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Mach Number Distributions Along the Slotted Walls of the N.P.L. 20 in. x 8 in. High-Speed Wind Tunnel

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1965

Price 4s. 6d. net

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SUMMARY

A brief description is given of a new working section fitted to the N.P.L. 20 in. × 8 in. high-speed wind tunnel to incorporate slotted walls. Mach number distributions along these walls are given to show the improvement effected by placing perforated screens in the plenum chambers, and the influence of the model on the measurement of tunnel speed.

1. Introduction

A new working section with interchangeable liners on the two 8 in. walls was fitted to the 20 in. × 8 in. high-speed wind tunnel in the Aerodynamics Division of the National Physical Laboratory, in 1953, to replace the original working section that incorporated flexible steel walls for reducing tunnel interference at high subsonic speeds[1,2].

The main reason for making this change was to facilitate the incorporation of slotted walls to give a continuously varying Mach number through 1.0 for the two-dimensional aerofoil tests that constitute the main item of the tunnel's programme. Moreover, it seemed reasonable to suppose that, on the basis of the work described in Refs. 3 and 4, a configuration of slots could be chosen for which interference effects would be small. Results comparable in accuracy to those obtained in the original working section with flexible walls would thus be obtained without the extra labour of finding and manipulating the correct setting of the walls for each speed, model configuration and incidence; or, if fixed straight walls are considered as the alternative, without the labour and uncertainty of calculating interference corrections for each case. The new working section also made it possible for the operating range of the tunnel to be extended to supersonic speeds, with solid liners taking over from the slotted walls for Mach numbers above 1.2.

The objects of the present note are: briefly to describe the new working section, particularly the slotted walls; to give details of the Mach number distributions measured along the working section before and after perforated screens were fitted in the plenum chamber to improve the distribution; and to illustrate the effect of the presence of a model on the measurement of tunnel speed.

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Replaces A.R.C. 20 287.

The recommendation for the publication of the work was made in 1959 but was unfortunately allowed by the authors to lapse. It has been revised and acted upon at this stage because of the increasing interest in recent years in the research being carried out in the wind tunnel concerned and in similar research in similar tunnels.

2. Description of the New Working Section

The changes were confined to the section between the lines AA, BB in Fig. 1. New plates are bolted between the contraction and the injection sections to form the fixed parallel side walls (Fig. 2). The end, or "top" and "bottom", walls are formed by plates hinged at the bottom (Fig. 1) and carrying the removable liner blocks. The hinged plates are provided with telescopic struts containing springs to balance the weight during opening and closing, and the liners can thus readily be changed without disturbing the model or its pressure connections (see Fig. 3). Rubber seals around the edges of the liners are inflated only when the hinged plates are closed.

Solid, wood-block liners are provided for subsonic running and for supersonic speeds ($M = 1.3$, 1.4, 1.6). Two sets of liners with slotted walls are available for transonic running.

The new side plates were designed to meet the more stringent requirements of supersonic running. They are stiffer than the old ones to reduce deflection, more accurately ground, and contain fewer metal-to-metal and glass-to-metal joints. The only joints likely to affect the flow near the model are those round the turntable provided for incidence changing; this turntable also contains the flow visualisation windows. [The porthole that can be seen in Fig. 3 below the model position was provided to permit the subsequent fitting of windows to pass the compensating beam of an interferometer. However, in the interferometer design most recently developed by Tanner the compensating beam is not passed through the working section and so these windows will not now be needed; metal plugs have therefore been fixed and ground flush on the inside.]

3. The Slotted Liners

Two sets of slotted liners are provided having different ratios of open to total area, namely: 1/30th, to give small interference effects in two-dimensional tests at high subsonic speeds; and 1/8th, to give a higher top speed, to give small interference effects in tests on half wings, and to allow comparisons to be made with results obtained in other transonic tunnels not fitted with walls having small open area. The details of the liners with 1/8th open area are shown in Fig. 4, which also illustrates the method of construction adopted for both sets. The liners are made up of brass slats mounted via struts on to a wooden base, with gaps between them to form the slots. Rigidity between struts is ensured by making the slats $\frac{1}{4}$ in. deep; their edges are chamfered as shown to avoid undue resistance to inflow and outflow through the slots. Each liner has seven slats to form six full slots, with two additional half slots between the end slats and the fixed walls. A row of pressure holes is provided along the centre slat. The slats were shaped in plan at the front to form the appropriate slot-entry shape. In elevation they are straight with a very small divergence (17 minutes, or 0.005 in. per inch run) to continue the parallel section (17 in. x 8 in.) from the end of the contraction to a point 38 in. further downstream, with the appropriate allowance for the boundary layer growth on the four walls. They then bend through approximately 4° to form the slotted expansion, after the manner described in Ref. 3. Auxiliary suction is not used.

The details of the liners with 1/30th open area are similar to those shown in Fig. 4 for the 1/8th liners, but with appropriately narrower slots in the parallel portion. These slots widen abruptly at the beginning of the expansion, and auxiliary ones are cut through the slats, to increase the open area to 1/5th and so to assist the discharge of the air from the plenum chamber back into the main stream.

The change in open area at the beginning of the expansion can be seen clearly in Fig. 3. The slot-entry shape for the 1/30th liners is also different from that for the 1/8th liners (see below).

The fixed dimensions of the contraction and injector sections impose certain limits on the design, particularly as regards the lengths of the shaped entry and parallel portion of the slots, the depth of the plenum chamber, and the angle of the expansion at the end. In particular the depth of the plenum chamber was made only 0.125 of the tunnel height, which, as subsequent work by Sutton has shown, is insufficient to avoid pressure gradients along the working section of the empty tunnel. Following Sutton, these gradients were subsequently eliminated by placing a screen of perforated metal to span the plenum chamber at the appropriate depth below the slots and to run the whole length of the parallel working section; details of this are described in the next section. This modification incurred a slight reduction in top speed and so a new design of the liner will be fitted as soon as the current programme of work can be interrupted for this purpose. In the new design the wooden base plate will be replaced by a metal one to increase the plenum chamber depth to 0.191 of the tunnel height. Also, the slots will be cut off at the beginning of the expansion and a sonic throat installed, similar to that described in Ref. 6.

The slot-entry shape for the liners with 1/30th open area was a straight taper to full width in 2.3 in. from the beginning (i.e., 0.13 × tunnel height). The slot-entry for the liners with 1/8th open area was shaped in the manner described in Ref. 7, and shown in Fig. 5, to run out to the full slot width in 10 in. (i.e., 0.59 tunnel height). Although the results of Ref. 7 suggest that this entry length was not sufficient to avoid completely the over-expansion at the run-out for the highest Mach numbers, it was decided to sacrifice a little in terms of flow uniformity at these speeds in order to allow sufficient length of parallel slot upstream of the model position for tunnel speed to be measured there reasonably well at lower speeds. This dilemma could perhaps have been avoided by reducing the model chord below the 5 in. normally used for two dimensional models in this tunnel and so reducing the strength of the equivalent doublet for a given thickness/chord ratio. This chord length is, however, the minimum that will give a Reynolds number sufficiently high (1.5 to 2.0 × 10^6) to allow proper simulation of the interactions between shock waves and turbulent boundary layers that occur at full scale. This is considered to be of overriding importance in the type of work to be undertaken, namely, research aimed at providing the basic understanding of the effects of the separation and other flow phenomena rather than at providing design data of a high accuracy. The relatively high blockages (3% for a 10% thick aerofoil at zero incidence) are also likely to aggravate the difficulties of eliminating blockage interference; but again, this is accepted for the sake of proper simulation of boundary layer effects. The effect of the presence of a model on tunnel speed measurement is described in §.5 and the blockage and other interference effects are to be considered elsewhere (see Ref. 8, for example).

4. The Use of Perforated Screens in the Plenum Chamber to Produce Uniform Flow Along the Working Section

As originally installed, both sets of slotted liners gave a rising pressure, (i.e., falling Mach number) along the working section. This is shown, for example, by the bottom distribution, A, in each of Figs. 6 (a), (b), (c) for the liners with 1/8th open area. This gradient resembles that observed by Sutton[5] in the original slotted liners of the three foot square tunnel at the Royal Aircraft Establishment (Bedford),

and/

and ascribed to secondary flow effects in the shallow plenum chamber. The mixing layer from the slotted walls spreads into the plenum chamber and when it approaches the solid base it introduces a region of increased shear that supports a finite pressure gradient, rather like that near the point of re-attachment of a separated boundary layer on an aerofoil; in this analogy the secondary flow in the plenum chamber takes the place of the reverse flow under the separated boundary layer on the aerofoil. Sutton found that this pressure gradient could be eliminated in the R.A.E. tunnel by fitting perforated screens a little way below the slots to restrict the transport of streamwise momentum into the lower parts of the plenum chamber, thereby keeping the speed of the secondary flows there low and, as a consequence, the static pressure variations small. A similar remedy was accordingly tried here. A flat screen of perforated steel, 0.032 in. thick, and with 99 holes of 0.069 diameter per square inch, giving an open area of 37% was fitted in each plenum chamber for the walls with 1/8th open area. The screens span the plenum chamber and run for the full length of the parallel working section as shown in Fig. 1. They produced practically no improvement in the Mach number distributions in the first position tried, namely, $1\frac{1}{4}$ in. below the top of the slots (see curves B of Figs. 6 (a), (b), (c)). They were then moved closer to the slots in stages until, at $\frac{3}{4}$ in. below the top of the slots, they gave a uniform distribution over an appreciable length. (See curves D). Thus, for $M = 0.6$ to 0.8 (Figs. 6 (a) and (b)) the distribution at the wall was uniform to within ±0.0015 on Mach number, from hole 8, just downstream of the end of the shaped slot-entry, to hole 22, a point one chord length downstream of a standard model in the standard position, - a total length of about $1\frac{1}{2}$ tunnel heights. The non-uniformities on the axis were slightly greater, at ±0.0025 on Mach number, as shown by the plus symbols and broken lines superimposed on the curves D. For $M = 1$ (Fig. 6 (c)) the Mach number was uniform at the wall to within ±0.002 back to hole 21; but on the axis it started to fall off slightly at hole 20, $1\frac{1}{2}$ in. further forward. The distribution at the walls for $M = 1.1$ (see top of Fig. 9) was uniform to within ±0.003 on the Mach number for just over one tunnel height, between hole 10 (6 in. downstream of the end of the shaped slot-entry) and hole 22. It is interesting that this combination of short slot entry and screens, a little way below the slots, gives a uniform expansion to maximum speed at $M = 1.1$ without any over-expansion, and that this maximum is not reached until 6 in. along the parallel part of the slots. At lower speeds the flow seems to over-expand slightly in the shaped entry (see Figs. 6(a) and (b)).

With the screens in the final position there was a reduction in the top Mach number (with model in) from 1.11 to 1.07, due possibly to a disturbance springing from the downstream end of the screens and propagated into the stream in the expansion region.

Finally, similar screens were fitted into the plenum chambers of the liners with 1/30th open area at $\frac{3}{4}$ in. below the top of the slots and gave similar improvements, as shown in Fig. 7, although the non-uniformities now rise to ±0.003 on Mach number at $M = 1$ for a length equal to nearly 2 tunnel heights. The centreline traverses in the final arrangement are shown in Fig. 5 and in this case are, if anything, slightly better than the wall distributions, except at $M = 1$ where the Mach number again starts to fall off slightly earlier on the axis than on the wall. The distribution at $M = 1.05$ was uniform to within ±0.004 on Mach number (see top of Fig. 10 (b)).

5. Mach Number Distributions Along the Walls in the Presence of a Model; Measurement of Tunnel Speed

The usual practice in the N.P.L. transonic tunnels is to measure tunnel speed on one of the slotted walls at some point upstream of the model. This requires that the reference pressure hole should be sufficiently far downstream to be unaffected by any disturbance from the beginning of the slots and for the expansion to speed to be complete, but not so far downstream as to come within the influence of the model itself. Some difficulty in meeting these requirements was expected in view of the fairly short working section relative to the tunnel height and in view of the relatively high blockages used.

In practice, satisfactory reference holes can be found at all speeds for the liners with 1/8th open area. This is shown in Fig. 9 where the pressures measured along the full length of one wall in the presence of a model of the standard chord length, of average thickness and at zero incidence, are compared with the corresponding measurements in the absence of the model. The uniform speed can be measured reasonably well at hole 8, say, without any influence on the model for all Mach numbers up to and including 1.0. For higher Mach numbers, this hole may fall within the region of the initial expansion, but, fortunately, as the bow wave moves towards the model with increasing speed so the upstream influence on the model is restricted, and the uniform supersonic speed can be measured by a hole further downstream, hole 10 or 11, say.

For the liners with 1/30th open area, a reference hole can be found to give satisfactory tunnel speed measurements for all Mach numbers up to about 0.9, but some degree of uncertainty occurs for higher speeds when the model thickness is of the order of 10% chord. Thus the comparison between the Mach numbers measured on the wall with models of 10% and 4% thickness and without model (Fig. 10 (a)) shows that the uniform speed can be measured at, say, hole 4, without much influence from the model for Mach numbers up to 0.9. Fig. 10 (b) shows that this hole is influenced by the thicker model at $M = 0.95$ and falls within the region of supersonic expansion into the slots for Mach numbers greater than 1.0. Hole 6 can be used satisfactorily to measure the top speed ($M = 1.05$) for both thicknesses.

Increasing the model incidence does not lead to any appreciable spread of the upstream influence of the model until the incidence becomes fairly high. Thus for $M = 0.6$ and a standard sized model, Figs. 11 (a) and (b) show that the uniform upstream speed can be measured reasonably well for incidences up to 10°. Some uncertainty occurs at slightly lower angles as the Mach number is increased. The curves of Figs. 11 (a) and (b) indicate, however, that the blockage effect downstream of the model increases with increasing incidence above 6°, as indicated by the curve of the mean of Mach numbers on the two walls at fixed positions. This is thought to be due to an increased blockage from a wake that is thickened by separation on the model from 6° upwards, and is likely to have an appreciable effect on the flow on the model. It is discussed in Ref. 8, together with other interference effects.

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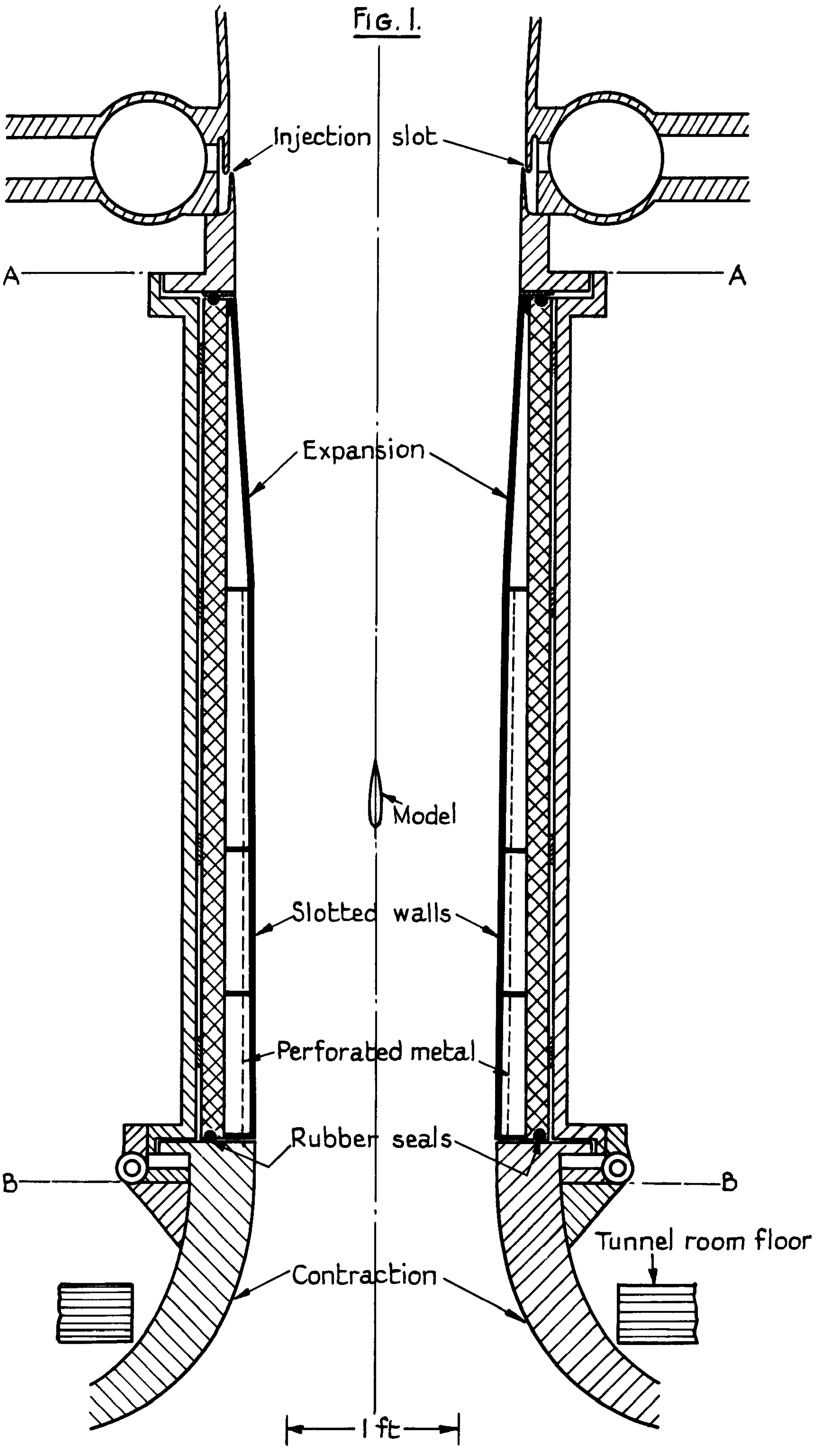
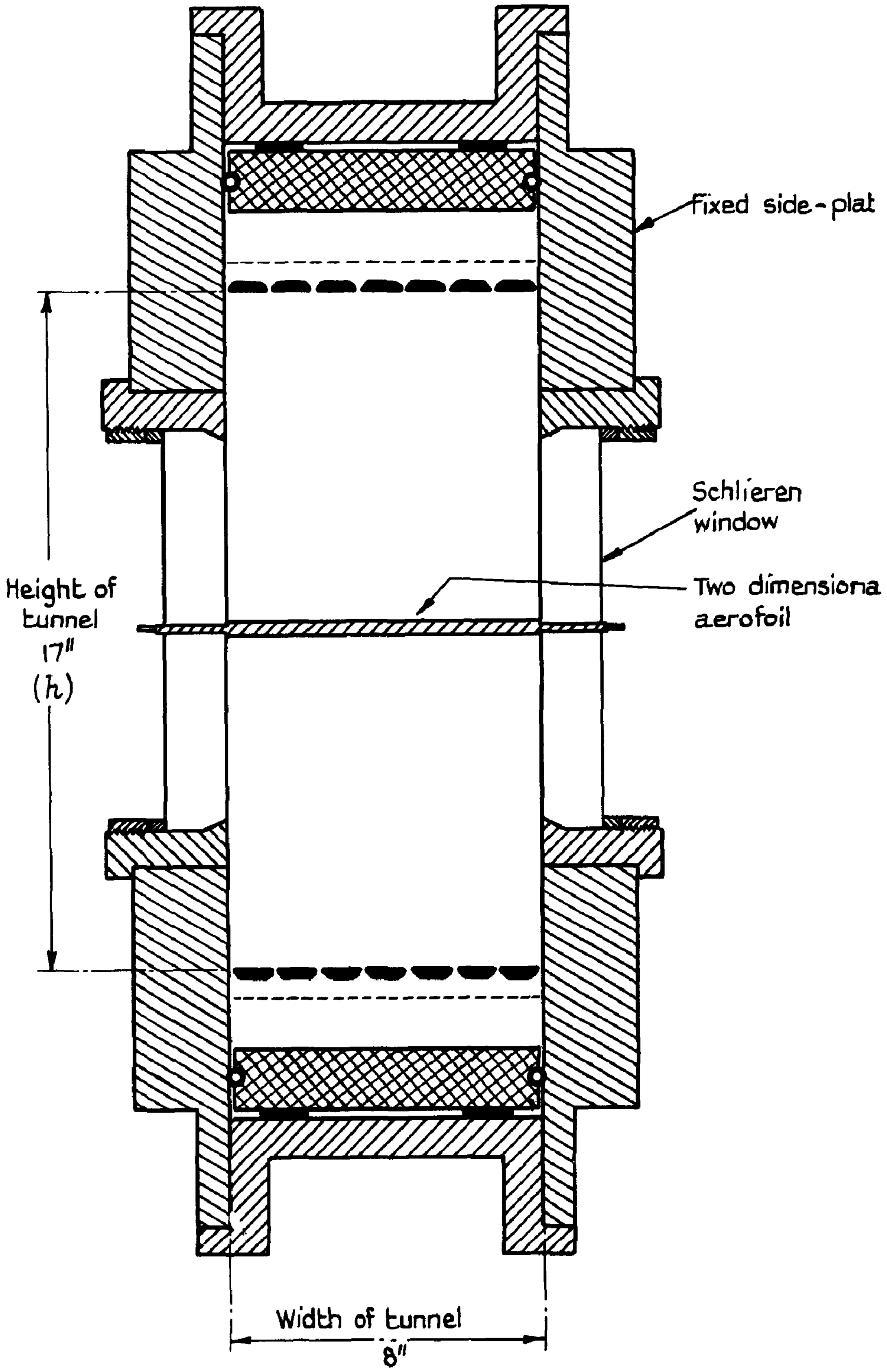
FIG. 1.



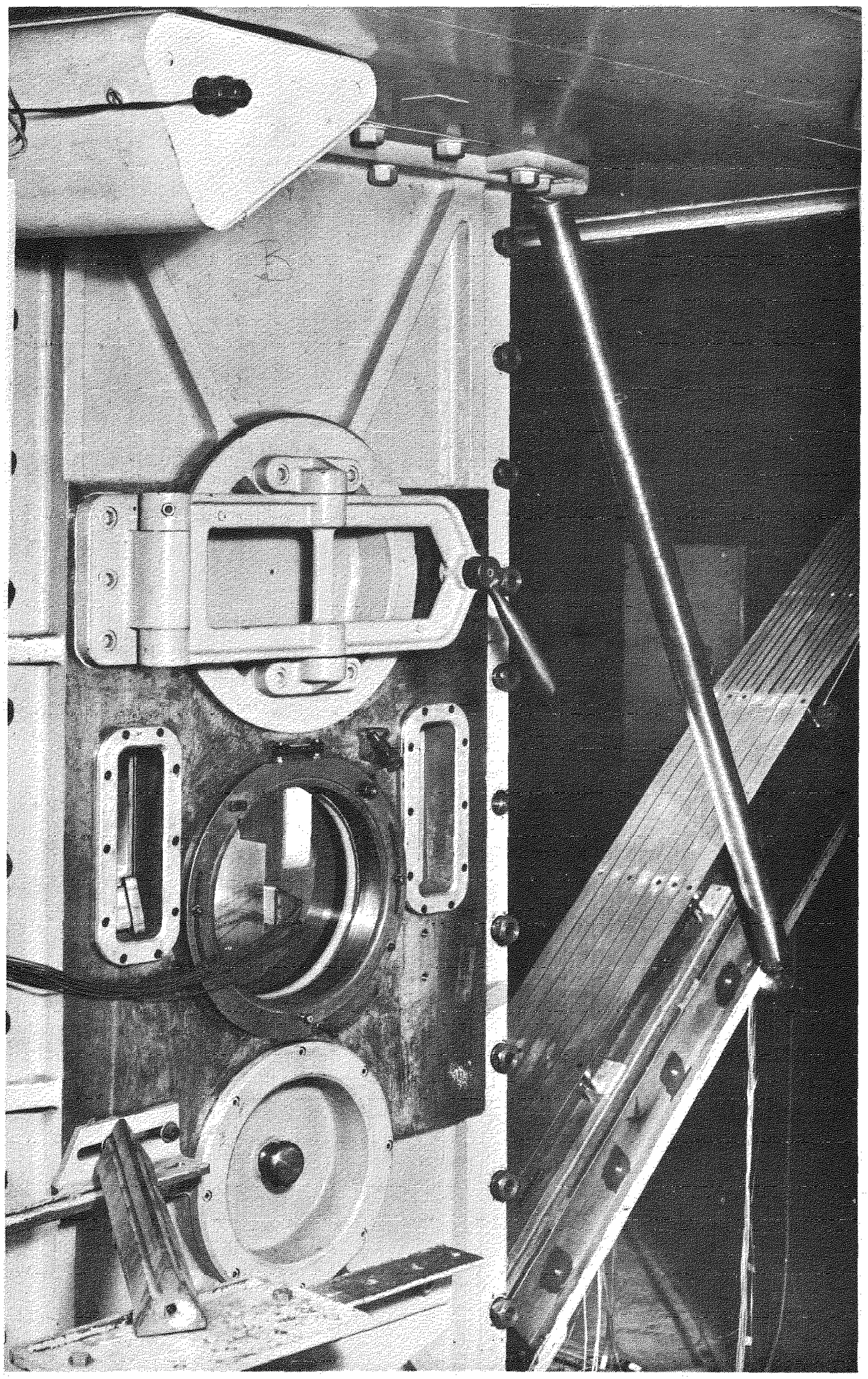
Vertical section of working section, parallel to fixed side-walls.

FIG. 2.

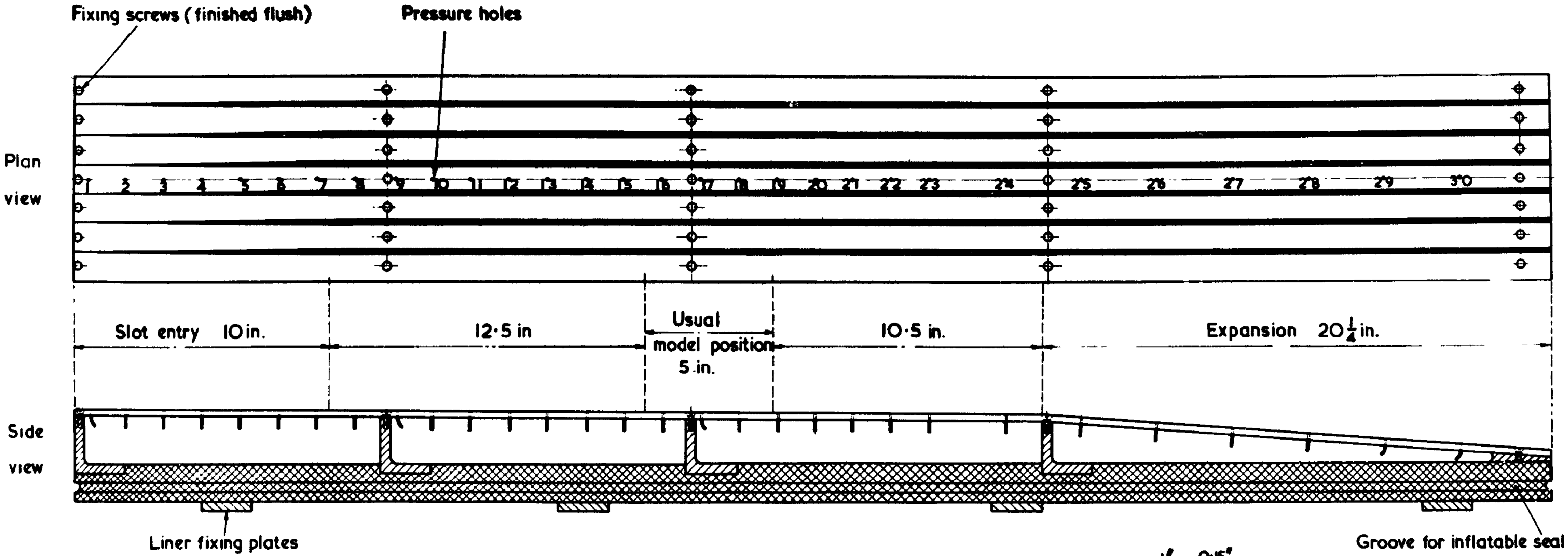


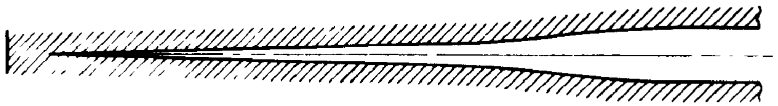
Horizontal section of working section

FIG. 3

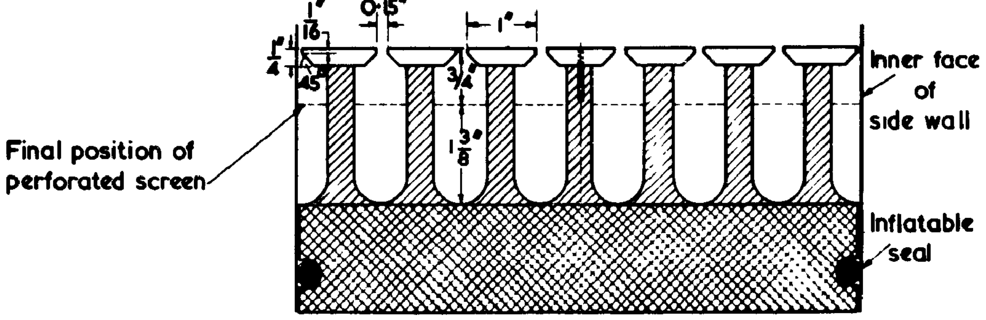


View of working section showing one hinged end-wall in open position





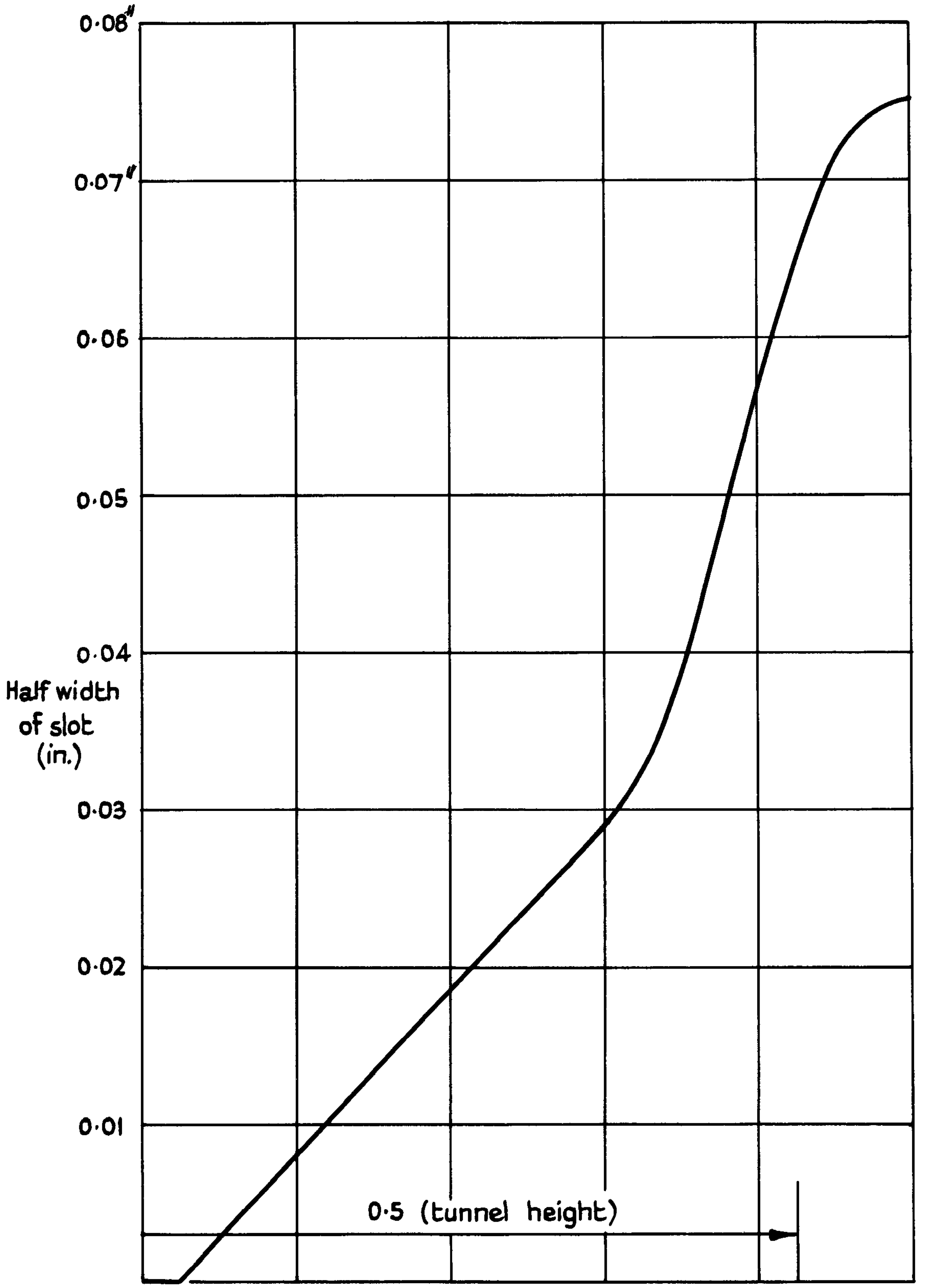
Enlarged view of slot entry (vertical scale = 5 times horizontal)



Typical section showing details of slots struts etc. (enlarged scale)

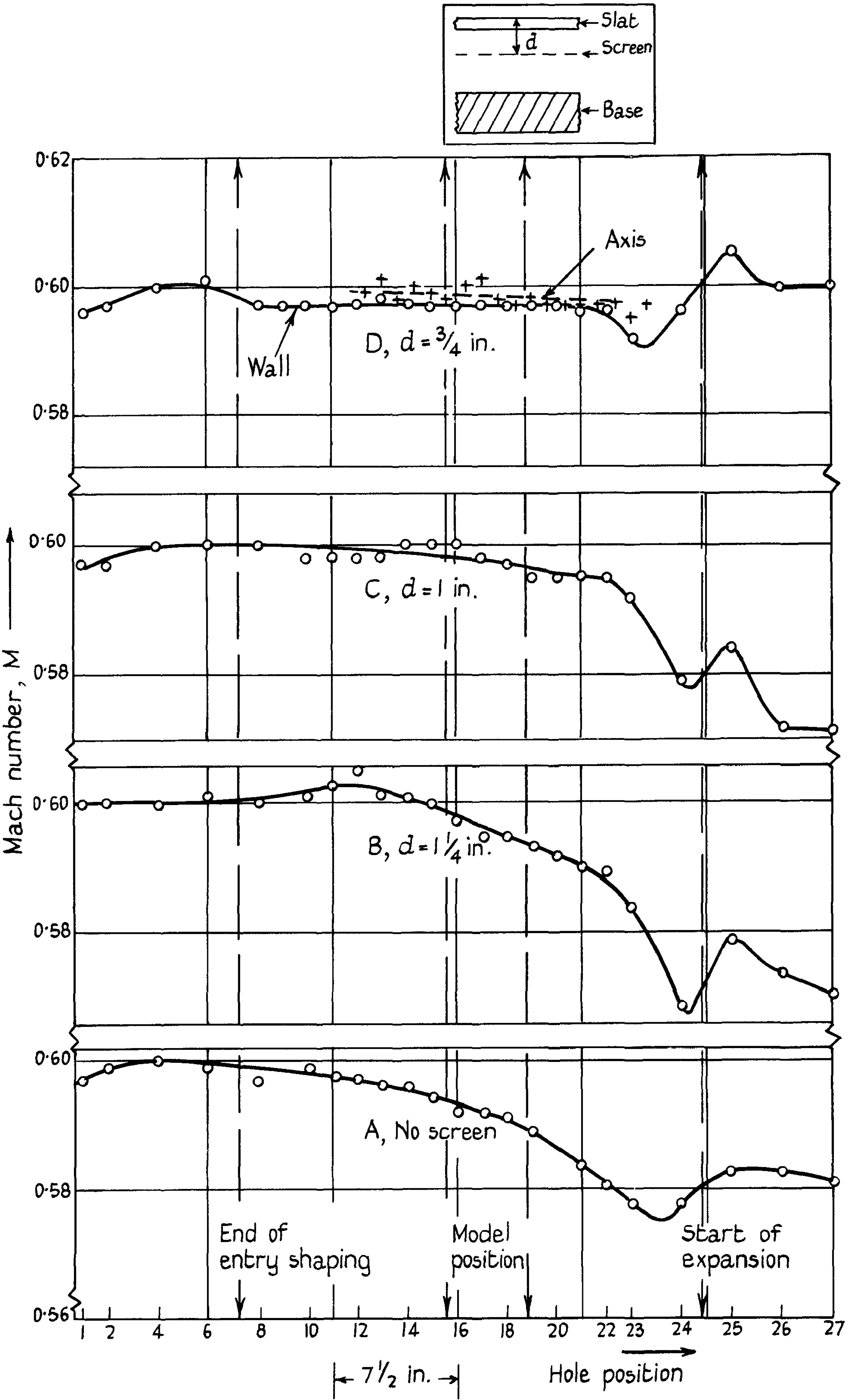
FIG. 4 DETAILS OF $\frac{1}{8}$th TRANSONIC LINERS

FIG. 5.



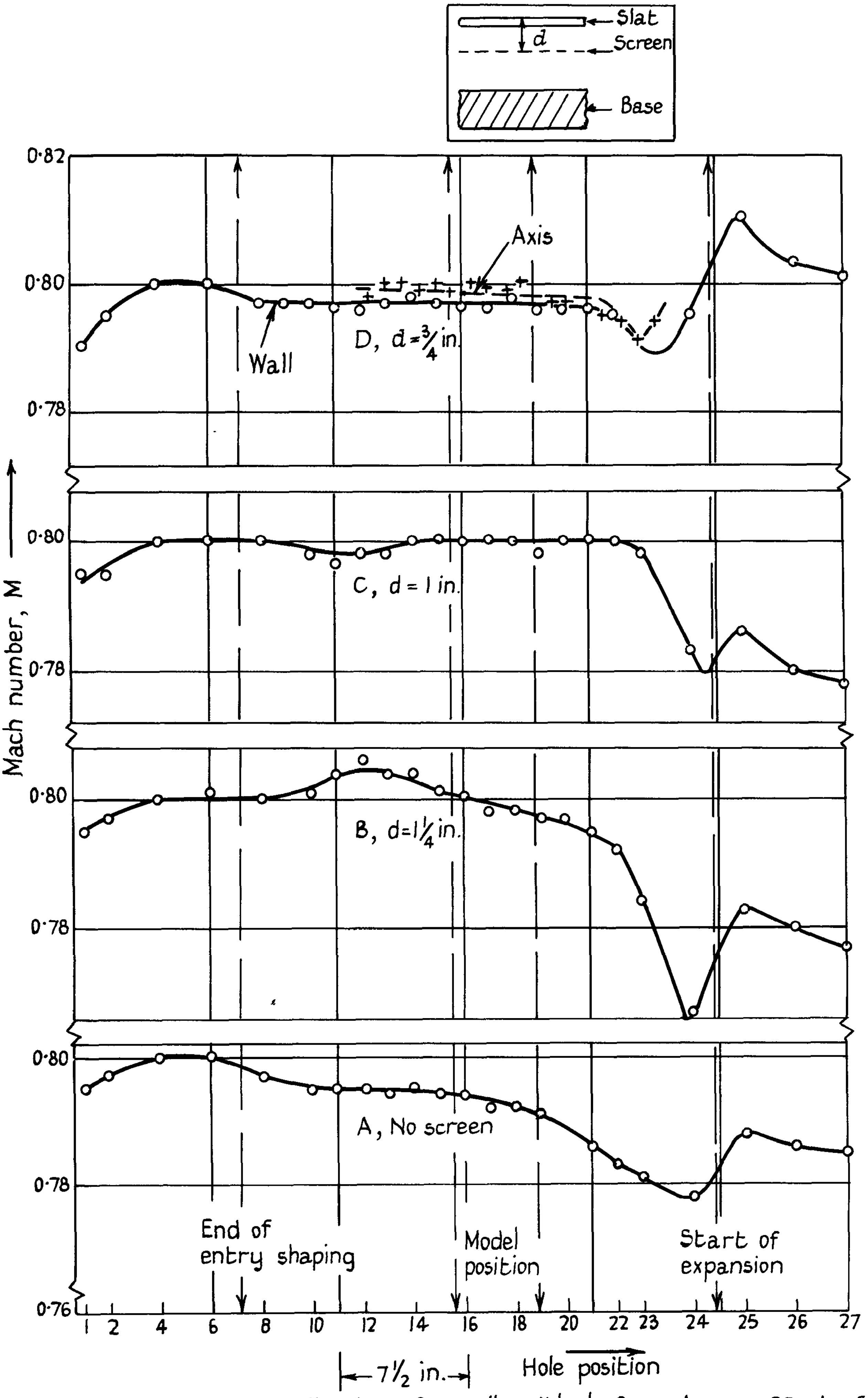
Slot - entry shape for the liners with $\frac{1}{8}$ open area.

FIG. 6(a).



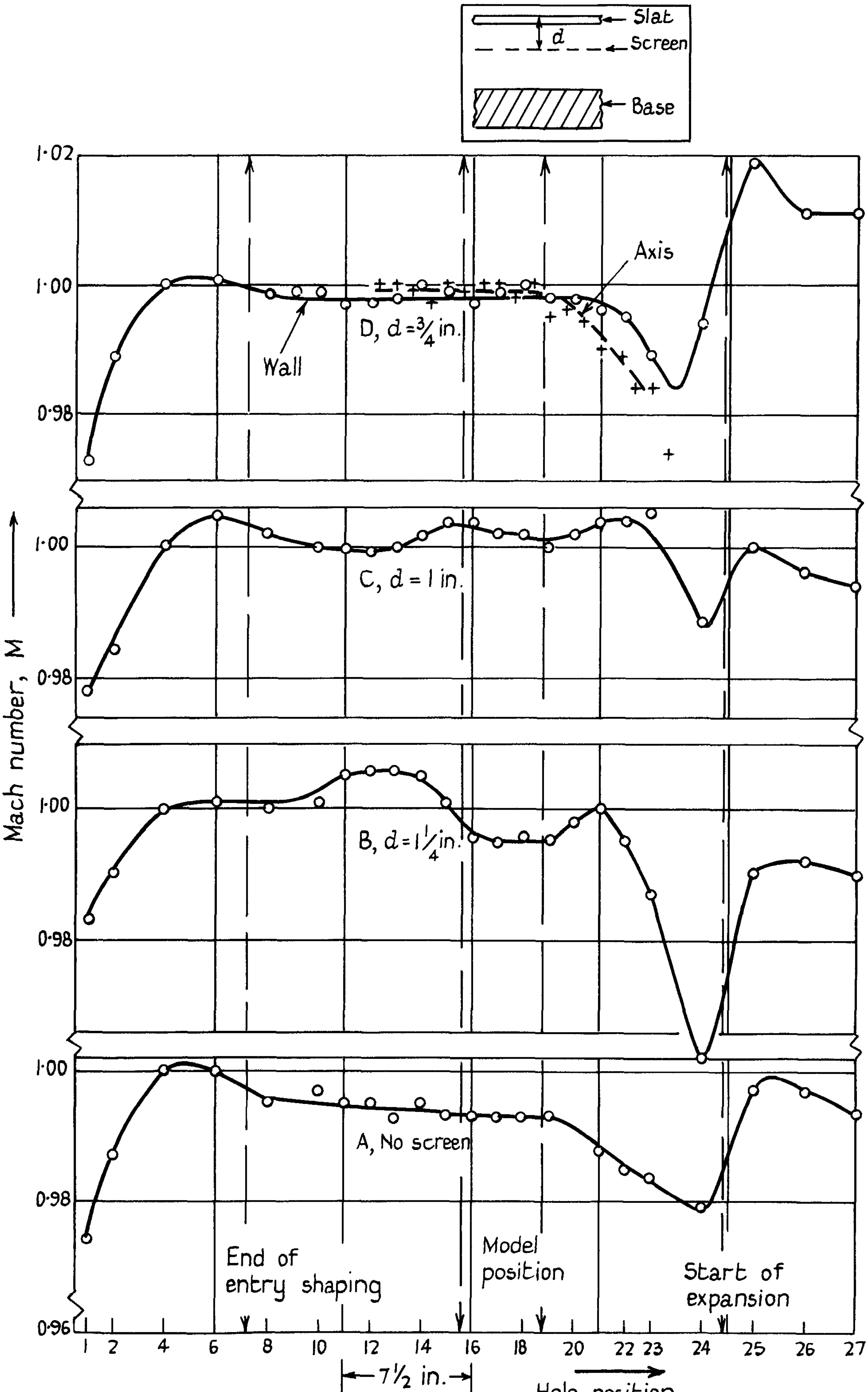
Mach number distributions for walls with $\frac{1}{8}$ Open Area; effect of adding perforated screens in plenum chambers. (a) M = 0·6.

FIG. 6(b)



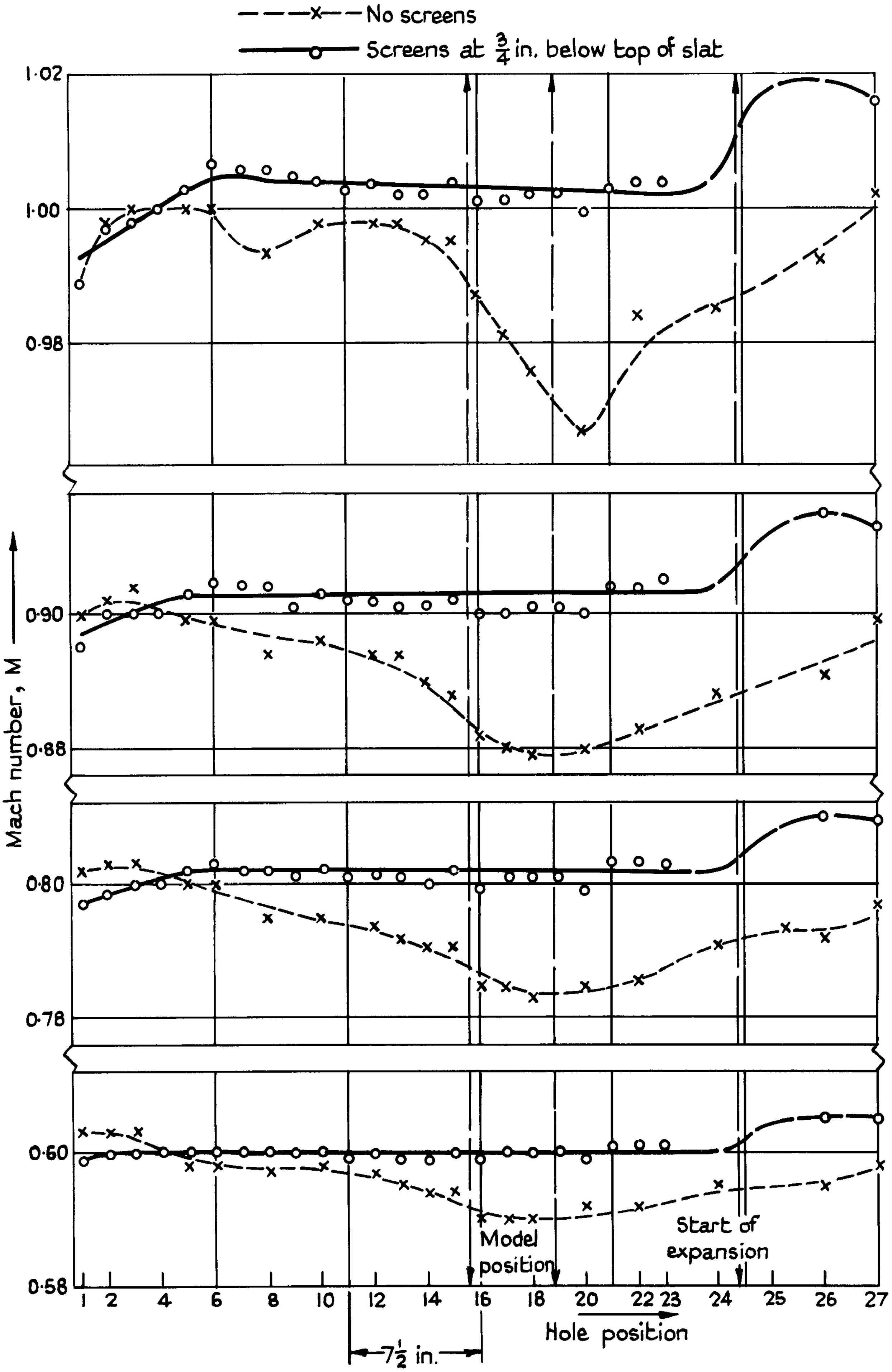
Mach number distributions for walls with $\frac{1}{8}$ Open Area; effect of adding perforated screens in plenum chambers. (b) M = 0·8.

FIG. 6 (c)



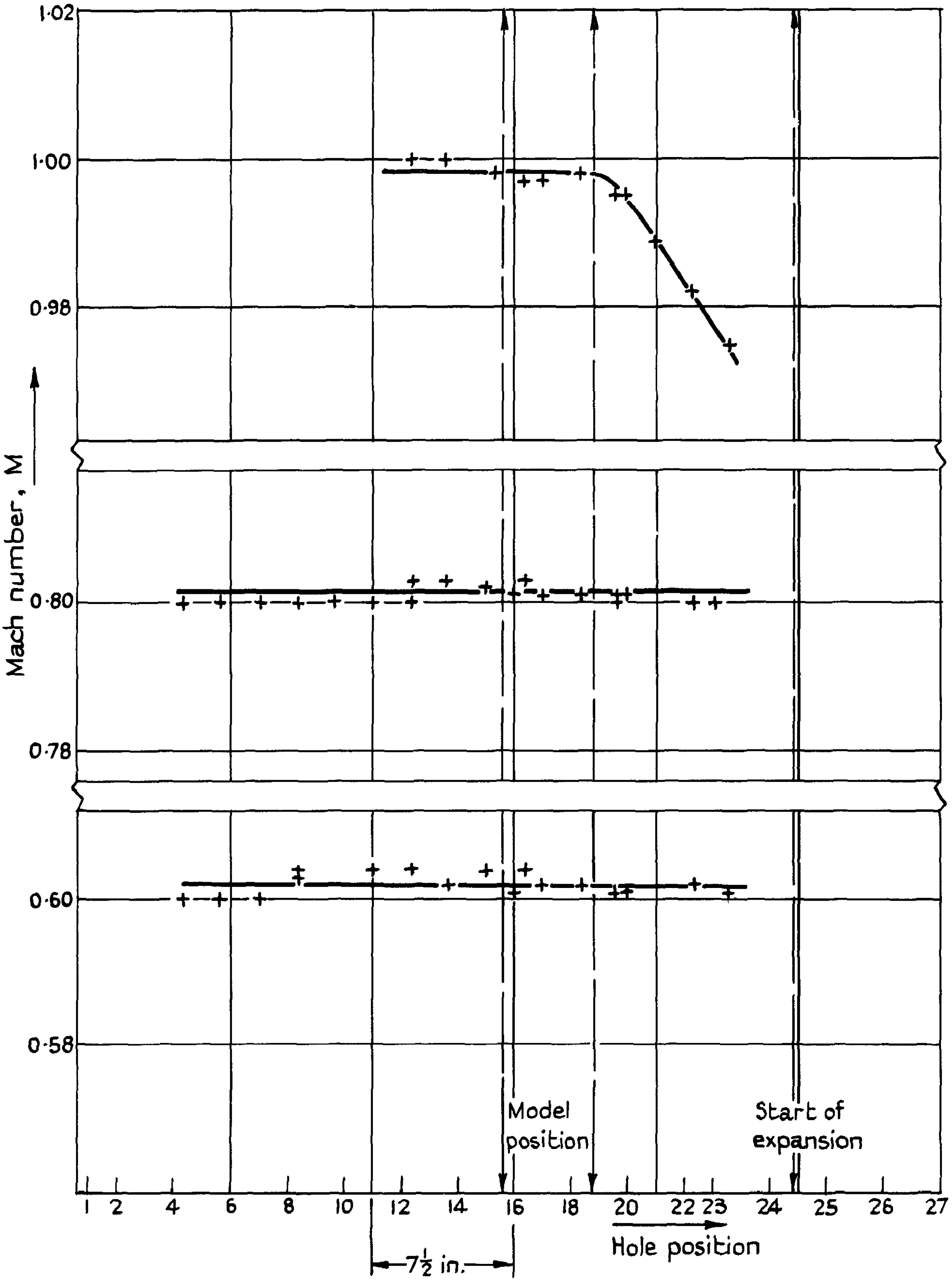
Mach number distributions for walls with $\frac{1}{8}$ Open Area; effect of adding perforated screens in plenum chambers. (c) M = 1·0.

FIG. 7.



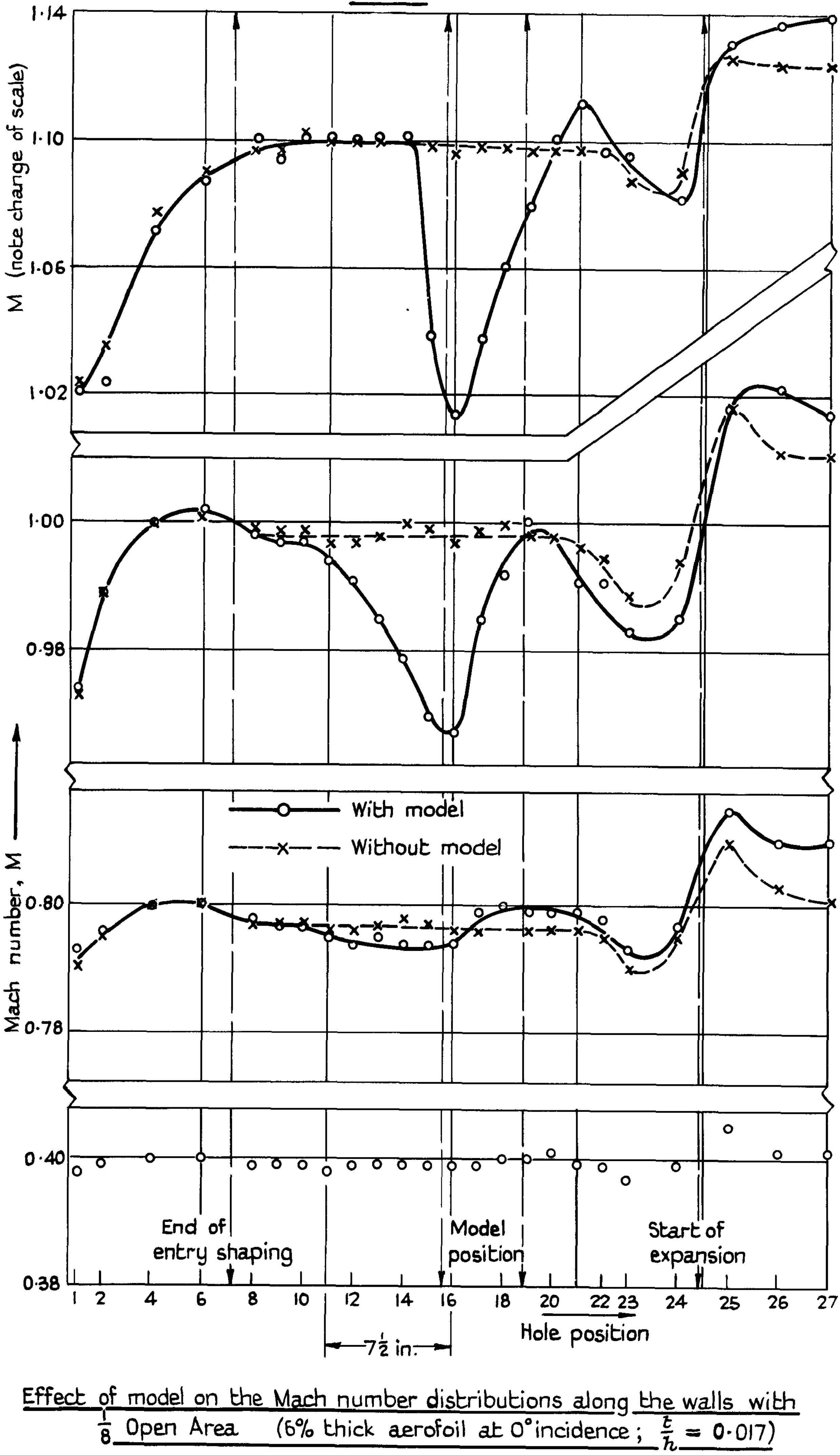
Mach number distributions along the walls with $\frac{1}{30}$ Open Area; effect of adding perforated screens in plenum chamber.

FIG. 8



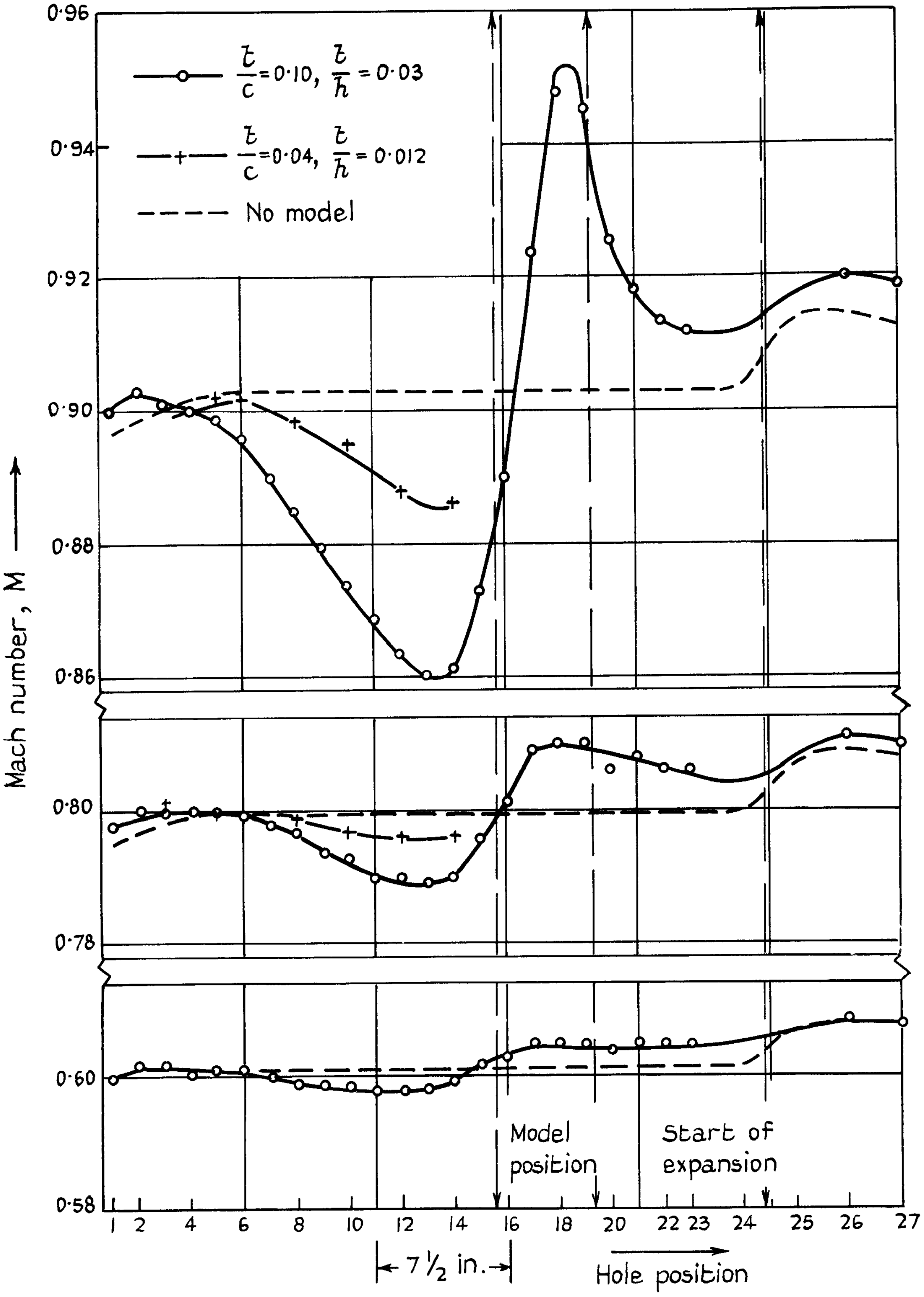
Mach numbers along the axis for the walls with $\frac{1}{30}$ Open Area; perforated screens in plenum chamber.

FIG. 9.



Effect of model on the Mach number distributions along the walls with $\frac{1}{8}$ Open Area (6% thick aerofoil at 0° incidence; $\frac{t}{h} = 0{\cdot}017$)

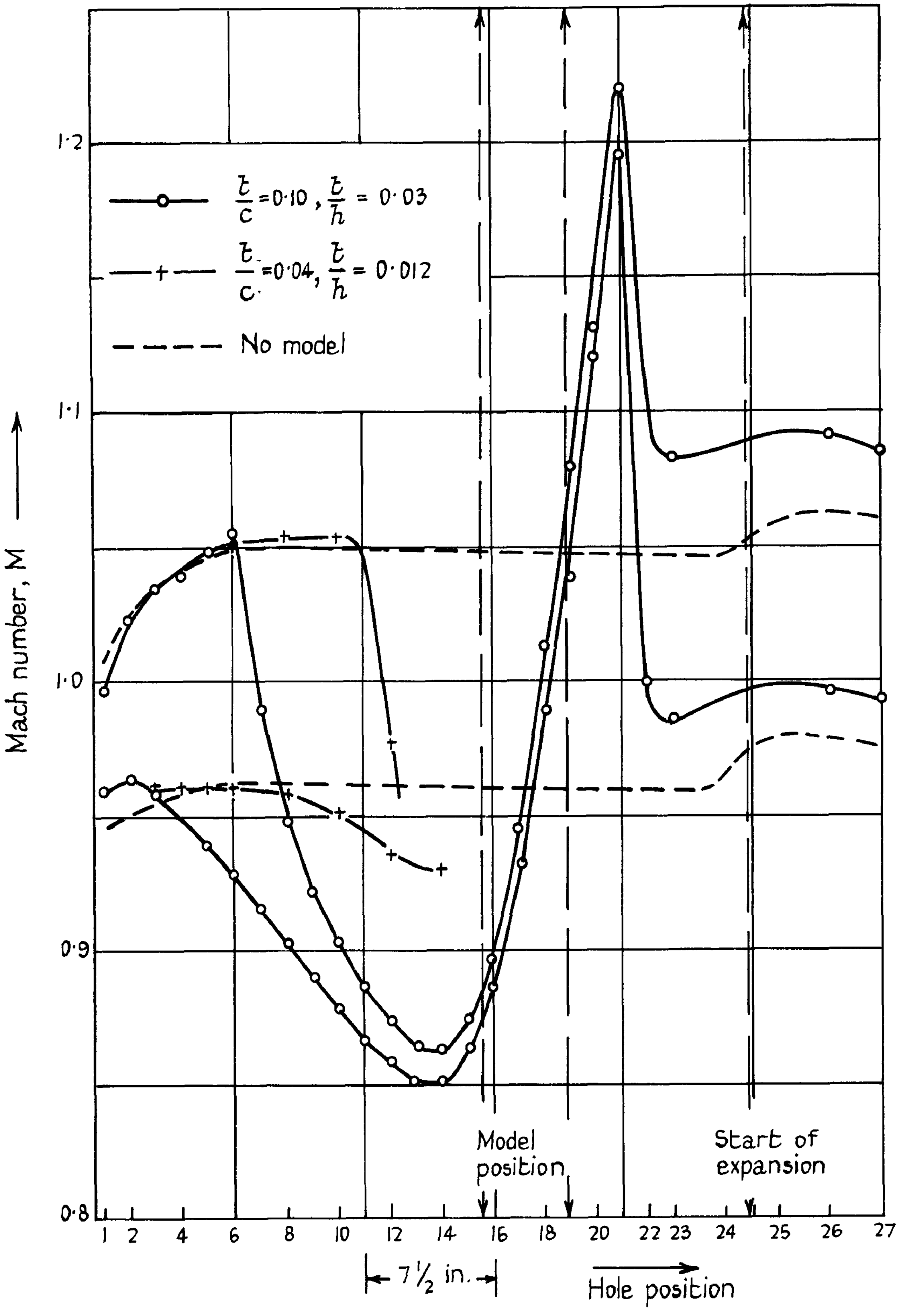
FIG. 10(a).



Effect of model of two different thicknesses on the Mach number distributions along the walls with $\frac{1}{30}$ Open Area. (0° incidence)

(a) M = 0·6, 0·8, 0·9.

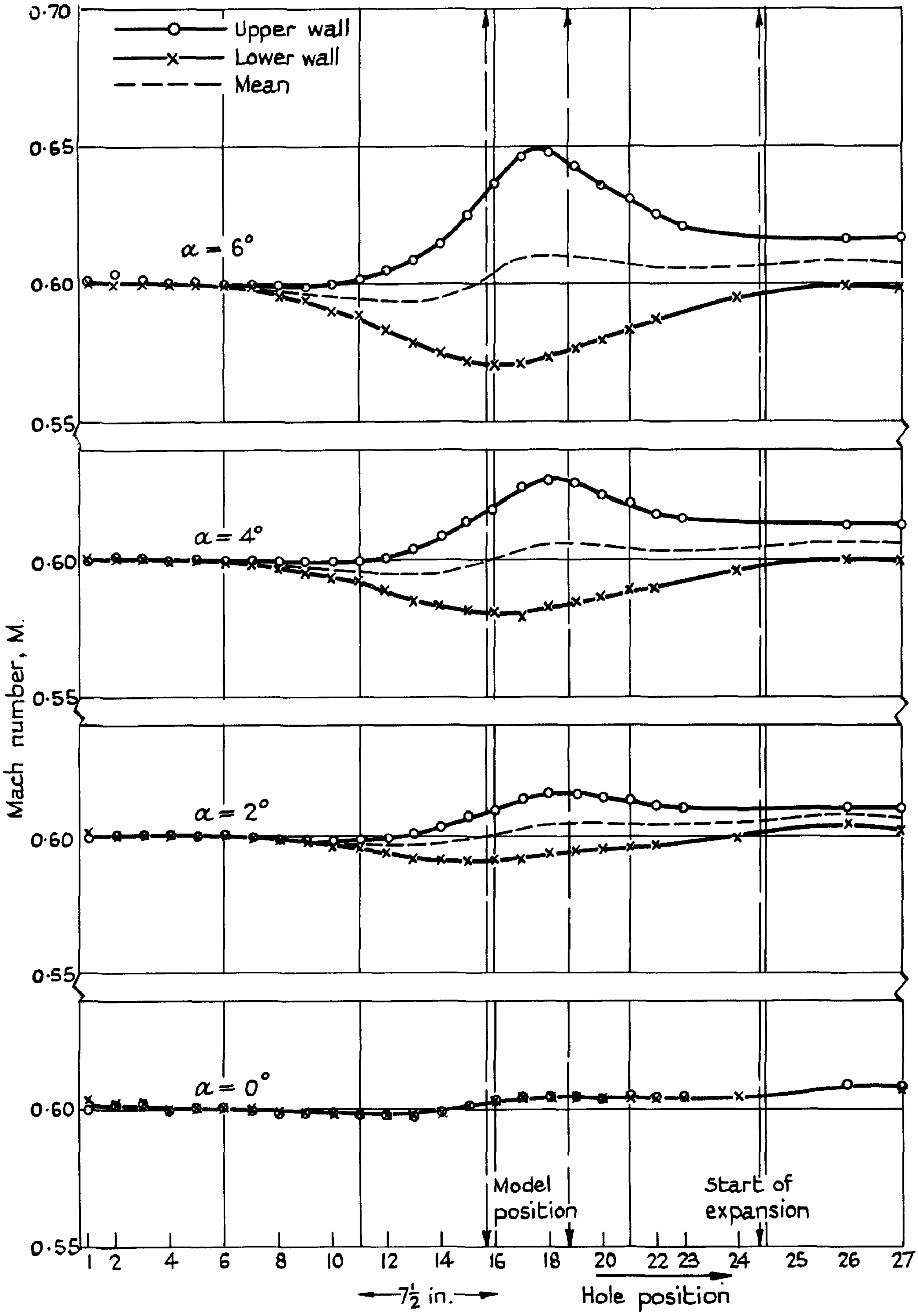
FIG. 10(b)



Effect of model of two different thicknesses on the Mach number distributions along the walls with $\frac{1}{30}$ Open Area. (0° incidence)

(b) M = 0·96, 1·05.

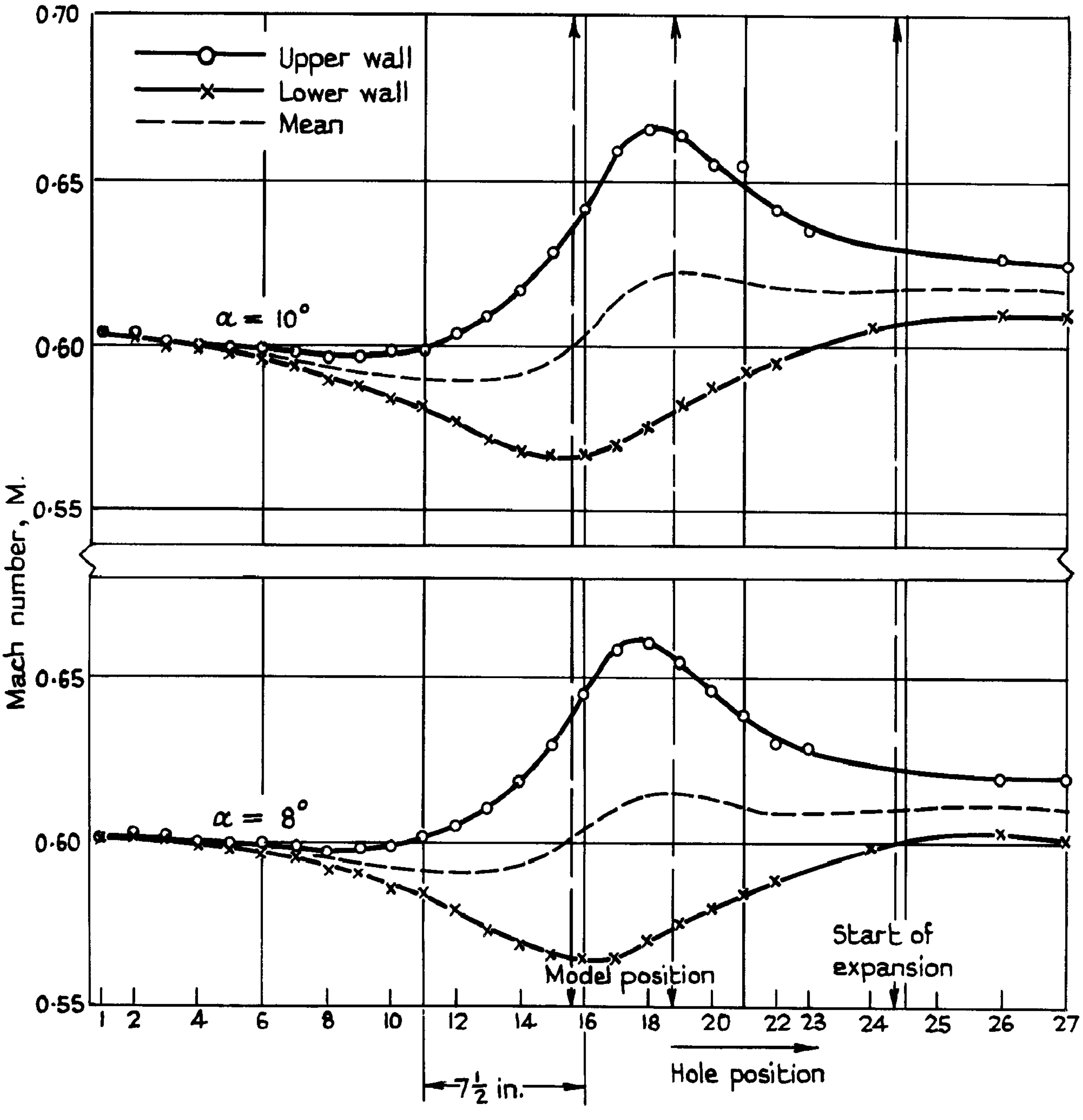
FIG. 11 (a)



Effect of increasing model incidence on the Mach number distributions along the walls with $\frac{1}{30}$ Open Area (5 in. chord model; $t/h = 0{\cdot}03$)

(a) $\alpha = 0°$ to $6°$.

FIG. 11 (b)



Effect of increasing model incidence on the Mach number distributions along the walls with $\frac{1}{30}$ Open Area (5 in. chord model; t/h = 0·03)

(b) $\alpha = 8°$ and 10°.

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