. 23), although the flow appeared to be attached over the whole forward face of each block and the slope was once again reduced. This is discussed further in section 6.

6. *Some General Remarks on the Performance of the Sonic Throats.*—The results obtained with all the sonic throats tested suggest that, provided the exit from the plenum chamber is not blocked, the efficiency of the tunnel when a sonic throat is present is associated with the expansion of the stream tubes that occurs before the air begins to accelerate towards the throat.

In the case of blocks A an increase in slope of the forward face of the block probably deflected the flow at the rear of the slotted expansion from a point further upstream (Fig. 27a), and this reduced the expansion of the stream tubes.

With blocks B the removal of the slotted expansion allowed the expansion of the stream tubes to begin further upstream and thus to have increased in amount before the air met the forward face of the blocks (Fig. 27b).

The deflection of the flow towards the centre-line of the tunnel with the blocks C2 reduced the expansion of the stream tubes present in comparison to B2 (Fig. 27c).

The blocks C corresponding to higher Mach numbers did not cause an inward deflection of the flow and their smaller slope allowed more stream-tube expansion to take place.

The behaviour of the blocks D is anomalous. These blocks sealed the downstream end of the plenum chamber. Although neither pair allowed any stream-tube expansion, the performance at a Mach number of 0·5 was inferior to that of the corresponding blocks B and C, whereas at a Mach number of 0·7 the series D were inferior to the series C but superior to series B.

The reason why the expansion of the stream tubes in the main stream should influence the performance of the tunnel is obscure, since it can be argued that the acceleration up to the sonic throat will nullify the effects of the expansion. On the other hand, the effects of the boundary-layer separation at the foot of the shock wave downstream from the sonic throat would be expected to have a big influence on the efficiency of the tunnel. The expansion of the stream tubes may influence the boundary layer over the throat and hence the extent of the separation. It may also, however, influence the flow within the plenum chamber, or the mixing of the air from the plenum chamber with the air in the main stream.

There is insufficient evidence available from these tests to enable the mechanism by which the efficiency of the tunnel is increased under certain conditions to be established.

Fig. 28 shows the variation, with the upstream slope of the throat, of the increase of blowing pressure required to maintain sonic conditions across the various throats, expressed as a fraction of the blowing pressure in the corresponding unchoked condition. The points corresponding to each pair of blocks are labelled. Curves have been drawn through the points corresponding to the three approximate Mach numbers 0·5, 0·7 and 0·9.

These curves illustrate very well the rapid decrease of blowing pressure that can occur as the slope of the upstream face of the throat is reduced. They also show how this favourable trend may be modified by an increase of the unattached flow over the blocks, *e.g.*, C2, or the blocking off of the plenum chamber, D1 and D2.

The effective width of each sonic throat has been evaluated from the free-stream Mach numbers measured in the parallel length of the slotted walls. The difference between this value, w_S, and the distance apart of the blocks, w_B, gives a measure of the effective boundary-layer thickness at the throat. This thickness, expressed non-dimensionally as a fraction of the distance of the centre of the throat from the beginning of the slots, is plotted in Fig. 29, against the slope of the upstream face of the throat. When allowance is made for experimental error, the points for each approximate Mach number seem to lie on one of a set of parallel lines. They show that at any Mach number the effective boundary-layer thickness at the throat increases with the slope of the forward face, and that for a given slope the thickness increases with Mach number.

7. *The Effect of a Variation of the Height of the Tunnel, Downstream from the Slots, on the Performance of the Tunnel in the Unchoked Condition.*—The work on sonic throats, described above, showed that an increase in the amount of attached flow under the mixing region improved the overall performance of the tunnel. This section describes some tests made with a series of blocks which were of various constant thicknesses downstream from the parallel slotted section.

These blocks represented possible configurations of the 36-in. × 14-in. throat mechanism in which the slope of the upstream leaf was zero. The blocks C1 formed one pair of this set, and the other two pairs were designated C5 and C6 (Fig. 30). In each block a straight taper ran from the line which represented the downstream shoulder of the throat hinge to the tunnel circuit at the end of the working-section. Tests were also made with no blocks present.

The following table shows the ratio between the tunnel area immediately downstream from the slots and that at the end of the slotted section.

Condition	Area Ratio
No blocks	1·38
C1	1·22
C6	1·04
C5	1·00

The pressure distributions along the slotted walls were measured at various values of the total head of the inducing air. These distributions are not reproduced in this report since they exhibit no peculiarities of shape and are very similar to those for C1 shown in Fig. 20.

As well as its effect on blowing pressure, the area ratio also affected the maximum Mach number reached in the parallel slotted length of the tunnel (Fig. 31). With zero increase in area ratio, C5, the tunnel would not run supersonically but choked at a free-stream Mach number of 0·88. A small increase in area ratio (C6—4 per cent) permitted supersonic operation, but the maximum Mach number reached (1·07) was not as great as that obtained (1·17) with the blocks C1, which gave an area ratio of 1·22. Increasing the area ratio still more by removing the blocks caused a slight drop in the maximum Mach number reached. This drop was probably caused by the presence, in this condition, of an inward step, towards the centre-line of the tunnel, just upstream from the injector slots, which produced a separation of the flow over the slots. These results suggest that the supersonic Mach number in the working-section can be controlled by limiting the expansion of the flow downstream from the end of the slots.

Also shown in Fig. 31 are the results reported in Ref. 2 for various amounts of slotted expansion of the walls. It will be noticed that for small values of the area ratio the curves are very similar but that for the larger values considerably higher free-stream Mach numbers were obtained in Ref. 2. It must be pointed out, however, that these high Mach numbers were obtained only in the preliminary tests with a 6·56-in. high tunnel, and a correspondingly deeper plenum chamber. It is known that this increase in plenum chamber depth would produce a higher maximum Mach number. A point is included in Fig. 31 which is taken from the main tests of Ref. 2. These tests were made with a 7½-in. high tunnel and the point plotted is in good agreement with the present tests.

Fig. 32 shows the change of blowing pressure (expressed as a percentage of the pressure required to drive the unmodified tunnel at the same free-stream Mach number), as a function of the percentage expansion for three different Mach numbers, 0·6, 0·8 and 1·0.

Only in the absence of any blocks was the tunnel performance worse than that of the unmodified tunnel, i.e., $\Delta P/P$ positive ; this is attributed to the step in the tunnel just upstream of the injector slots.

As the expansion was decreased to a low value, the increment of blowing pressure changed sign and continued to decrease, at least until the expansion ratio reached a value as low as 4 per cent. The zero expansion case continued to show a slight improvement at a Mach number of 0·6, but at 0·8 there was a definite worsening in the performance. This free-stream Mach number is fairly close to the choking Mach number, 0·88 in this case ; it would therefore appear that the onset of choking in the tunnel nullifies any good effects associated with the improvement of the pressure recovery upstream from the injector slots.

In general the gains obtained by decreasing the expansion ratio increased as the free-stream Mach number increased, and with 4 per cent expansion at unit free-stream Mach number the decrease in blowing pressure was as large as 12 per cent.

The curves of Figs. 31 and 32 suggest that an area ratio of 15 per cent would lead to a reduction of 7½ per cent in blowing pressure at unit free-stream Mach number and would lower the top Mach number in the working-section by only ½ per cent.

8. *The Effect of a Wedge-shaped Fairing extending Upstream from the Blocks into the Plenum Chamber.*—Wedge-shaped fairings were made which extended for 6 in. from the upstream faces of the blocks C5 and C6 into the plenum chamber (Fig. 33). At their downstream end they were the same height as the blocks.

The slotted-wall pressure distributions were measured with these fairings in position and were compared with those obtained using the same blocks without fairings (section 7).

The presence of the fairings caused the distribution above the rear two-thirds of them to deteriorate ; this deterioration was accompanied by a fairly large fall in pressure at the end of the slotted section (Fig. 34). Only the distributions for C6 are shown in Fig. 34 as those for C5 showed very similar trends.

Photographs of the flow with and without the fairings (Fig. 35), suggest that there was slightly less separation present at the beginning of the blocks when the fairing was in position ; this was reflected in a slight drop, about 1½ per cent, in the blowing pressure required for a particular Mach number.

9. *Conclusions.*—(*a*) Control of the subsonic Mach number in the working-section of a tunnel fitted with slotted-wall liners can be obtained by the use of a sonic throat downstream from the working section.

(*b*) Such a throat prevents disturbances from the diffuser, or injector in an induction tunnel, being propagated upstream into the working-section. It does not eliminate disturbances arising from the region in which mixing occurs between the air in the main tunnel circuit and air which is re-entering the circuit from the plenum chamber.

(*c*) The Mach number obtained in the working-section of the tunnel is approximately that to be expected from the ratio of the area between the walls, at the beginning of the slots, to the area at the throat.

(*d*) It is possible that control of the free-stream Mach number at low supersonic speeds can be achieved with a throat mechanism by restricting the amount of expansion of the air in the main stream downstream from the end of the slots.

(*e*) In general the sonic throats increase the power required to run the tunnel at a particular Mach number. The slope of the upstream face of the throat appears to be an important factor in determining the increment of power required.

(*f*) The power required to run the tunnel also depends upon the amount of expansion of the stream tubes at the end of the slotted section. If the region of the mixing of the plenum-chamber air with the main stream is allowed to spread outwards before it encounters the upstream face of the throat, thus encouraging a greater region of attached flow on the throat, the power required to run the tunnel is reduced.

(*g*) The performance of the tunnel in its unchoked condition can be improved by improving the pressure recovery downstream. This can be done by replacing the original slotted expansion of the walls with solid parallel walls which give an area ratio slightly larger than that of the parallel slotted walls. The amount of this area ratio provides a balance between power economy and maximum available Mach number in the working-section. Thus, in the present tests an area ratio of 4 per cent gave a 12 per cent saving in blowing pressure at a free-stream Mach number of unity and reduced the top Mach number in the working-section by 9 per cent, whereas the corresponding figures for a 15 per cent expansion were $7\frac{1}{2}$ per cent and $\frac{1}{2}$ per cent.

(*h*) Wedge-shaped fairings, extending upstream into the plenum chamber from the blocks, produce a slight reduction in the power required to run the tunnel, but cause the flow along the walls above them to deteriorate.

LIST OF SYMBOLS

H	Total pressure of the main stream
h	Height of the tunnel at the beginning of the slots
M_0	Free-stream Mach number
P	Total pressure in the injector slots (the blowing pressure)
p	Static pressure
w_B	Width of the tunnel between the blocks of the sonic throat
w_S	Width of the sonic throat, calculated from the height of the tunnel and the free-stream Mach number
x	Distance downstream from the beginning of the slots
x_B	Distance of the sonic throat downstream from the beginning of the slots
α	Angle of inclination of the upstream face of the sonic throat to the main stream

REFERENCES

No.	*Author*	*Title, etc.*
1	Bo K. O. Lundberg	Aeronautical research in Sweden. *J. R. Ae. Soc.* Vol. 59, No. 538 (p. 662, Fig. 34). October, 1955.
2	D. W. Holder, R. J. North and A. Chinneck	Experiments with slotted and perforated walls in a two-dimensional high-speed tunnel. R. & M. 2955. November, 1951.
3	D. W. Holder and R. J. North	The 9-in. × 3-in. Induced-Flow High-Speed Wind Tunnel at the National Physical Laboratory. R. & M. 2781. June, 1949.

APPENDIX I

Values of α, M_0, and P/H for each Configuration Tested

Condition		α (deg)	M_0	P/H
Unmodified tunnel		—	0·54	1·67
			0·67	2·01
			0·77	2·34
			0·87	2·68
			1·00	3·15
			1·16	4·56
Blocks	A1	38·7	0·51	5·08
	A2	60·0	0·49	5·48
	A3	20·8	0·52	4·21
	A4	26·6	0·71	4·08
	A5	20·7	0·88	3·76
9 per cent slotted expansion	Blocks B1		0·53	1·67
			0·66	2·01
			0·77	2·34
			0·88	2·68
			1·00	3·15
			1·15	4·56
	B2	18·0	0·53	3·55
	B3	14·8	0·64	3·28
	B4	12·3	0·74	3·03
	B5	9·4	0·92	2·89
No slotted expansion	Blocks B1		0·55	1·68
			0·68	2·02
			0·80	2·36
			0·90	2·71
			1·03	3·18
			1·17	4·55
	B2	18·0	0·53	3·31
	B3	14·8	0·63	3·08
	B4	12·3	0·73	2·88
	B5	9·4	0·90	2·81
Blocks	C1		0·55	1·68
			0·68	2·02
			0·81	2·36
			0·92	2·70
			1·05	3·18
			1·17	4·54
	C2	11·3	0·53	3·46
	C3	7·3	0·74	2·59
	C4	3·8	0·92	2·73
Blocks	D1	5·8	0·54	3·59
	D2	1·7	0·75	2·64

Condition	M_0	P/H
No blocks	0·52	1·68
	0·64	2·02
	0·74	2·36
	0·84	2·70
	0·96	3·18
	1·15	4·49
Blocks C5	0·56	1·69
	0·71	2·03
	0·82	2·37
	0·88	2·65
Blocks C6	0·57	1·71
	0·73	2·06
	0·87	2·41
	1·00	2·77
	1·07	3·12
Blocks C5 (with fairing)	0·57	1·70
	0·71	2·06
	0·84	2·41
	0·89	2·76
Blocks C6 (with fairing)	0·58	1·71
	0·73	2·06
	0·88	2·41
	1·01	2·77
	1·07	3·12

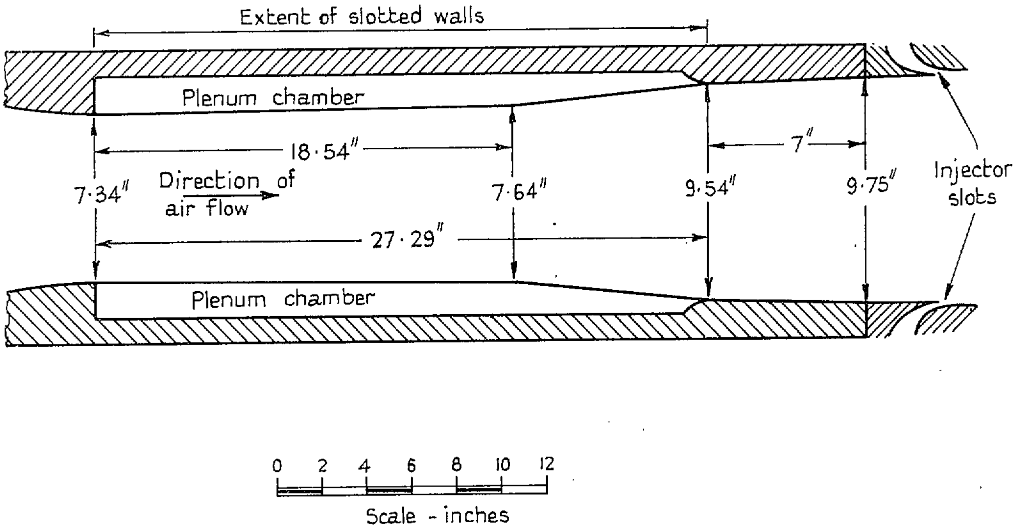


FIG. 1. Sketch of layout of basic slotted walls.

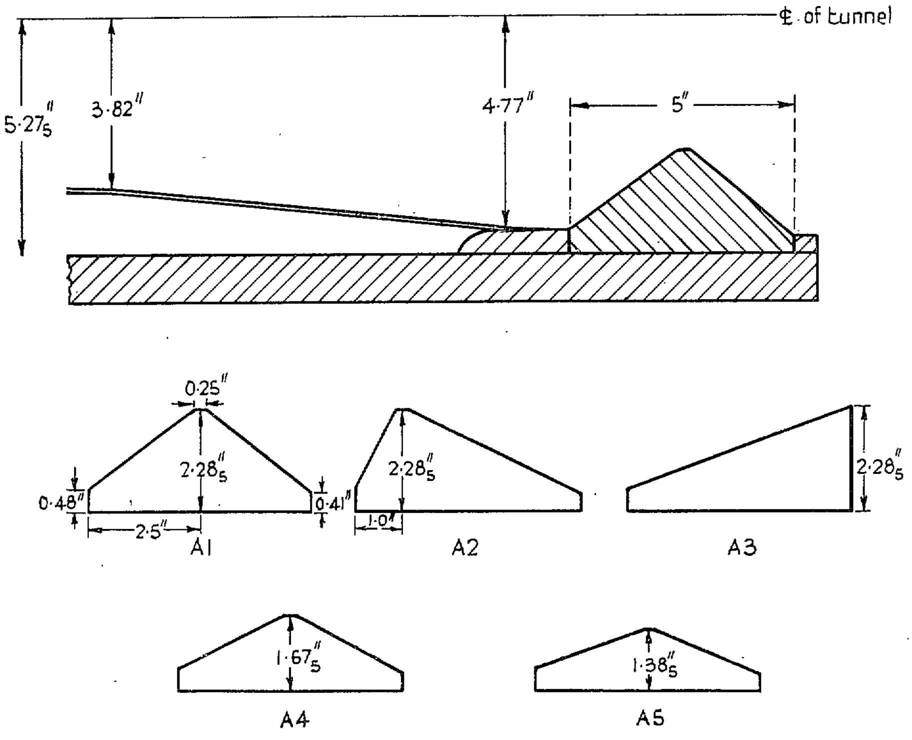


FIG. 2. Sketch showing position and dimensions of blocks A.

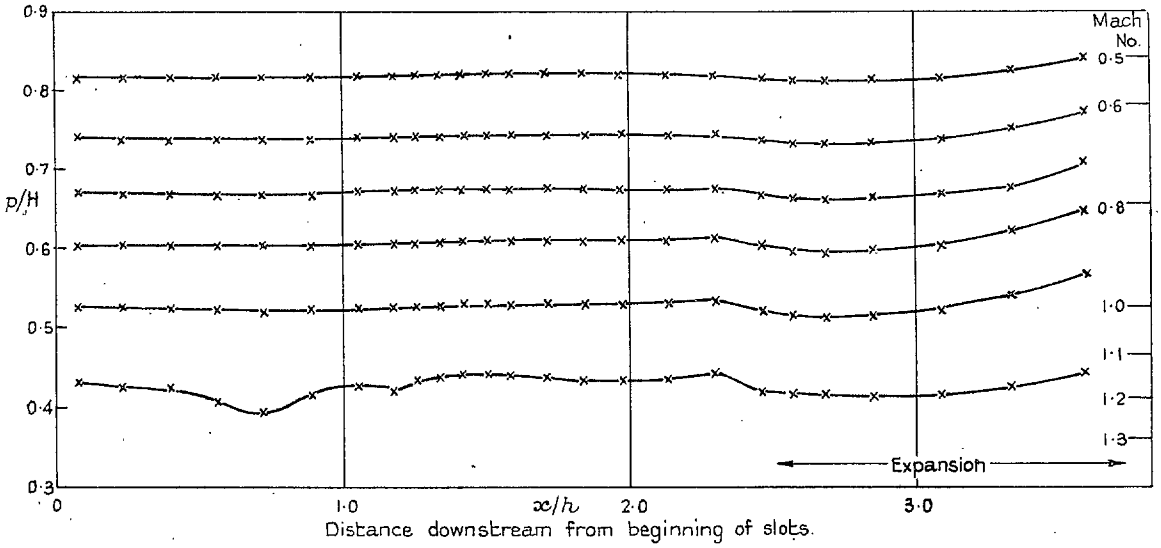


FIG. 3. Static-pressure distributions along the wall of the unmodified tunnel.

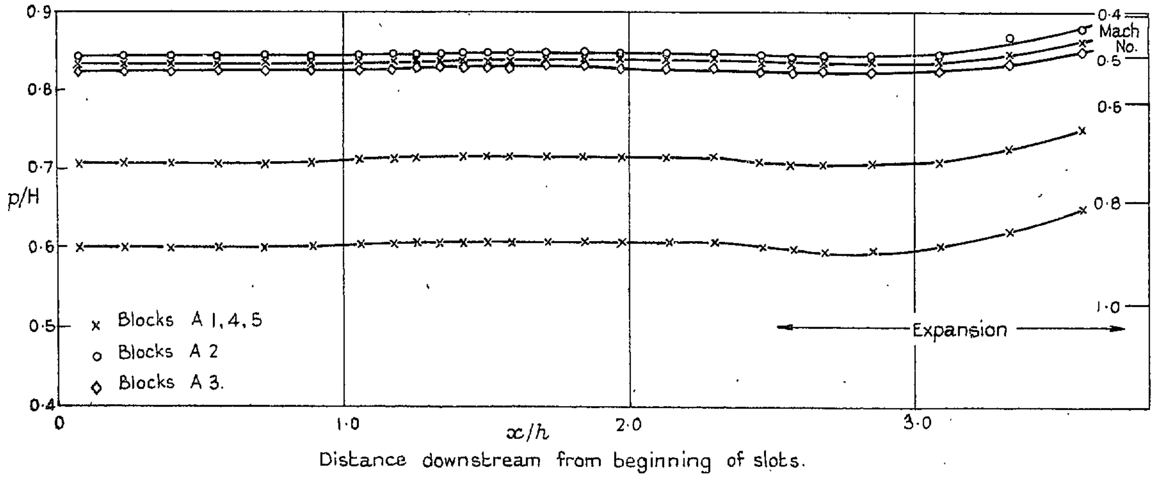


FIG. 4. Static-pressure distribution along the wall of the unmodified tunnel. Blocks A1 to A5 (Fig. 2) used to provide sonic throats downstream from expansion.

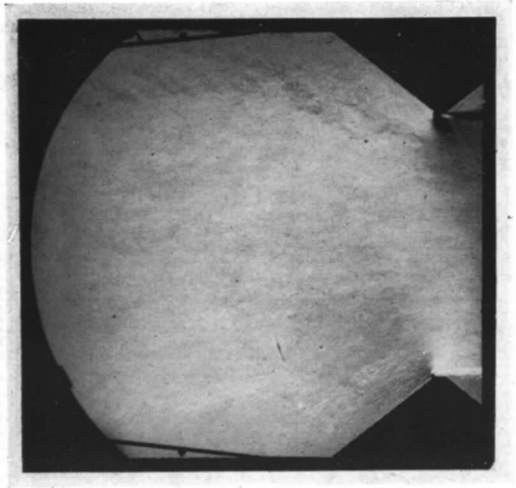


Fig. 5. The flow over the blocks A1 ($M_0 = 0{\cdot}51$).

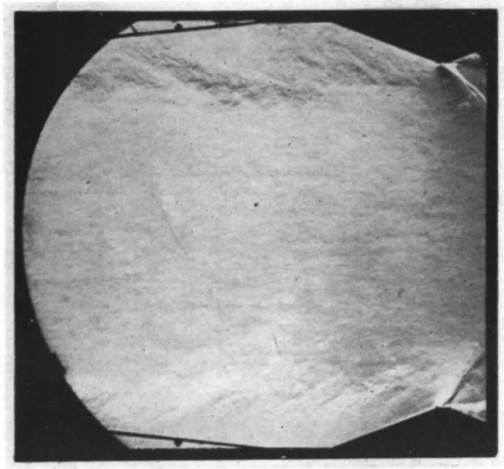


Fig. 6. The flow over the blocks A5 ($M_0 = 0{\cdot}88$).

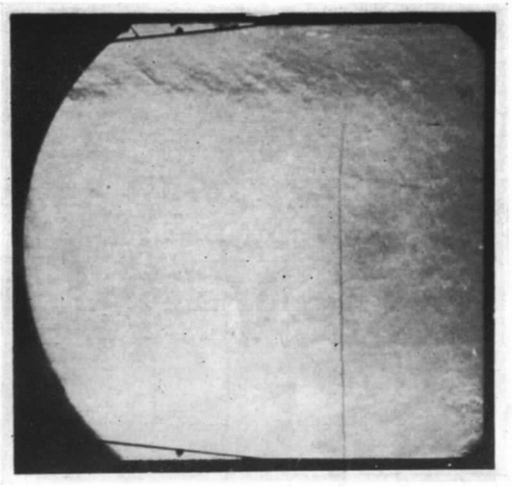


Fig. 7. The flow in the unmodified tunnel at $M_0 = 0{\cdot}87$ (This photograph covers the same area as Fig. 6).

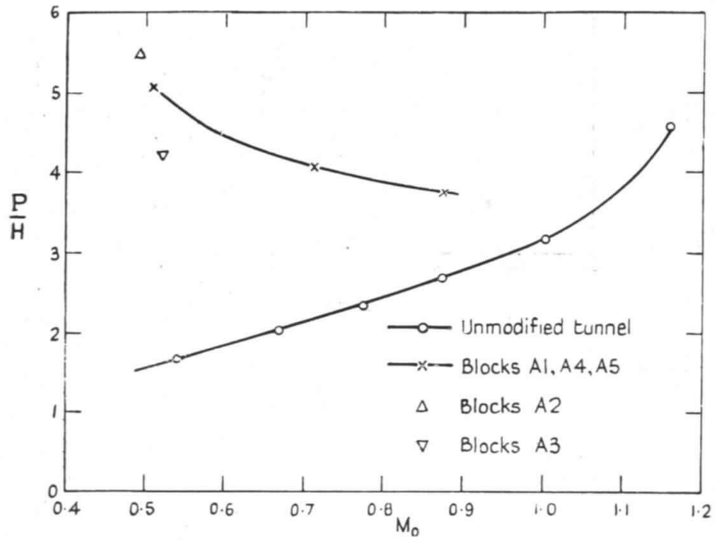
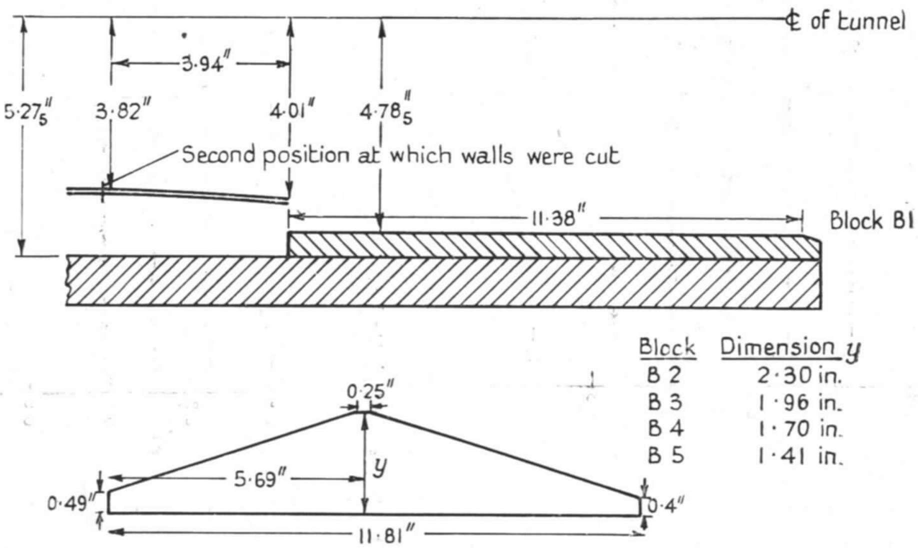


Fig. 8. Variation of blowing pressure with free-stream Mach number.—Unmodified walls and blocks series A.



Block	Dimension y
B 2	2·30 in.
B 3	1·96 in.
B 4	1·70 in.
B 5	1·41 in.

Fig. 9. Sketch showing position and dimensions of blocks B.

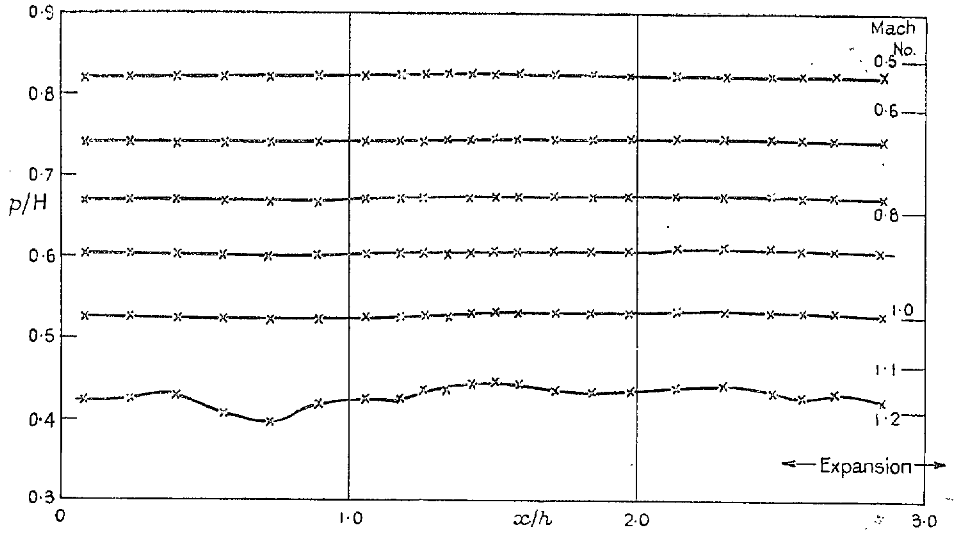


FIG. 10. 9 per cent slotted expansion.—Blocks B1 (FIG. 9) ; static-pressure distributions along the slotted walls.

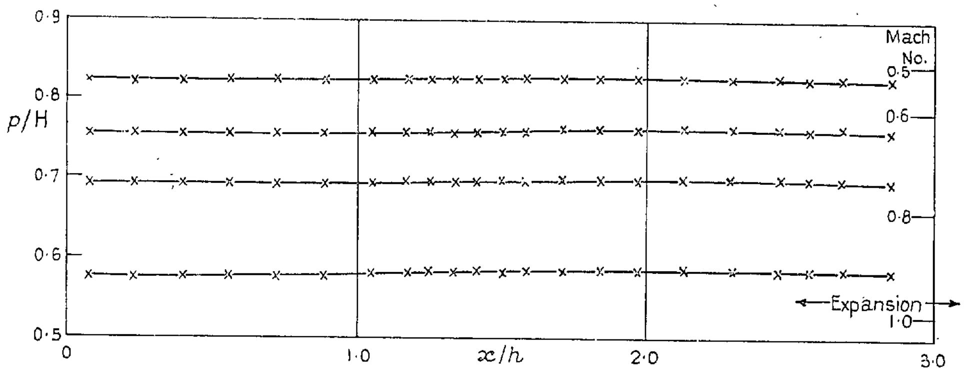


FIG. 11. 9 per cent slotted expansion.—Blocks B2 to B5 (FIG. 9) used to provide downstream sonic throats ; static-pressure distributions along the slotted walls.

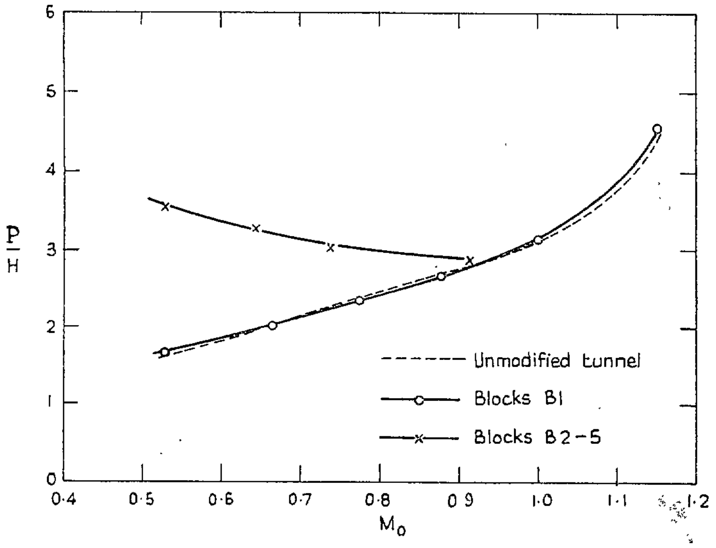
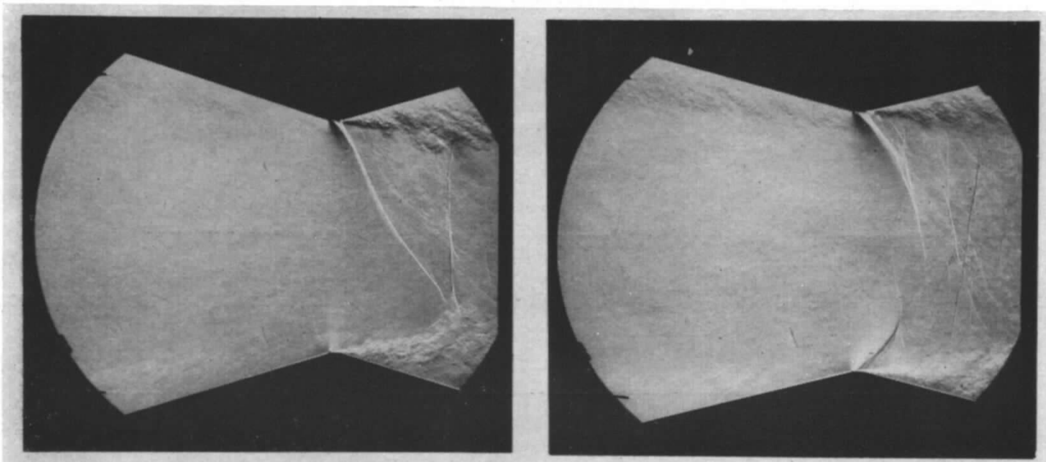
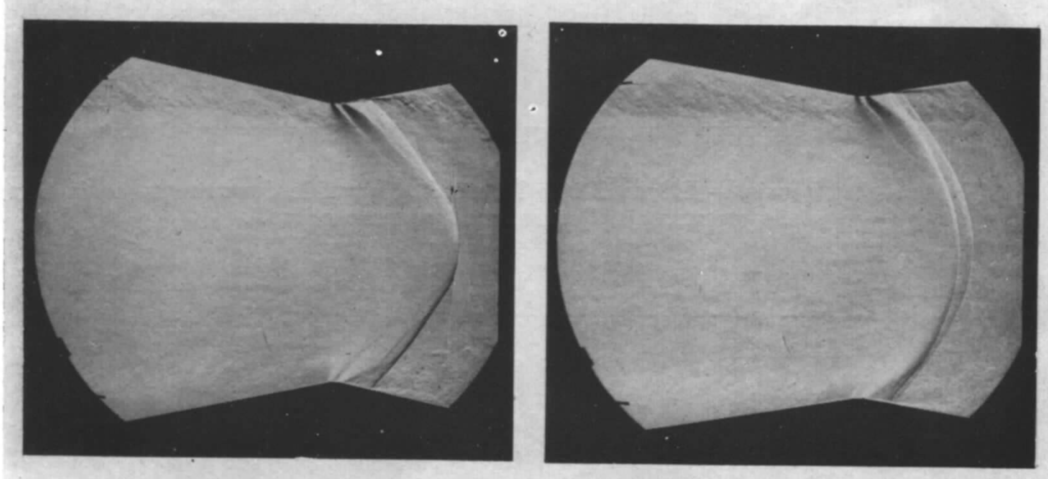


FIG. 12. Variation of blowing pressure with free-stream Mach number.—9 per cent slotted expansion ; blocks series B.



Blocks B2 ; $M_0 = 0{\cdot}53$ Blocks B3 ; $M_0 = 0{\cdot}64$



Blocks B4 ; $M_0 = 0{\cdot}74$ Blocks B5 ; $M_0 = 0{\cdot}92$

FIG. 13. The flow over the series B blocks.—9 per cent slotted expansion in tunnel.

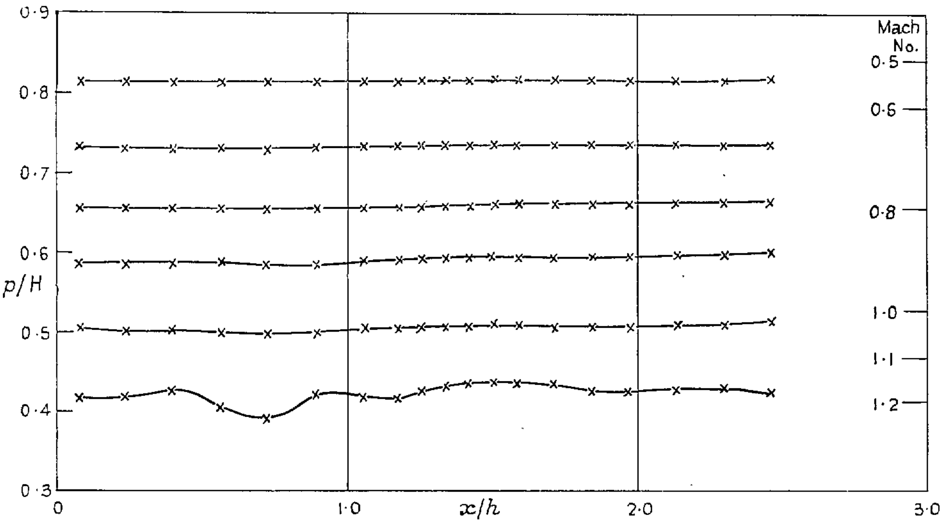


FIG. 14. No slotted expansion.—Blocks B1 ; static pressure distributions along the slotted wall.

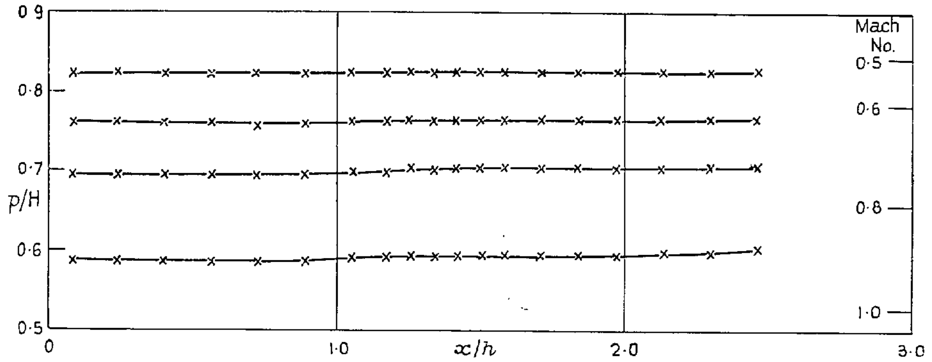


FIG. 15. No slotted expansion.—Blocks B2 to B5 used to provide downstream sonic throats ; static-pressure distributions along the slotted wall.

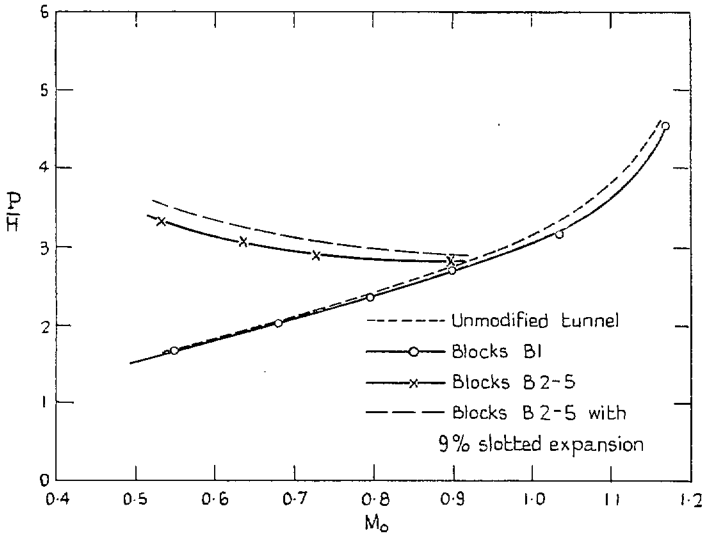
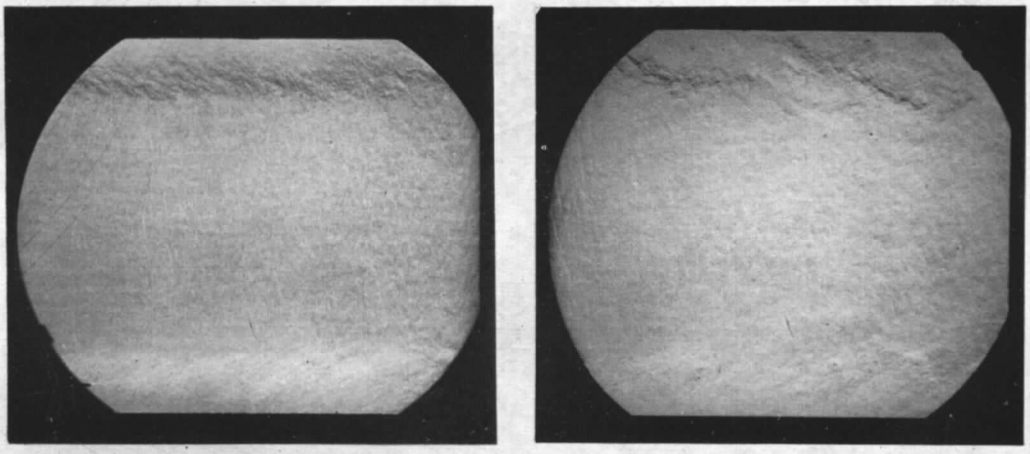


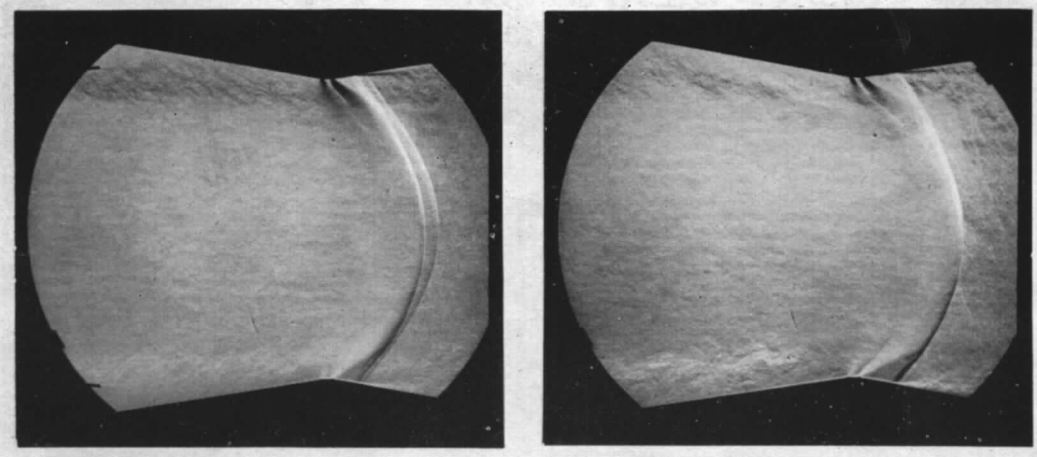
FIG. 16. Variation of blowing pressure with free-stream Mach number.—No slotted expansion ; block series B.



9% Slotted expansion

No slotted expansion

(a) Blocks B1



9% Slotted expansion

No slotted expansion

(b) Blocks B5

FIGS. 17a and 17b. Comparisons of the flow in the rear of the working-section with and without a 9 per cent slotted expansion.—Series B blocks ; free-stream Mach number approximately 0·9.

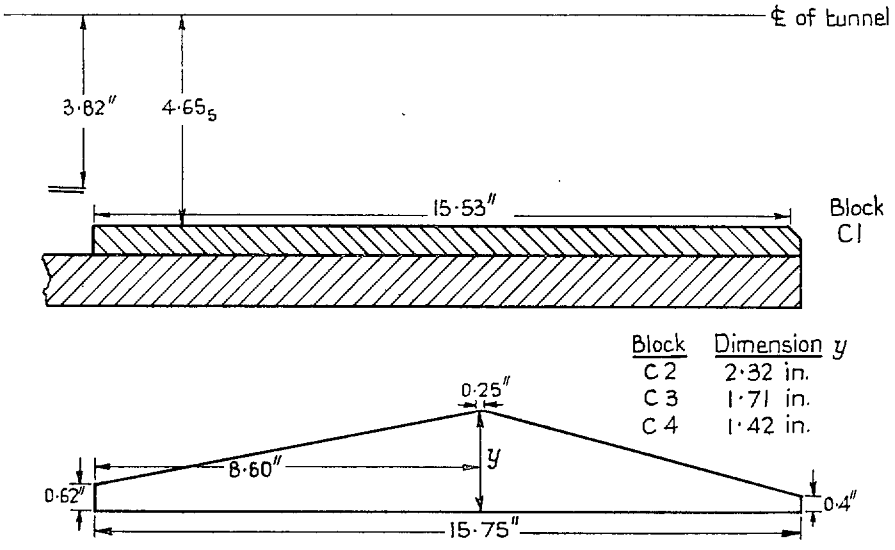


FIG. 18. Sketch showing position and dimensions of blocks C1 to C4.

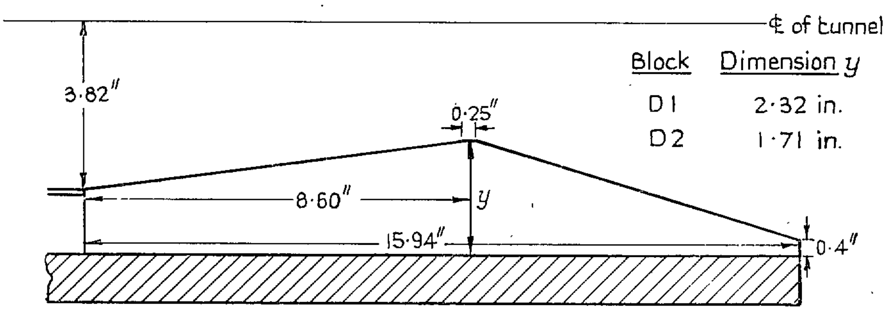


FIG. 19. Sketch showing position and dimensions of blocks D.

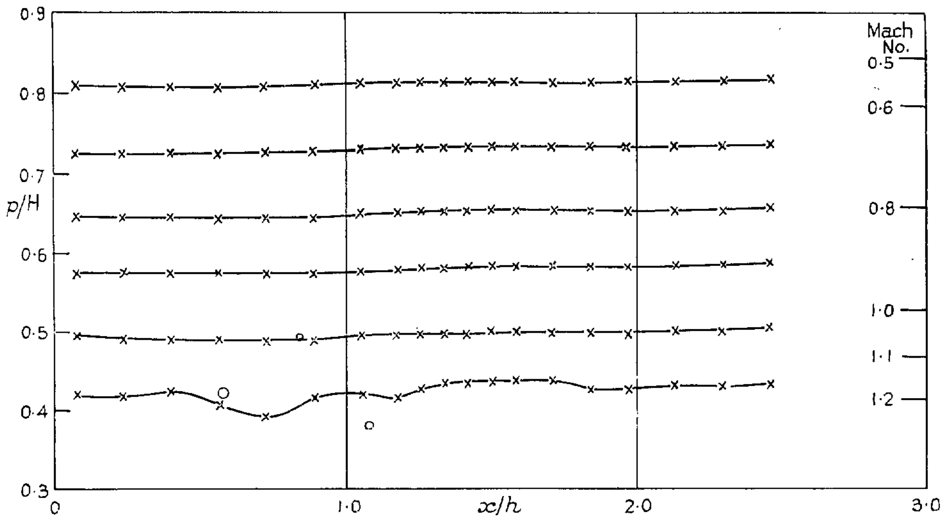


FIG. 20. Block C1 (FIG. 18).—Static-pressure distributions along the slotted walls.

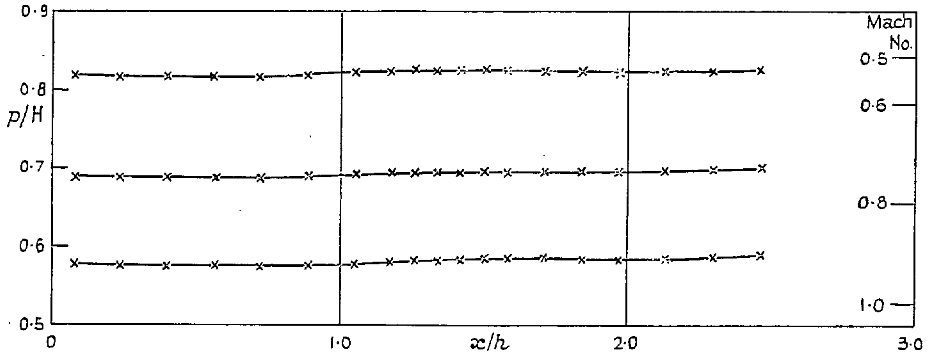


FIG. 21. Blocks C2 to C4 (FIG. 18) used to provide downstream sonic throat.—Static-pressure distributions along the slotted walls.

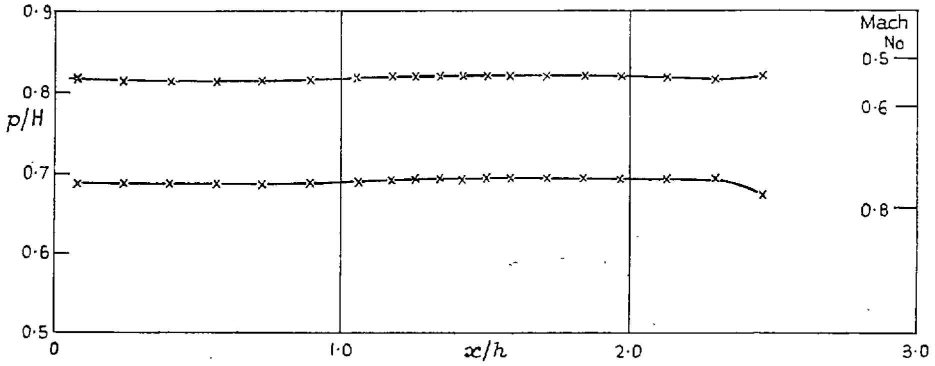


FIG. 22. Blocks D1 and D2 (FIG. 19) used to provide the downstream-sonic throat.—Static-pressure distributions along the slotted wall.

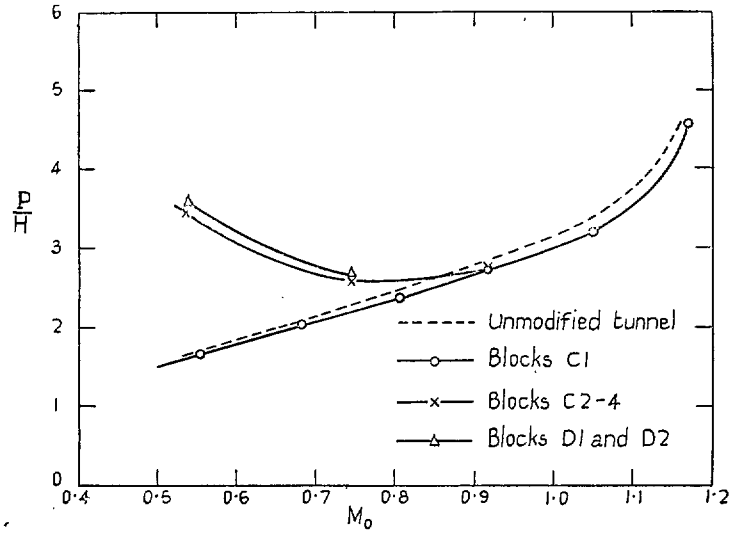
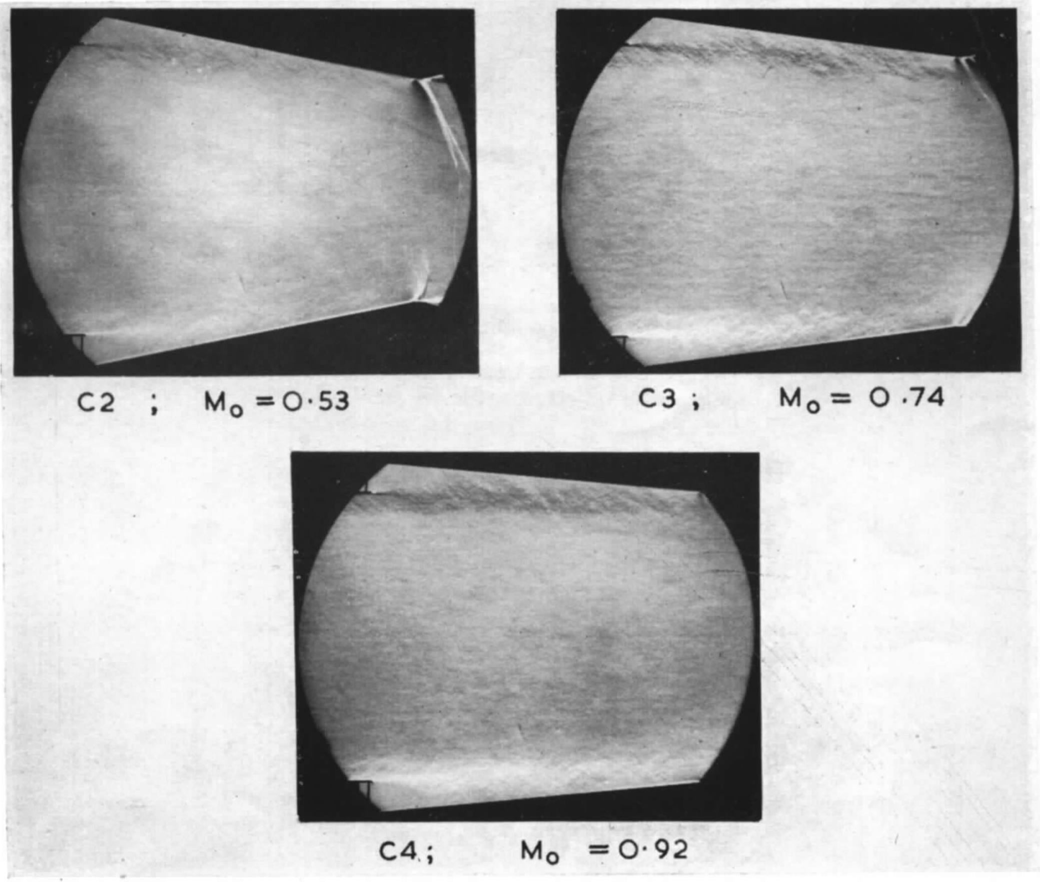


FIG. 23. Variation of blowing pressure with free-stream Mach number.—Blocks series C and D.


C2 ; $M_o = 0\cdot53$

C3 ; $M_o = 0\cdot74$

C4 ; $M_o = 0\cdot92$

FIG. 24. The flow over the series C blocks

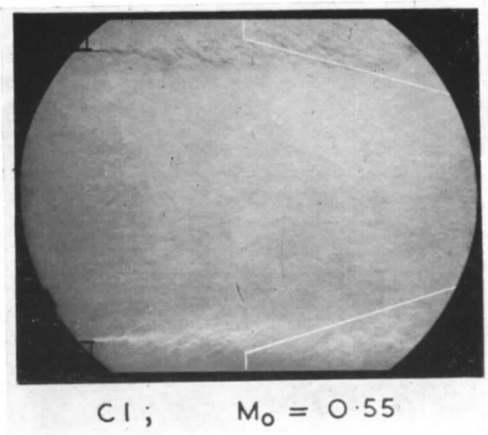

C1 ; $M_o = 0\cdot55$

FIG. 25. The flow just downstream from the slots with blocks C1 in position. The position of blocks B2 is shown in white.

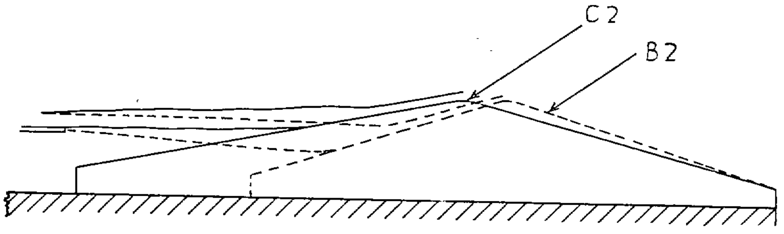
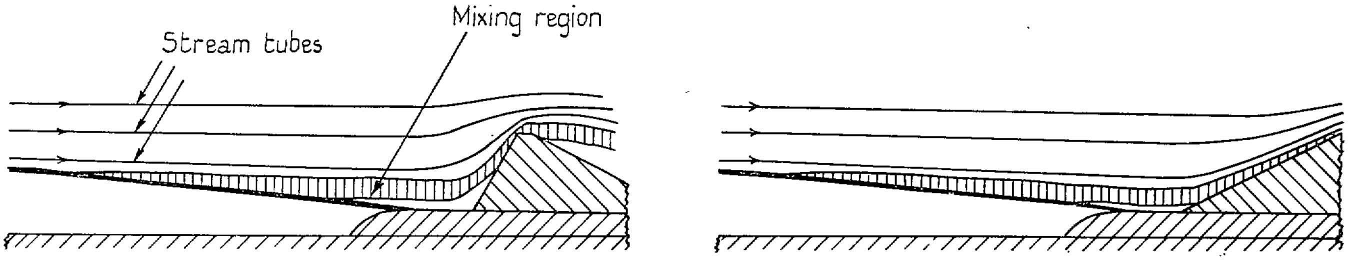
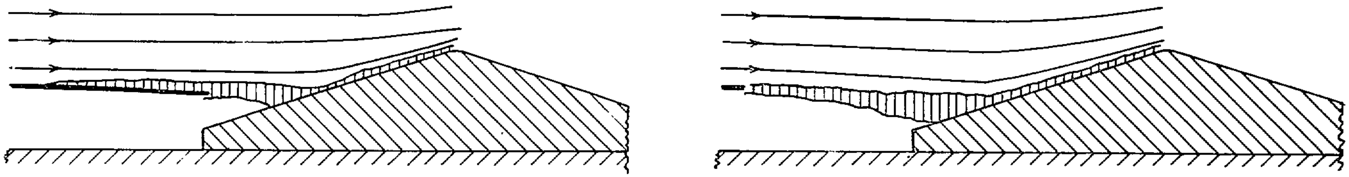


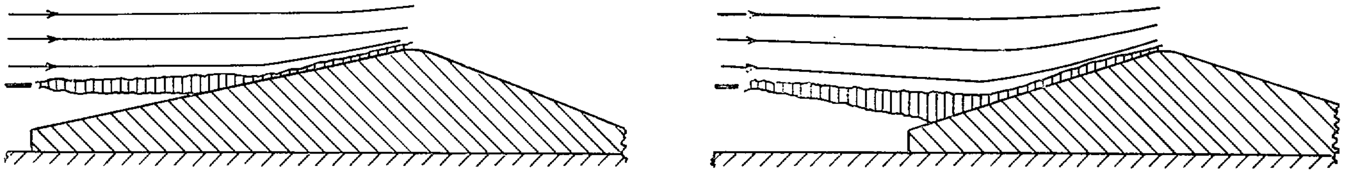
FIG. 26. Comparison of the probable flow pattern over the upstream faces of blocks B2 and C2.



(a) Blocks A 2 and A 3.



(b) Blocks B 2, with and without the 9% slotted expansion



(c) Blocks C 2 and B 2.

FIGS. 27a to 27c. Sketches of the probable flow between the end of the slots and the sonic throats formed by some of the blocks used.

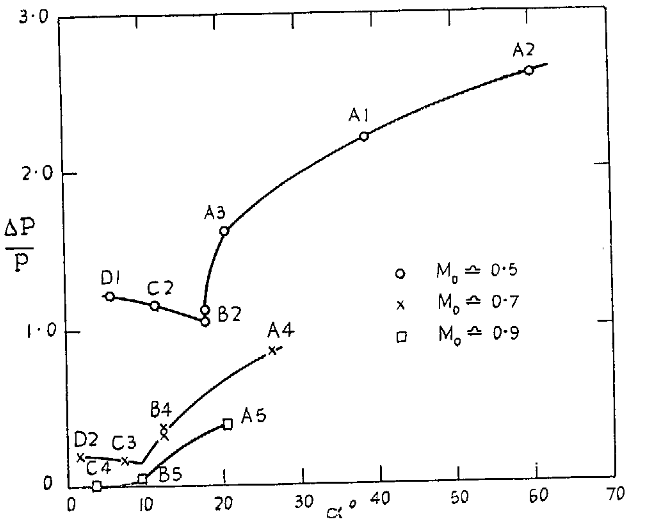


Fig. 28. The increase of blowing pressure required with the various sonic throats, as a function of the slope of the upstream face of the throat.

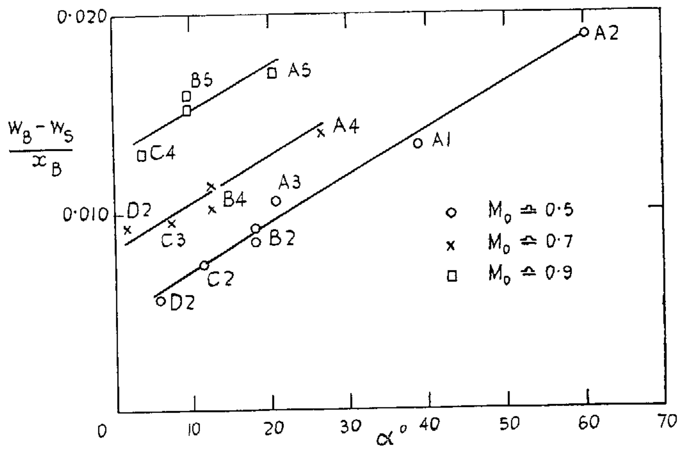


Fig. 29. The variation of the effective boundary-layer growth to the sonic throat with the slope of the upstream face of the throat.

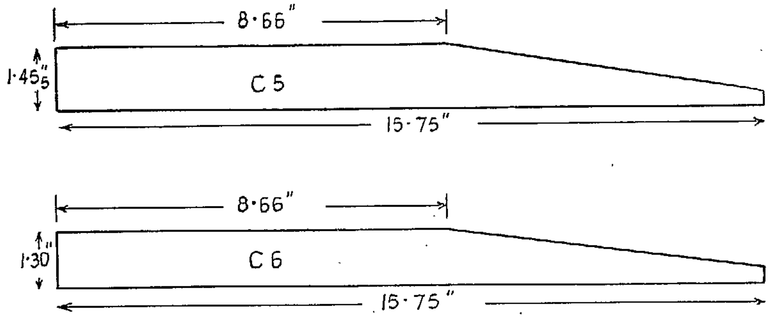


Fig. 30. Dimensions of blocks C5 and C6.

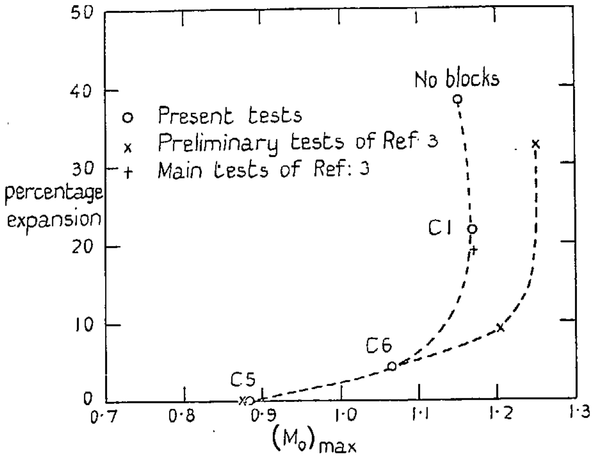


Fig. 31. The maximum free-stream Mach number as a function of the percentage expansion from the end of the slots to the parallel blocks.

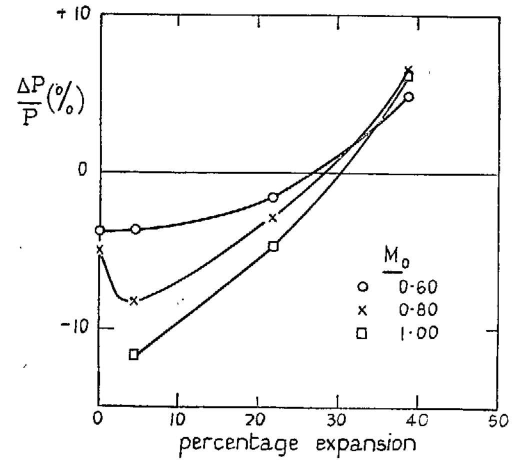


FIG. 32. The change in blowing pressure with the amount of the expansion from the end of the slots to the parallel blocks for three different free-stream Mach numbers.

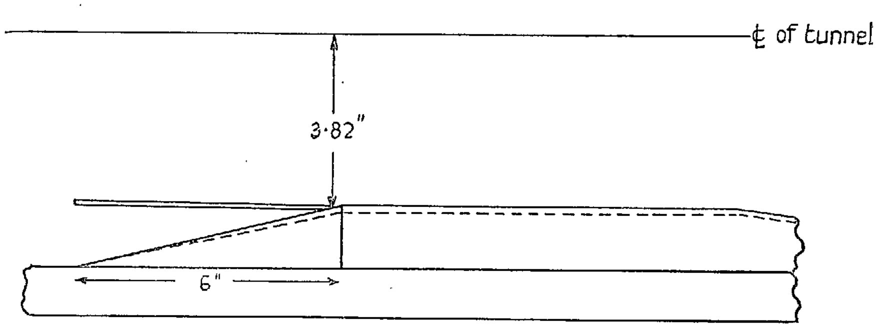


FIG. 33. Sketch showing position and dimensions of fairings to blocks C5 and C6.

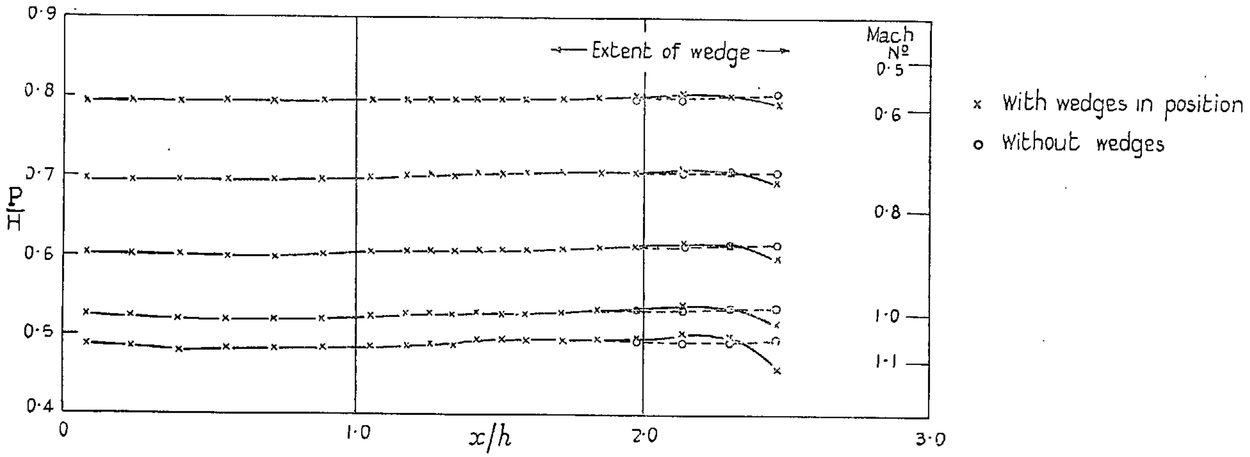
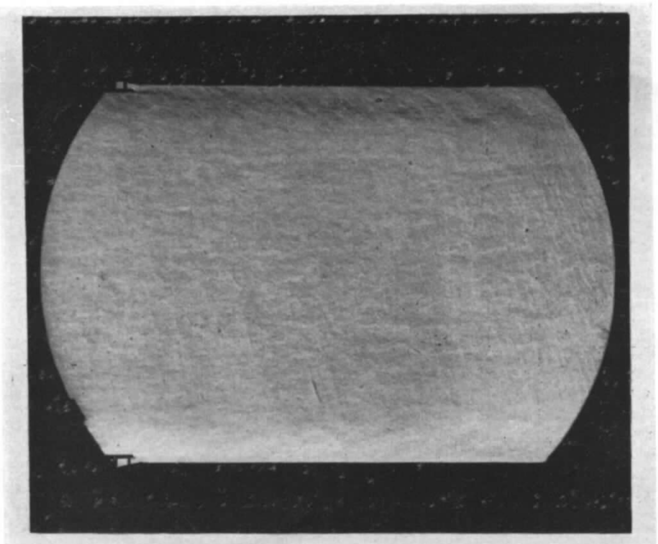
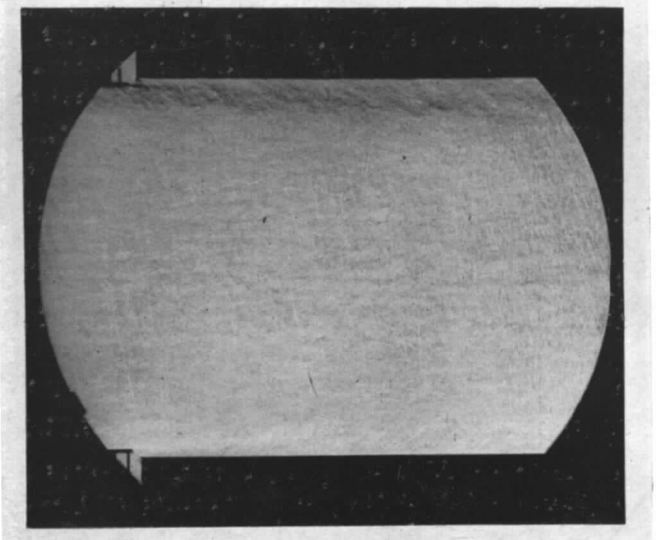


FIG. 34. The pressure distributions on the slotted walls using blocks C6 with and without a wedge-shaped fairing extending into the rear of the plenum chamber.



With fairing



Without fairing

FIG. 35. Photographs of the flow over the blocks C6 with and without a wedge-shaped fairing.

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