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By

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Measurements of Secondary Flow in the Boundary Layers of a 180 degree Channel

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Summary

Secondary flow measurements have been made within the turbulent boundary layers at two streamwise cross-sections of a 180 degree curved channel. The results indicate substantial three-dimensionality on all four walls of the channel. The secondary flows on the flat and convex surfaces are in accordance with those expected from considerations of the action of the centrifugal pressure gradients on the flat surfaces, while those on the concave surface appear to be dictated both by this effect as well as by the occurrence of longitudinal instability vortices. Some attempts have been made to reduce the cross-flows on the curved surfaces so that the influence of streamwise surface curvature on nominally two-dimensional turbulent boundary layers can be investigated.

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* Replaces A.R.C.30 428

Introduction

The experiments described in this paper were made in connection with an investigation of the effects of streamwise surface curvature on the development of a turbulent boundary layer. The primary aim of this new series of experiments was to eliminate some of the undesirable features of the preliminary measurements made by Patel (1968) and to obtain much more definitive results for both convex and concave surfaces. In the earlier measurements in the 90 degree curved duct the pressure gradients at the entry and the exit of the duct completely dominated the flow within the duct, with the result that the boundary layer on the convex surface developed under substantially zero pressure gradient over only a small length. To ensure a much larger region of zero streamwise pressure gradient it was decided to make the new measurements in a 180 degree duct. In the previous experiments the outer concave wall was made from a thin perspex sheet, and because of the method of construction it was not possible to measure the boundary layer developments on that surface. The new duct was therefore constructed with hardboard surfaces so that both concave and convex wall boundary layers could be studied. Two new 90 degree curved sections having the same overall dimensions as before were constructed to form a 180 degree extension to the 10 ft long working section of the blower tunnel. The major details of the apparatus and the notation used are shown in Figure 1. Care was taken to ensure that the joins between the various sections were smooth and free from leaks.

Before starting on the actual boundary layer measurements it was felt desirable to obtain some information regarding the extent and magnitude of the secondary flows within the concave and convex surface boundary layers. The secondary flow measurements were made particularly to ascertain to what degree the previous measurements had been, if at all, affected by three-dimensionality. These measurements form the subject of the present paper. There are several features of interest to workers contemplating further experiments on turbulent boundary layers on curved surfaces.

Measurements

Static pressure distributions along the centre-line of the convex and concave surfaces were measured by means of pressure tappings on the walls. These showed that the streamwise pressure gradient was substantially zero in the region $25° < \phi < 165°$. Preliminary explorations with a wool tuft suggested that the flow remained attached everywhere in the channel except in two small regions on the convex surface close to the exit. It was also found that quite large cross-flows existed on the curved surfaces in the exit region. To obtain a much more comprehensive picture of the flow pattern it was decided to measure the magnitude and direction of the velocity over entire cross-sections of the channel. Owing to the rather large number of measurements required it was found convenient to use a rake (or comb) of several three-tube yaw probes. Some of the details of this rake and individual probes are shown in Figure 2. It will be seen that the rake could measure both the magnitude and direction of velocity for distances up to 3 inches from the surface.

The nine yaw probes in the rake were calibrated in a 28 in. x 20 in. wind tunnel over a range of velocity and yaw angle. The calibration curves were found to be independent of tunnel speed in the range $40 < U < 75$ ft/sec and could be used to determine the flow direction within half a degree for angles of yaw up to $\pm$ 20 degrees. Before the rake could be used in the unknown three-dimensional flow in the curved channel it became necessary to define some reference directions and also to find a method by which the probes could be accurately located relative to these directions. In the following measurements the true horizontal and vertical planes have been used as the reference planes. The top and bottom flat surfaces of the channel, which were constructed parallel, were made horizontal by suitably adjusting the supports on which the duct rested. The curved surfaces thus became vertical. The rake was fitted with a cylindrical sleeve, as shown in Figure 2, which could accommodate a smooth fitting, accurately machined "bullet" containing a sensitive spirit bubble. The bubble was made to indicate horizontal position when the outermost probe was truly horizontal. Thus the outermost probe could be made to point in the true x direction. The rake was made perpendicular to the curved surfaces by means of another spirit level (shown dotted in Figure 2) and two set-squares specially constructed to indicate the radial y direction when laid on the curved surfaces. The sleeve on the yaw-comb (without the bullet) did not interfere with the readings of the probes.

Yaw-probe readings were taken at 40 different stations round the cross-section of the duct at two streamwise positions, namely $\phi = 135°$ and $173\frac{1}{2}°$. The maximum dynamic pressure recorded within the cross-section was selected as the reference to obtain the non-dimensional velocity components U_x/U_R and U_z/U_R. U_R is the reference velocity while U_x and U_z are the horizontal and vertical components of velocity.

Discussion of results

Figure 3a shows the top and bottom halves of the duct at $\phi = 135°$. The velocity profiles U_x/U_R are shown by the dotted lines and the cross-flow profiles U_z/U_R have been indicated by means of solid thick lines and circles. Since the rake measurements were restricted to the region within 3 inches of the walls, the velocity distribution in the central part of the duct was estimated from the radial equilibrium equation

$$\frac{U^2}{r} = \frac{1}{\rho}\frac{\partial p}{\partial r} .$$

It will be seen that the velocity distribution so obtained blends smoothly with the measurements on the convex and concave walls. The contours of constant U_x/U_R are also shown in Figure 3a. Figure 3b shows similar measurements made at the downstream station $\phi = 173\frac{1}{2}°$.

Comparison of Figures 3a and 3b shows that the general pattern of the cross-flow and streamwise velocity profiles remains unchanged with the streamwise distance. The cross-flows on the convex wall are larger near the corners and decrease in magnitude as the centre-line is approached. It appears that these cross-flows considerably thicken the boundary layer (as indicated by the bulges in the velocity contours) in a region between the centre-line and the corner. This thickening occurs nearer to the centre-line as x and ϕ increase. The effect of the cross-flows on the central region of the convex wall is therefore expected to be smaller at stations upstream of $\phi = 135°$. It will be seen later that this observation is important and vindicates the previous 90 degree curved duct experiments reported by the author (Patel, 1968). The secondary flow on the flat surfaces is, as expected, in the direction of the centrifugal pressure gradient i.e. from the outer to the inner corners. Thus the cross-flows on the top, bottom and convex surfaces are in accordance with those assumed in the earlier paper. The cross-flows on the concave surface do not, however, indicate the expected behaviour. Near the outer corners the flow is indeed towards the corners but its magnitude does not decrease near the centre-line. The most peculiar behaviour occurs at station 4,0 where the cross-flow is seen to be large away from the wall and almost negligible near it. Large cross-flows are also observed at and near the centre-line.

To investigate the differences between the flows on the concave and convex surfaces further measurements were made in the form of Preston tube traverses in the spanwise directions at the two cross-sections. A circular pitot and a static tube (both 0.042 in. diameter) were mounted on a cursor which could slide on a 36 inch steel rule. The rule was stuck to the wall with the use of a two-sided adhesive tape, and care was taken to ensure that both pitot and static tubes remained in contact with the surface whenever the cursor was moved along the rule by means of a flexible cable drive. The variation of the pitot-static pressure difference, Δp, (which may safely be assumed to be a function of the wall shear-stress) with spanwise distance z is shown in Figure 4. It will be seen that the convex wall results again indicate the thickening of the boundary layer and the separations at $\phi = 173\frac{1}{2}°$. However, the most significant feature of these measurements is the wave-like pattern observed on the concave wall. The pattern is reproduced almost identically at both streamwise stations. It is suggested that this wavy pattern results from weak vortices with axes parallel and close to the concave wall. In laminar boundary layers on concave surfaces the existence of Taylor-Görtler vortices due to Rayleigh's instability is well known. The present results seem to suggest that such vortices may also exist in turbulent boundary layers on a concave surface. If the existence of such vortices is accepted, it is possible to explain the rather complex cross-flow pattern observed on the concave surface by considering the superposition of two effects: (i) the flow from the centre-line towards the corners resulting from the centrifugal pressure gradient on the top and bottom surfaces, and (ii) the cross-flows resulting from a number of contrarotating instability vortices. The directions of the latter will depend upon the spanwise position and the distance between the adjacent vortices. Thus it is possible to obtain almost negligible cross-flows at some stations (e.g. station 5,0) and large cross-flows at others (e.g. stations 4,0, 7,0 and 8,0). Further complications arise due to the uneven thickening of the boundary layer on the convex wall and the resulting displacement effects on the irrotational flow.

As mentioned earlier the present measurements have been used to assess the influence of three-dimensionality in the 90 degree curved duct experiments described in the earlier paper (Patel, 1968). Figure 5 shows the velocity profiles measured in the central region of the convex wall at $\phi = 135°$ and $\phi = 173\frac{1}{2}°$. The corresponding cross-flow profiles are shown in Figure 6. It will be seen that the primary streamwise velocity profiles are similar and remain unaffected by the cross-flows such as are present. These cross-flows may therefore be regarded as small. Indeed at $\phi = 135°$ the flow between stations 6,I and 10,I (i.e. over a spanwise distance of 16 in.) may be considered almost two-dimensional. Moreover, Figure 6 shows quite clearly that the magnitude of the cross-flows increases rapidly with streamwise distance. Thus, the cross-flows in the region of the centre-line of the convex wall upstream of $\phi = 135°$ are expected to be much smaller and the assumption of two-dimensional flow made in the previous work for the boundary layer on the first 80 degrees of convex wall is fully justified.

Since the basic aim of these new experiments in the 180 degree curved duct was to measure the boundary layer developments on the convex and concave surfaces, it will be clear that such measurements could not be justified unless the cross-flows were substantially reduced, especially in the last 45 degrees of the duct. Some preliminary attempts at reducing the cross-flows have been made and are described below.

The cross-flows (with the exception of those associated with the suspected instability vortices on the concave wall) result from the action of the centrifugal pressure gradients on the boundary layers on the top and bottom surfaces. The quantity of fluid which is affected by these pressure gradients depends on the momentum defect within these boundary layers. The cross-flows can be reduced if this defect is decreased or removed altogether. In the present experiments the reduction in boundary layer thickness on the flat walls was achieved by providing two false end-walls in the curved portion of the duct, i.e. for $0 < \phi < 180°$. The new end-walls had smooth leading edges and, as shown in Figure 7, were set 6 inches away from the original flat surfaces. The joins between these and the curved surfaces were sealed.

As before, yaw-comb measurements were made at $\phi = 135°$ and $173\frac{1}{2}°$. The results are shown in Figure 7. Comparison of

Figure 7 with Figure 3 shows that: (i) the cross-flows have been reduced everywhere; (ii) the flow in the central part of the duct is improved and some of the waviness in the velocity contours has been eliminated; (iii) on the convex wall at $\phi = 173\frac{1}{2}°$ flow separation is no longer present, but the thickening of the boundary layer persists; (iv) at $\phi = 135°$ the central region of the convex wall (stations 6,I to 10,I) exhibits negligible three-dimensionality; and (v) the cross-flows on the concave wall have decreased but their relative magnitudes and shapes have remained unchanged.

To see if further improvements of the flow could be achieved, two more false end-walls were added in the last 90 degrees of the duct, i.e. for $90° < \phi < 180°$. These were set 4 inches away from the $0 < \phi < 180°$ end-walls. Yaw-comb observations were again made at the two streamwise stations. The results are presented in Figure 8. From this we see that the flow on the convex surface undergoes a further improvement but the cross-flows on the concave surface remain virtually unchanged. It will be noticed, however, that most of the reduction in cross-flow on the convex surface is restricted to small distances from the corners and that, owing to the reduction in the effective aspect ratio of the duct, very little gain is made in the expanse of nominally two-dimensional flow in the region of the centre-line. The three-dimensional nature of the boundary layer around the centre-line of the concave wall appears to be independent of the position of the end-walls and must therefore be due to a mechanism entirely different from that introduced by the centrifugal pressure gradient on the end-walls. As mentioned before, it is likely that the cross-flows in this region are dominated by instability vortices.

Conclusions

The following conclusions may be drawn from these measurements:

(1) The convex wall boundary layer is substantially two-dimensional in the neighbourhood of the centre-line for the first 80 degrees of the curved duct.

(2) To study the influence of concave curvature on a two-dimensional turbulent boundary layer it is necessary first to investigate in some detail the nature of spanwise instability vortices so as to determine the curvature parameter which governs their appearance and strength. This observation is of particular importance in supersonic flow where concave curvature is more common.

(3) If experiments on curvature effects are carried out in curved ducts it is necessary to have a large enough aspect ratio or some control over the boundary layers on the flat end-walls so that reasonably two-dimensional flow can be obtained on the convex surface.

Acknowledgement

The author is grateful to Dr. N.A. Cumpsty for his assistance in making the measurements.

Reference

Patel, V.C. 1968 The effects of surface curvature on the development of a turbulent boundary layer. A.R.C.30 427 (To be published as R.& M. 3599)

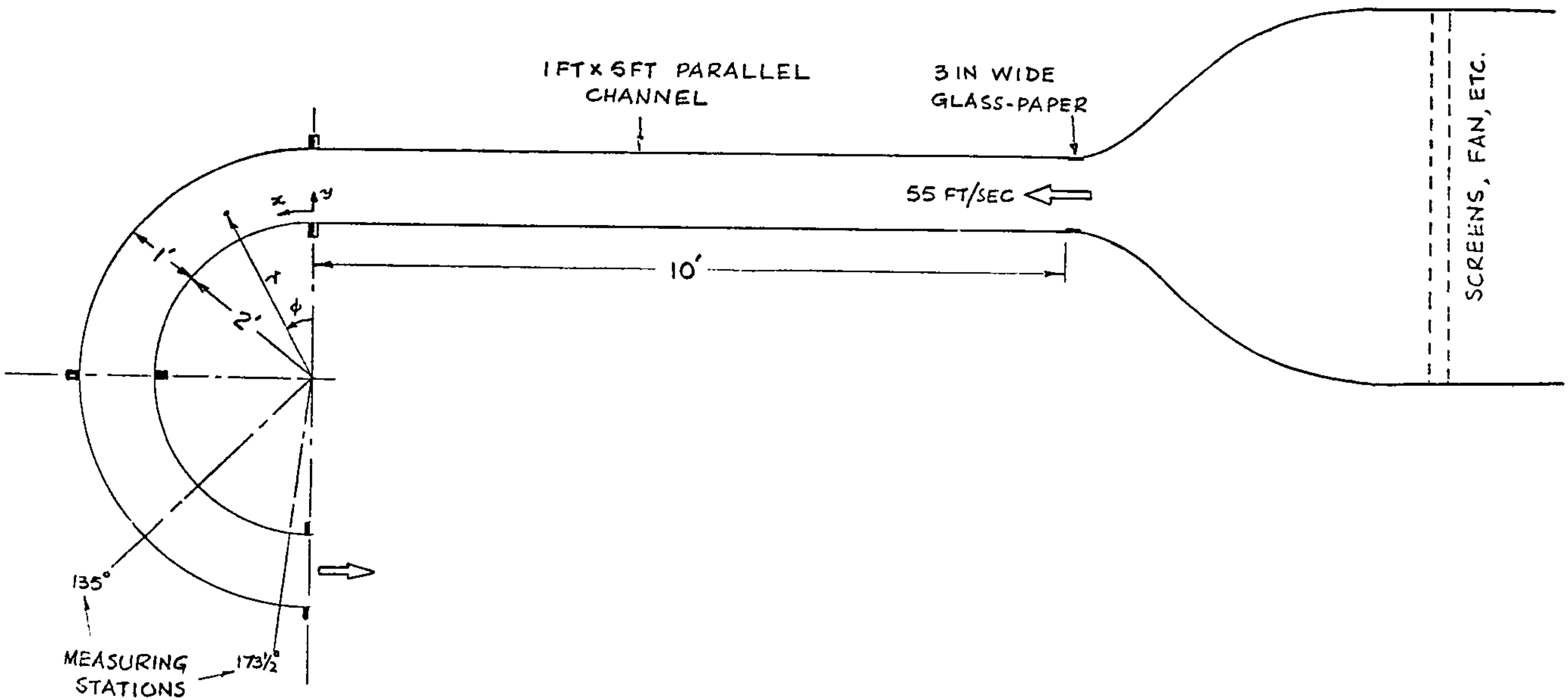
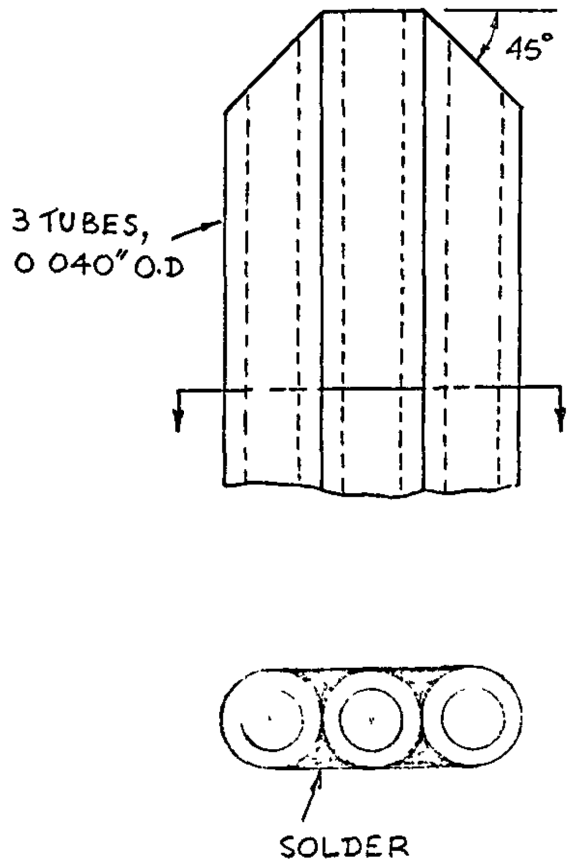
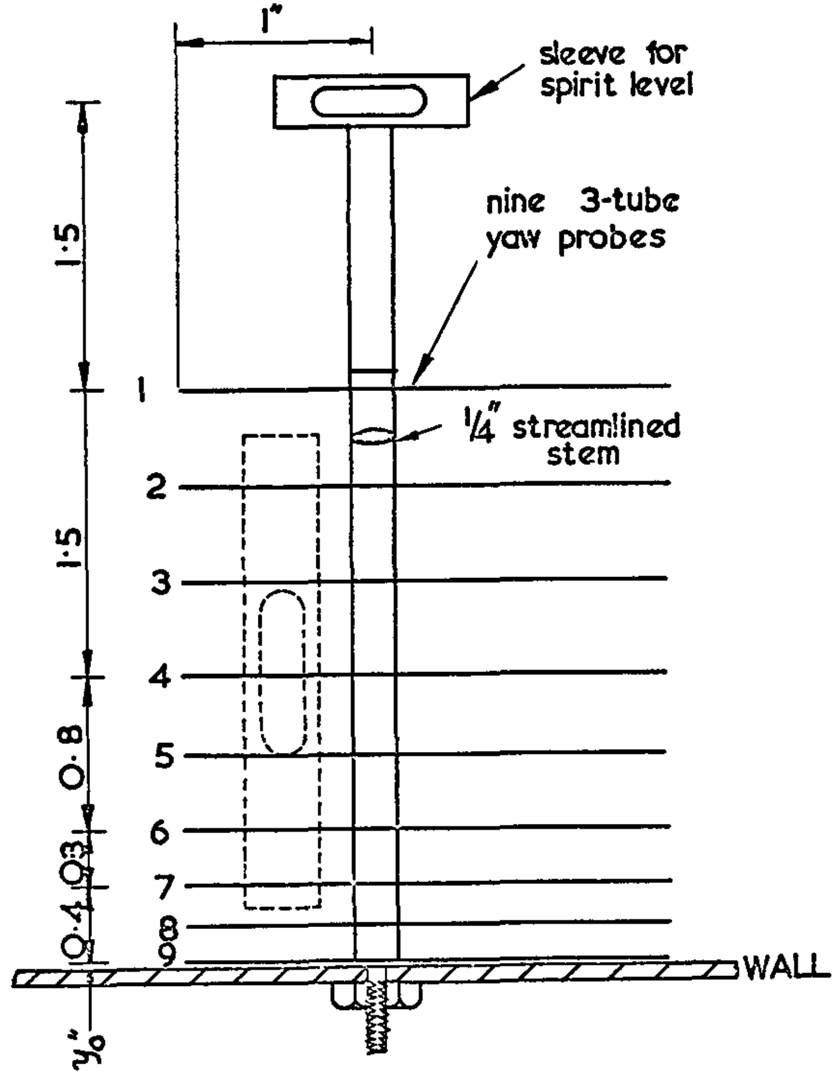


FIGURE 1 EXPERIMENTAL ARRANGEMENT.



DETAILS OF A TYPICAL YAW PROBE



RAKE OF YAW PROBES

FIGURE 2

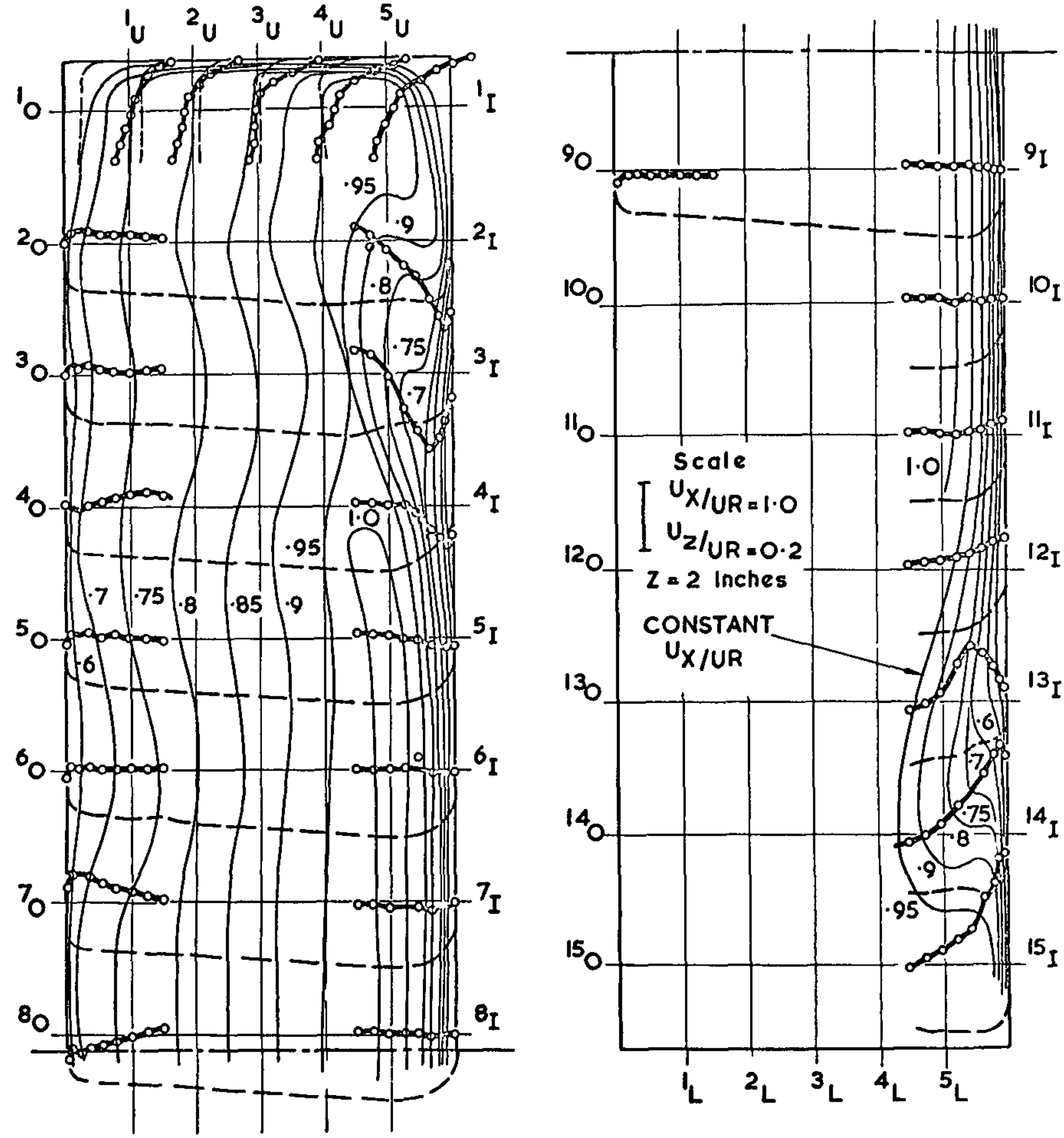


FIG. 3a CROSSFLOWS AND VELOCITY DISTRIBUTION IN THE 180° CURVED DUCT AT $\phi = 135°$

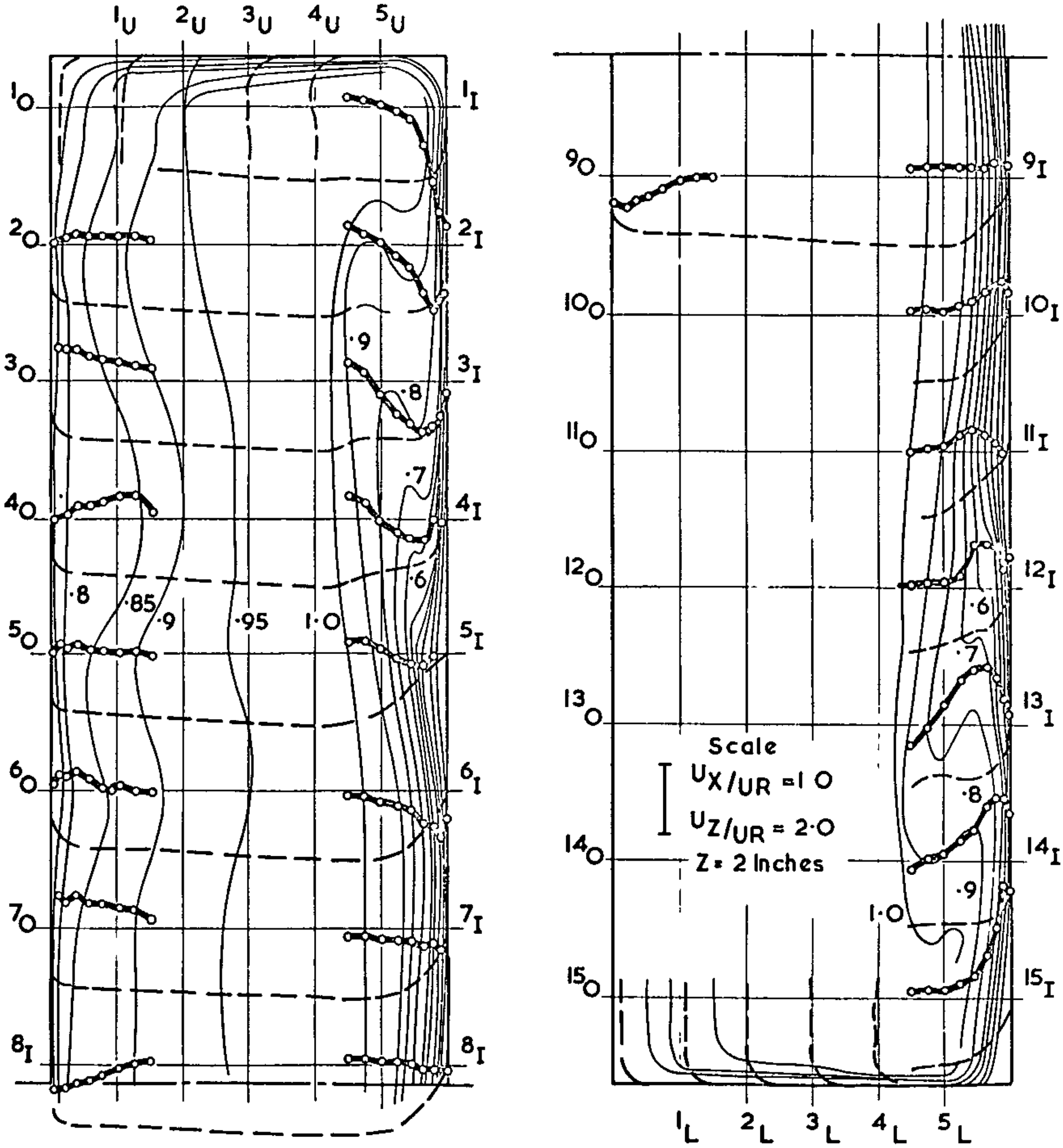


FIG. 3b CROSSFLOWS AND VELOCITY DISTRIBUTION IN THE 180° CURVED DUCT AT $\phi = 173\frac{1}{2}°$

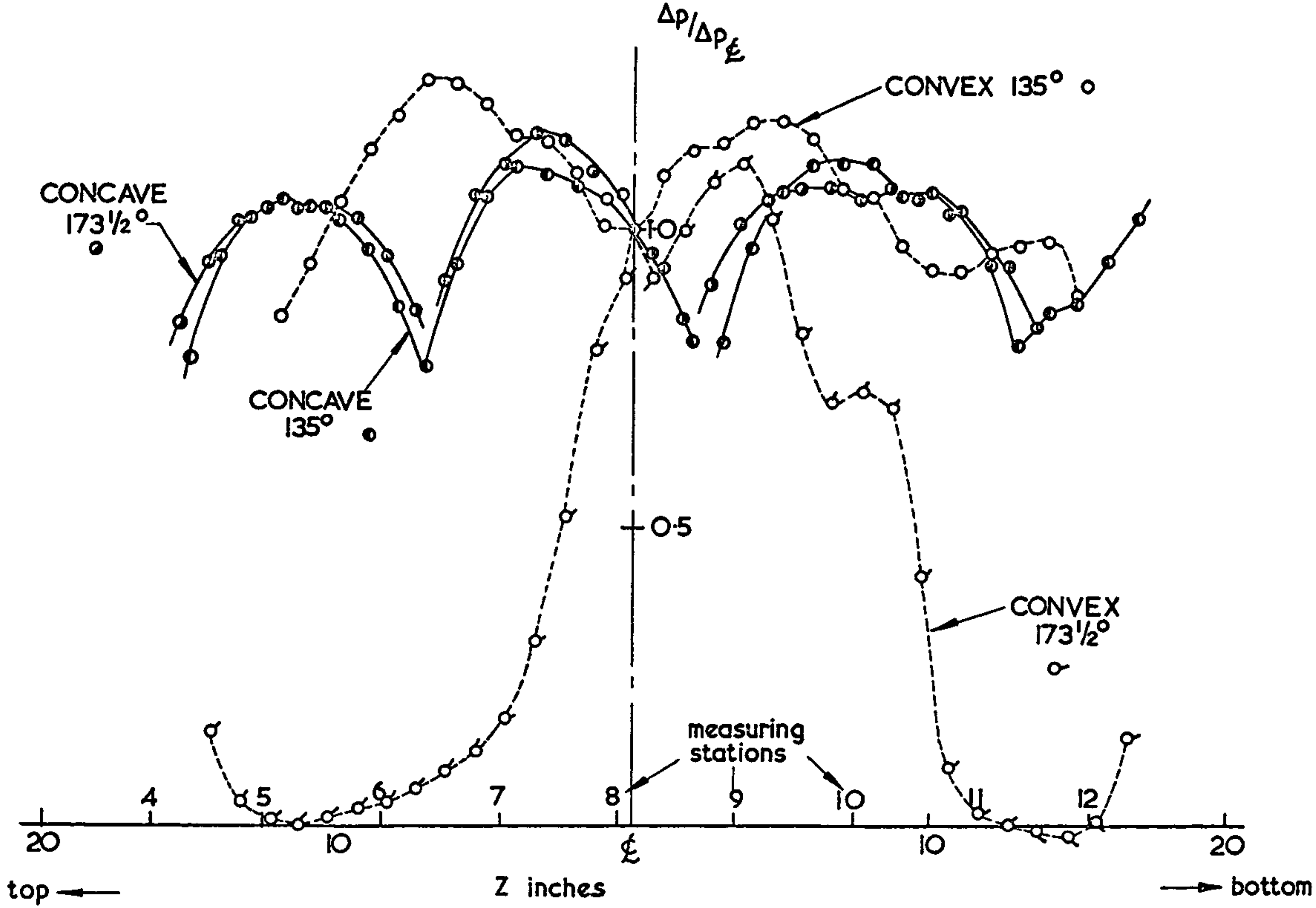


FIGURE 4. SPANWISE VARIATION OF PRESTON TUBE PRESSURE DIFFERENCE

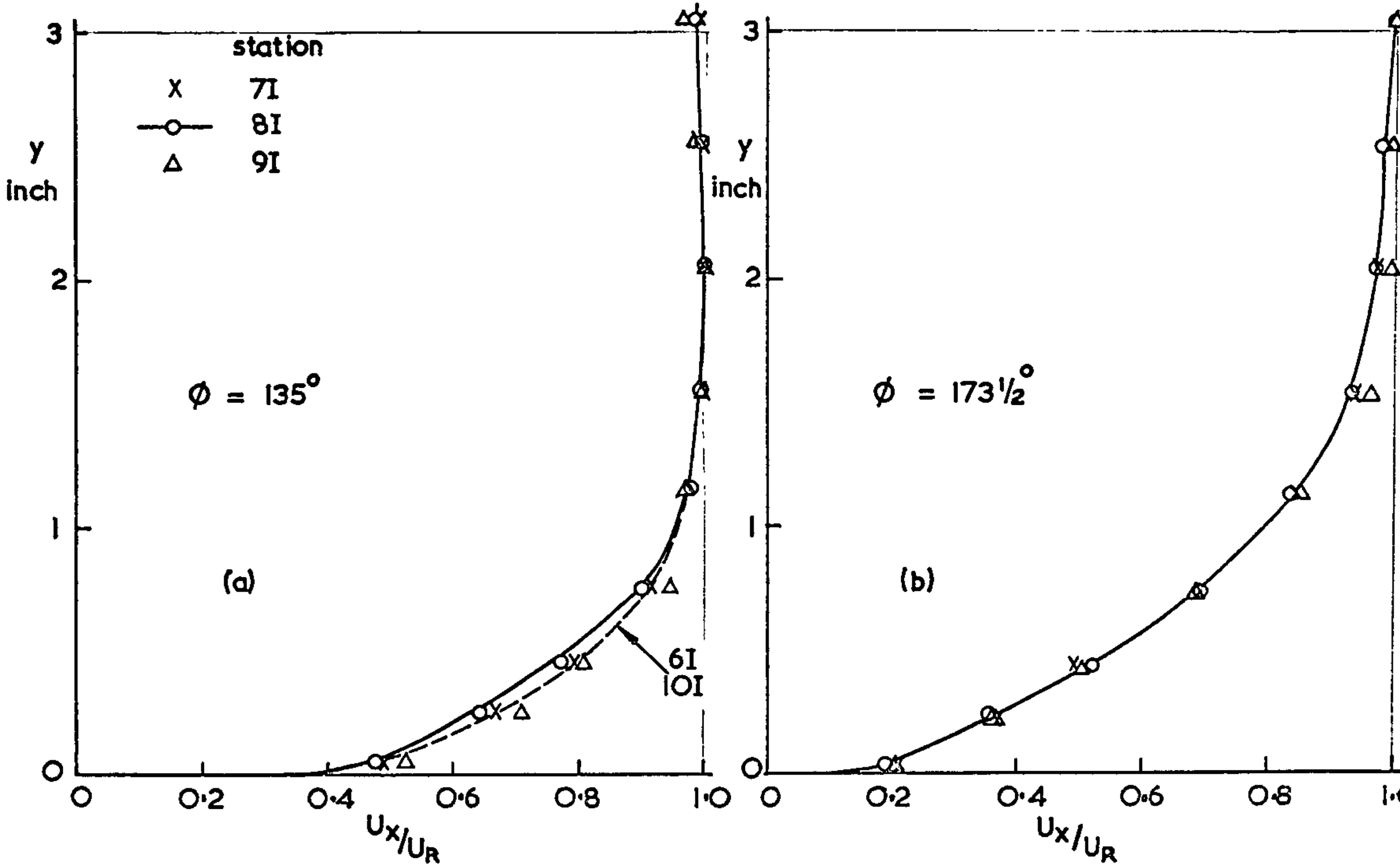


FIGURE 5. VELOCITY PROFILES IN CENTRAL REGION OF THE CONVEX WALL

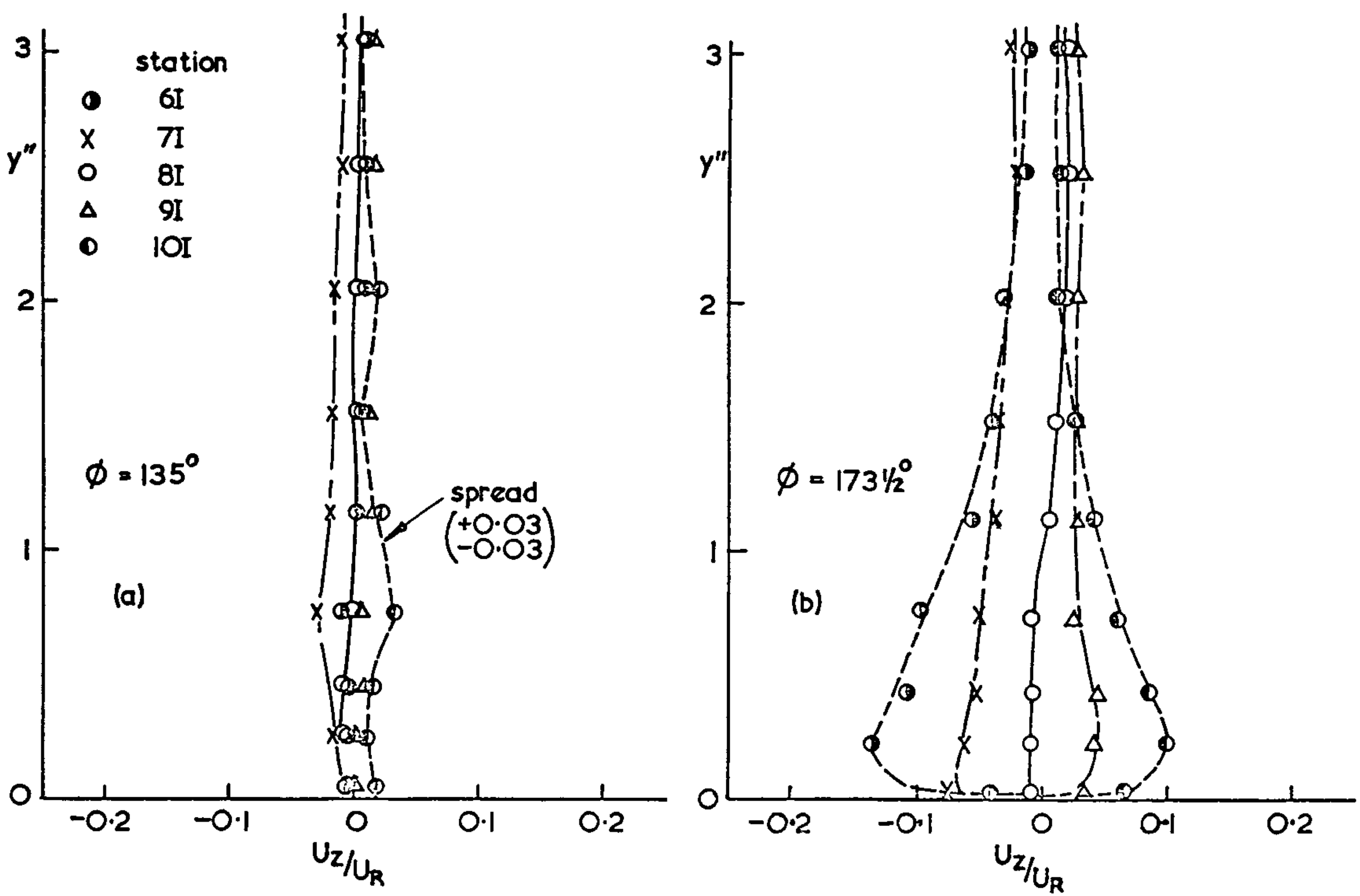


FIGURE 6. CROSS FLOW VELOCITY PROFILES IN CENTRAL REGION OF CONVEX WALL

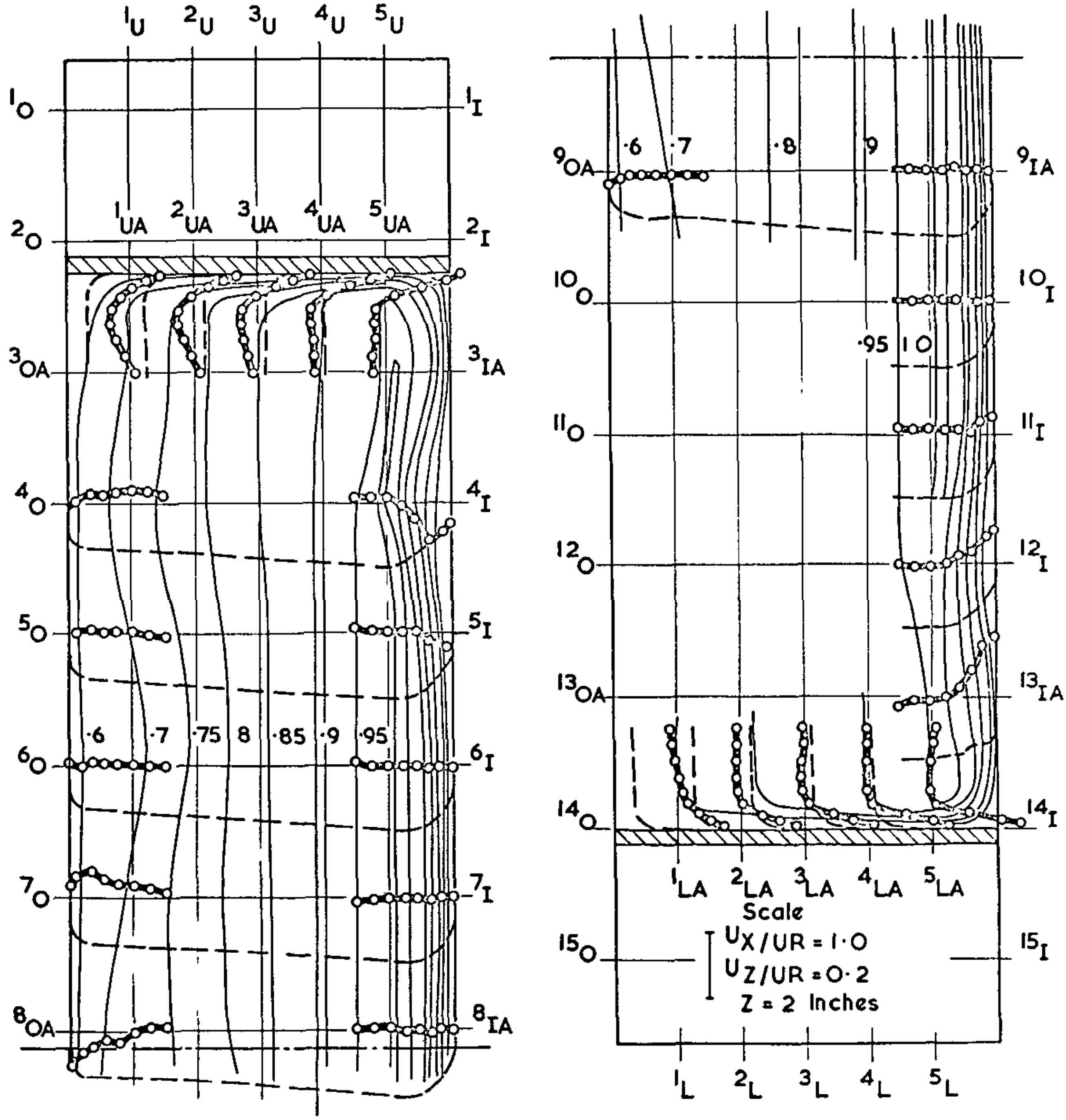


FIG 7a $0 < \phi < 180^\circ$ FALSE END WALLS, FLOW AT $\phi = 135^\circ$

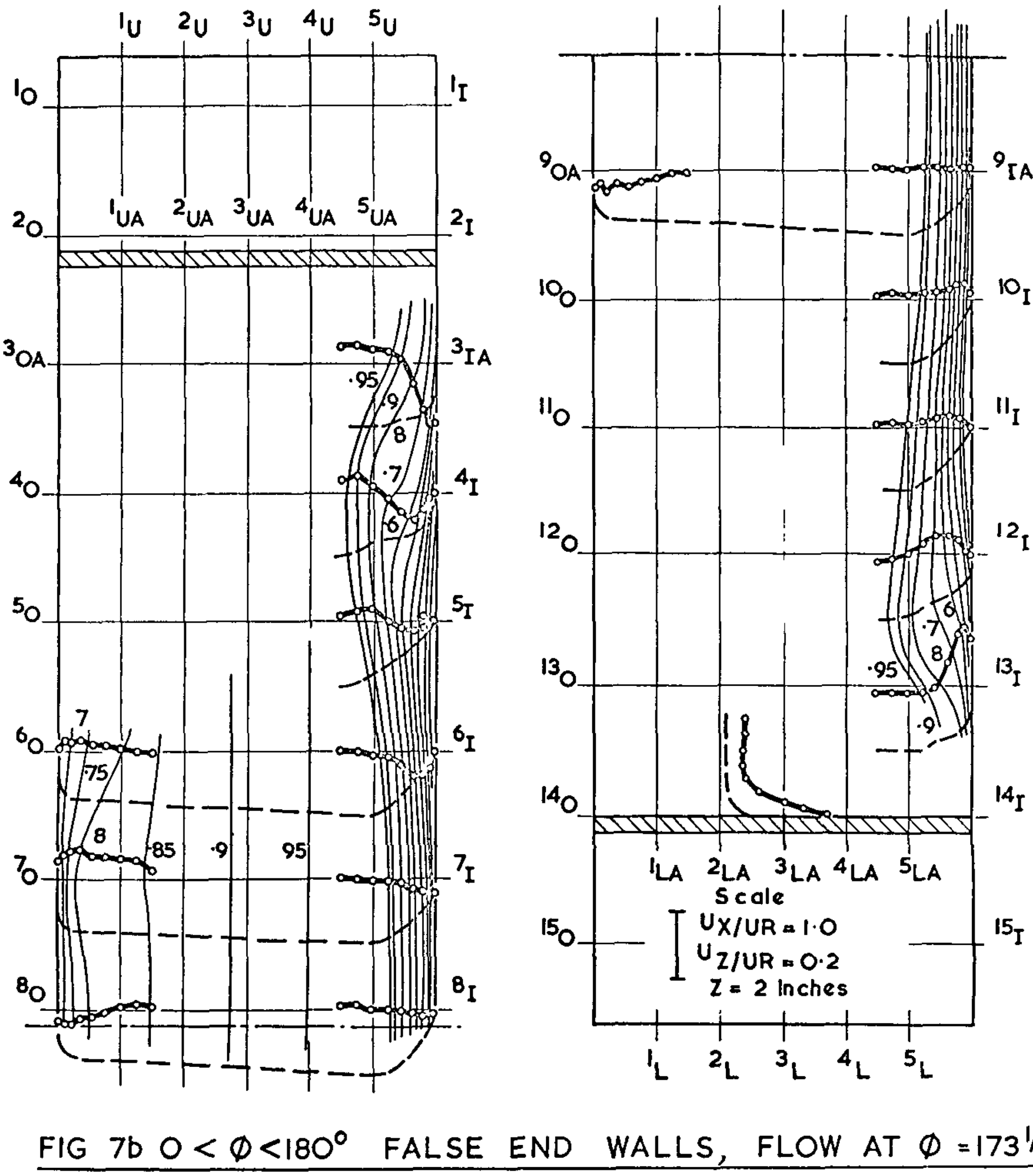


FIG 7b 0 < Ø < 180° FALSE END WALLS, FLOW AT Ø = 173½°

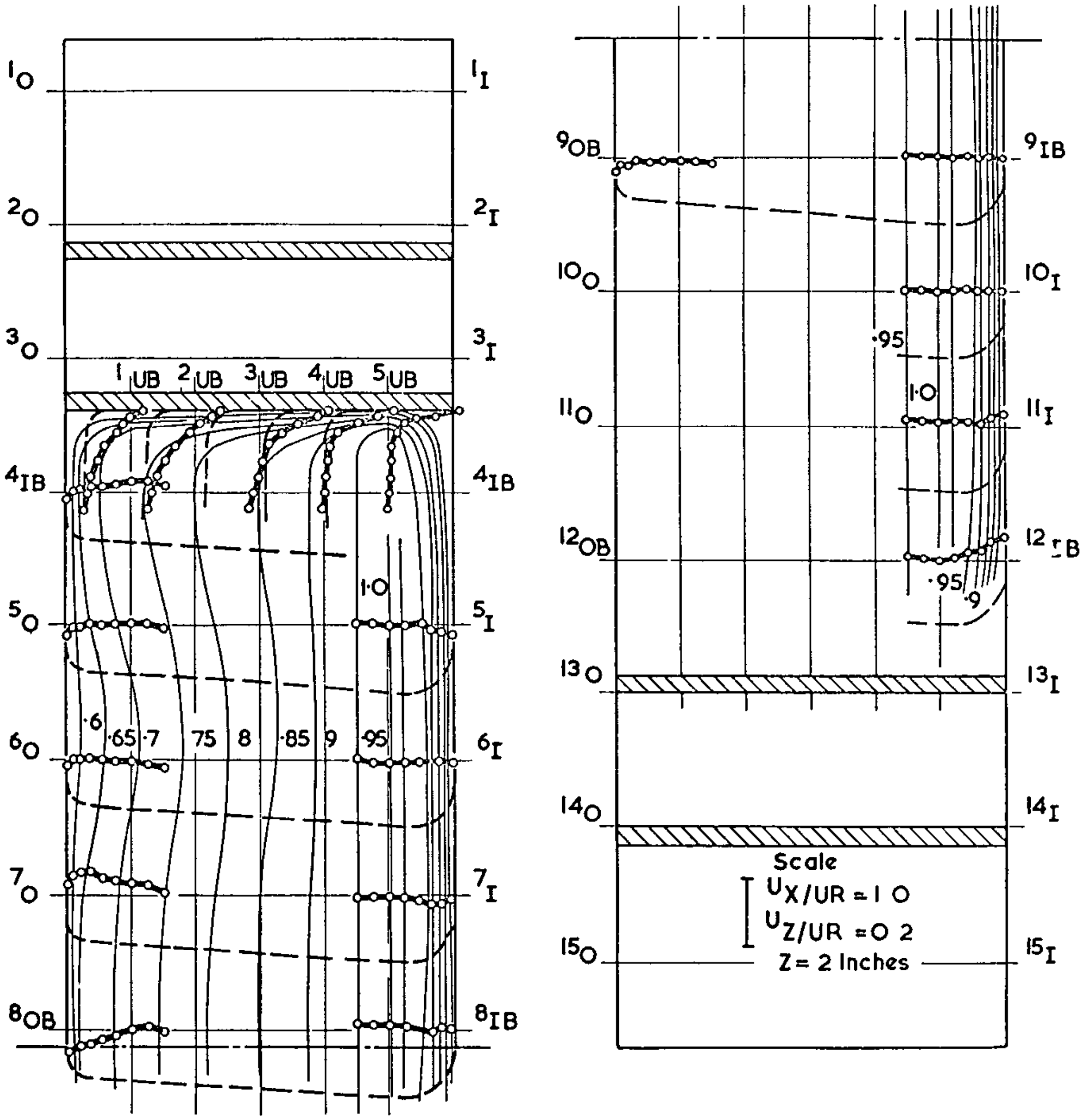


FIG. 8a $0 < \phi < 180°$ AND $90 < \phi < 180°$ FALSE END WALLS,
FLOW AT $\phi = 135°$

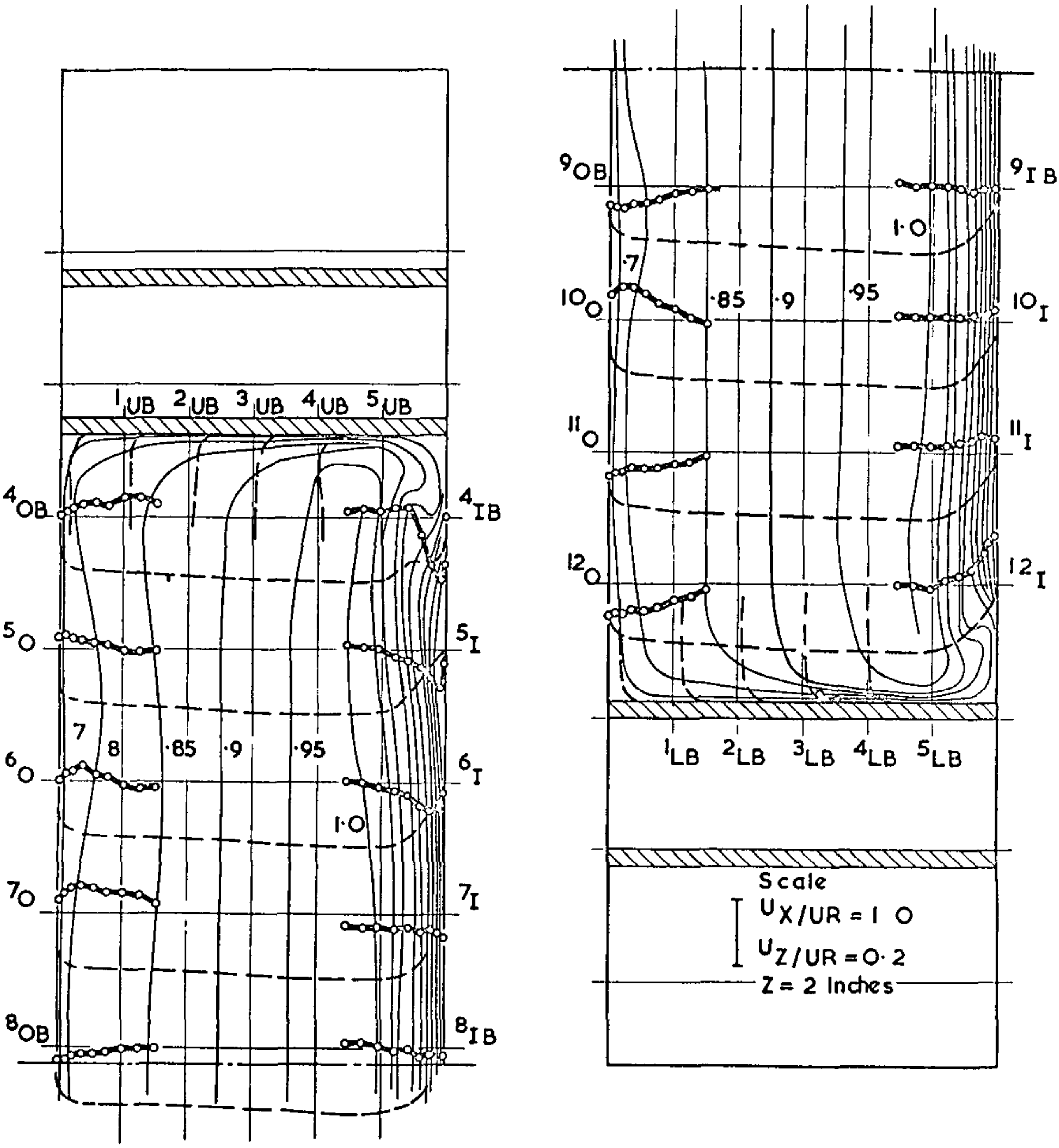


FIG. 8b $0 < \phi < 180°$ AND $90 < \phi < 180°$ FALSE END WALLS.

FLOW AT $\phi = 173\frac{1}{2}°$

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