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Three-Dimensional Disturbances in a Two-Dimensional Incompressible Turbulent Boundary Layer

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Summary.

Measurements in turbulent boundary layers have shown large transverse variations of skin friction. It appears that these are associated with three-dimensional disturbances originating in the transition region. The disturbances cannot be explained by irregularities in the damping screens and cannot be eliminated by fixing transition.

1. *Introduction.*

A number of experimental investigations during the past ten years have revealed three-dimensional flow phenomena in nominally two-dimensional boundary layers. These experiments have mostly dealt with those aspects of three-dimensional flow which appear in the laminar-turbulent transition region, e.g., papers by Schubauer[1], Fales[2], Hama, Long and Hegarty[3], Nickel[4], and Klebanoff, Tidström and Sargent[5]. The experiments described here were made in order to investigate further the development of the three-dimensional disturbances in the turbulent boundary layer shortly after the transition region and the variations of skin friction found by Head and Rechenberg[6] around the circumference of a pipe. Three-dimensional effects were observed, similar to those found by Schultz-Grunow and Hein[7], Gregory and Walker[8], Ginoux[9], and Favre and Gaviglio[10]† in different contexts.

As the problems became more complex in the course of the investigation it was only possible, due to the limited amount of time available, to answer a small number of the questions which arose. Experiments were made with three test arrangements in order to eliminate as far as possible any effects due to imperfections of the apparatus. The three arrangements used were

1. A cylindrical pipe with a developing turbulent boundary layer.
2. A flat plate with transition fixed by a trip wire.
3. A NACA 64010 aerofoil with free and fixed transition.

Some further qualitative observations were also made on the plane wall of a wind tunnel.

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* Replaces A.R.C. 24 131.

† Ref. 10 was obtained when this report was already finished.

2. *The Influence of Damping Screens on Three-Dimensional Disturbances.*

The results given in Ref. 1 suggested that in the work of Head and Rechenberg[6] the disturbances in the boundary layer, and hence the variations of skin friction around the circumference of the pipe, were due to irregularity of the screens in the entry and the dust unavoidably deposited on them. Some further experiments were therefore made, using essentially the same apparatus as that described in Ref. 6. This consisted of an entry funnel with a 9:1 contraction, leading to a copper pipe of 203 mm external diameter and a centrifugal blower. Changes in the material and the number of screens had already shown[6] that the circumferential variations of skin friction could not be eliminated. As can be seen from Fig. 1 not even a thorough cleaning by a vacuum cleaner could alter the main pattern of the variations, though the positions of some of the smaller-scale variations were changed. A repeat of this experiment two weeks later showed again a slightly different pattern. Small changes of this kind were observed several times but the pattern remained fixed over a sufficiently long time for the experiments to be completed. The variation of skin friction was measured by means of a sublayer fence[11, 6], which was calibrated against a Preston tube. During the experiment the pipe Reynolds number Re_D was kept constant and equal to $3 \cdot 48 \times 10^5$.

To see whether marked variations of skin friction also existed in other circumstances, measurements were made on a flat plate mounted in a wind tunnel, with transition fixed by a trip wire of diameter $0 \cdot 75$ mm located 120 mm from the leading edge. The distribution of skin friction in the spanwise direction was measured by means of a Preston tube[12] at four distances from the leading edge. Fig. 2 shows the variation in the spanwise direction z of the pressure difference between the Preston tube and an appropriate static hole at the edge of the plate. The distance x is measured downstream from the trip wire. These results give only a qualitative record of the changes of skin friction, because there may have been some spanwise variation of static pressure which would affect the results. The results suggest that the maximum amplitude and wave length of the disturbances increase with distance downstream. This result is also consistent with the earlier measurements in the pipe[6] though the amplitudes on the flat plate are much smaller. Finally, the series of measurements on an aerofoil confirmed the existence of spanwise variations of skin friction in a turbulent boundary layer. In the three experimental arrangements the gauze screens or honeycombs were different. Moreover Klebanoff[5] has shown that the three-dimensional disturbances are almost certainly created in the boundary layer itself and are independent of disturbances in the free stream. Also, Ginoux[9] has observed similar disturbances in the reattachment region of a laminar boundary layer, which were apparently not caused by irregularities in the screens. For these reasons it was assumed in the present work that further improvements and alterations to the screens would not be profitable and the investigation was continued on the assumption that the three-dimensional disturbances are created in the boundary layer.

3. *Transverse Variations of Skin Friction Following Free and Forced Transition in a Boundary Layer.*

As the work of Klebanoff[5] *et al.* has shown that three-dimensional disturbances originate in the transition region of a boundary layer it is reasonable to assume that these same disturbances are continued in the turbulent boundary layer further downstream. This would be consistent with the experimental results described here and would perhaps explain why the variations of skin friction in the pipe with natural transition[6] differed from those on the flat plate with forced transition. Thus both the amplitude and the wave length of the irregularities may be in some way dependent on the nature of the transition process. On the other hand Head and Rechenberg[6] found no evidence that any different transition device would produce a more uniform skin-friction distribution. The matter was therefore investigated further, using the same pipe as Head and Rechenberg.

As the position of the transition region in the entry funnel was unknown, several experiments were made with different transition devices in different positions to find a position ahead of the test section where transition could possibly be influenced. This position was finally found at the exit of the entry funnel. (The pipe Reynolds number was kept constant at $3 \cdot 48 \times 10^5$.) In trying different transition devices the object was to smooth the irregularities as much as possible in order to show the influence of the trip wire quite distinctly. Fig. 3 shows the least irregular of the various skin-friction distributions obtained. In this case a stainless-steel tube of $3 \cdot 02$ mm outer diameter was used as a trip wire. The measuring stations were at 560 and 1650 mm downstream from this position. The skin friction at the wall was measured by means of Preston tubes, their outer diameters being $1 \cdot 1$ mm and $1 \cdot 63$ mm. As before, the measured pressure difference was made dimensionless by dividing it by the dynamic pressure in the free stream. The skin-friction distribution at the same measuring stations after natural transition was used for comparison. Since the same measuring positions were used as in Ref. 6 it could easily be verified that the skin-friction pattern had not altered substantially after half a year had passed and the screens had been cleaned twice. The comparable range in Fig. 8 of Ref. 6 is situated between 2 and $6 \cdot 5$ in. By addition of the trip wire the maximum variation of the mean value could be reduced from 25% to $8 \cdot 2$%. Further experiments showed that no improvement in uniformity could be obtained by using larger trip wires, e.g. a wire of diameter $4 \cdot 22$ mm gave greater amplitudes than the 3 mm one. Thus there is some evidence that the strength of the disturbances depends on the size of the transition-fixing device, as found also in Ref. 3. If a critical height is exceeded, the three-dimensional disturbances seem to be increased by vortex shedding at the top of the wire as reported in Ref. 3.

From Fig. 3 it can be seen that with forced transition the skin-friction pattern at $x = 560$ mm is fairly well reproduced at $x = 1650$ mm, i.e. the disturbances appear to follow the configuration determined by the transition process without any large change. With free transition the behaviour is not as simple. In both cases, however, the maximum amplitude increases with distance downstream.

Further experiments were made on a NACA 64010 aerofoil. It was hoped to obtain more evidence from this, using the china-clay method to reveal the irregularities in the boundary layer. The wing had a chord of 1020 mm and its span of 710 mm extended across the working section of a wind tunnel. To obtain some quantitative information, the distribution of skin friction in a transverse (z) direction was measured with a Preston tube, both with free and with forced transition. Before the Preston tube was moved into a new position in a transverse direction it was lifted from the surface. The Reynolds number per metre, based on the velocity of the undisturbed stream, remained equal to $1 \cdot 44 \times 10^6$ throughout the measurements.

The china-clay patterns showed spanwise irregularities which might well have been related to the measured variations of skin friction, but the evidence from the china clay was not yet considered to be convincing and the photographs are therefore not reproduced here. Agreement between skin-friction measurements and china-clay pattern on a flat plate was found in Ref. 10.

In an attempt to obtain more information a small cylindrical roughness element was located immediately after the leading edge of the wing 200 mm from the centre-line. The increased skin friction in the resulting turbulent wake is clearly shown in Fig. 4. For the station $x/c = 0 \cdot 856$ the skin friction is smaller in the region of the wake than in the undisturbed flow because the boundary layer is thicker in the wake. Measuring station $x/c = 0 \cdot 45$ is situated in that part of the laminar region in which the three-dimensional disturbances have already grown rapidly and which is called stage two in Ref. 5. Of the three measuring stations used the greatest amplitudes are obtained at $x/c = 0 \cdot 635$; this is shortly before the flow becomes fully turbulent. In the range $+100 < z < +200$ the china clay showed that the laminar zone extended rather further downstream but in spite of the strong disturbances in the transition region the skin-friction distribution became more uniform towards the trailing edge.

The distribution of skin friction with forced transition is shown in Fig. 5. A steel tube of 1·1 mm o.d. was used as a trip wire, its position being 30·4 mm from the leading edge. The major transverse variations of skin friction are preserved over the chord of the wing, while the maximum amplitude increases from 7·6% to 20%. The peaks and valleys at $x = 0 \cdot 856$ in the range $-200 < z < +100$ are largely consistent between Figs. 4 and 5. The amplitudes are rather smaller after forced transition but the wave length is nearly equal for both types of flow.

4. *Distribution of Mean Velocity Across the Boundary Layer and Influence of an Adverse Pressure Gradient on the Skin-Friction Distribution.*

As shown previously for the transition region[5] and for the turbulent boundary layer[13] the transverse variations of skin friction are accompanied by variations in the velocity profiles. This tendency is confirmed by Fig. 6 which shows the transverse distribution of velocity in the pipe at five values of the distance y from the wall. In this case the boundary-layer thickness δ is about 10 mm and the maximum percentage variation of velocity increases as y decreases. In Ref. 5 a similar graph is shown for the transition region and in this case the existence of longitudinal vortices could be confirmed. Such longitudinal vortices in the turbulent boundary layer might provide an explanation for the transverse variations of skin friction. Experiments which were intended to give a qualitative picture of these possible vortices are described in Section 5.

A question yet to be explored was the way in which an adverse pressure gradient would affect the transverse distribution of skin friction and an experimental arrangement used by Head and Rechenberg[6] was used to investigate this. A plywood ring with a rubber sealing strip was fitted in the pipe downstream of the forward ($x = 560$ mm) measuring station. Measurements were made upstream of this ring and by moving the ring along the pipe the pressure gradient and skin friction at the measuring station could be adjusted as required. The skin-friction distribution was measured by means of a sublayer fence, so that it was possible to measure the skin friction even in the region of reversed flow downstream of the separation point. Fig. 7 shows the distribution of skin friction at five measuring stations in front of the step with natural transition. x is measured from the step in the upstream direction. The measured pressure difference is proportional to the skin friction and this was made dimensionless by dividing it by the dynamic pressure at $x = 1650$ mm in the centre of the pipe.* The adverse pressure gradient apparently does not change the wave length of the disturbance but the maximum amplitude increases from 26·5% for the flow without pressure gradient up to 464% close to separation. In this special case separation (as shown by zero skin friction) occurs along a curved line which seems to be determined further upstream by the transition process, at least as far as the wave length is concerned.

Velocity profiles were also measured at each station x, both on a peak and in a valley of the skin-friction distribution, four of which are shown in Fig. 8. To give an idea of the variations, the momentum thicknesses were evaluated for two of the profiles and these showed a remarkable

* Values of skin friction could be obtained by using a calibration curve sublayer fence—Preston tube.

difference. For station $x = 100$ mm the values are $(\delta_2)_{\text{Peak}} = 0{\cdot}88$ mm and $(\delta_2)_{\text{Valley}} = 1{\cdot}59$ mm. This variation is even larger than the one reported in Ref. 14, where it was first stressed—at least to the author's knowledge—that the boundary-layer thickness might vary strongly in a spanwise direction. From this it can be seen how arbitrary the starting value for a calculation of the turbulent boundary layer might be. It is obvious therefore that only average values for the boundary-layer thickness should be used if a comparison is to be made between measurements and calculations. Finally, Fig. 9 shows the influence of the Reynolds number on the skin-friction distribution. Within the range $2{\cdot}15 \times 10^5 \leqslant Re_D \leqslant 4{\cdot}2 \times 10^5$ which could be investigated with the available apparatus the Reynolds number hardly influenced the skin-friction pattern.

5. *Visualisation of a Turbulent Boundary Layer in a Plane Perpendicular to the Direction of Flow.*

Fig. 10 shows variations of skin friction on the plane wall of a wind tunnel as found by Rechenberg[13]. In order to study these variations in more detail, smoke was used to reveal the flow in the boundary layer using a technique developed by S. A. M. Thornley[15]. The light from an electronic flash bulb was concentrated into one plane perpendicular to the flow by means of two lenses and a slit of width $0{\cdot}635$ mm. The wind tunnel was of the 'blower' type, exhausting into the atmosphere, and photographs were taken with the camera axis inclined at a small angle to the direction of flow, so that the camera could be placed outside the stream. Smoke generated by smoke bombs or titanium tetrachloride was used to visualize the flow. Because of shortage of time only a few photographs could be taken and the optimum values of air velocity, smoke density and light intensity have not yet been found. The three photographs reproduced here (Figs. 11 to 13) give an indication of the type of flow which occurs. In all these the straight white line marks the wall of the wind tunnel and the pattern seen below this line is only a reflection. Figs. 11 and 12 were taken by introducing titanium tetrachloride into the boundary layer about 600 mm upstream from the plane of illumination. There was not enough time for the smoke to diffuse across the whole boundary-layer thickness so that it only shows the region near to the wall. Fig. 12 clearly indicates two longitudinal vortices, while Fig. 11 shows conglomerations of smoke which might be caused by the same flow phenomenon. Finally, Fig. 13 shows how the smoke appears when it is introduced 1830 mm upstream of the plane of illumination; in this case the upper boundary of the smoke is believed to be roughly at the edge of the boundary layer. Unfortunately, in the limited time available it was not possible to compare the flow photographs with measurements of skin-friction distribution and velocity components within the boundary layer.

6. *Conclusions.*

(1) The large variations of skin friction found in Ref. 6 were confirmed by using four different experimental arrangements and could not be explained by irregularities in the damping screens.

(2) The complete change in the pattern following a change from free to forced transition suggests that the origin of the skin-friction variations is closely connected with the transition process.

(3) An adverse pressure gradient considerably increases the amplitude of the variations of skin friction expressed as a percentage of the mean.

(4) The transverse variations of skin friction and dynamic pressure that were found in the boundary layers indicate that strong three-dimensional disturbances are usually (perhaps always) present in a nominally two-dimensional boundary layer. Smoke photographs suggest that these three-dimensional disturbances take the form of longitudinal vortices, the existence of which in the transition region has been previously demonstrated by Klebanoff *et al.*[5].

(5) The work described here must be regarded as incomplete and the conclusions are only tentative. If the conclusions are confirmed by further work, it will be necessary to reconsider much of the existing experimental data on turbulent boundary layers.

7. *Acknowledgements.*

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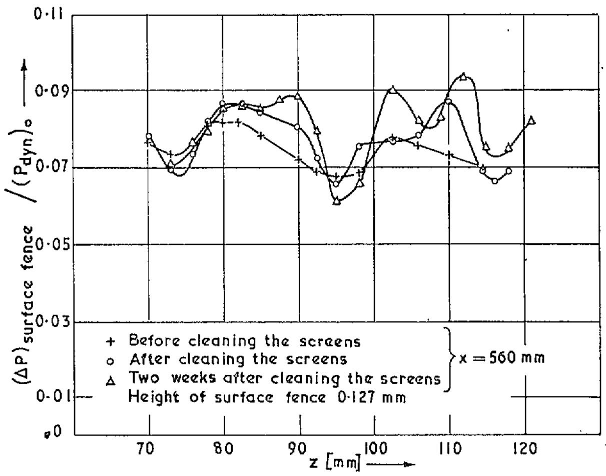

FIG. 1. Transverse distribution of 'skin friction' in a pipe as shown by a surface fence.

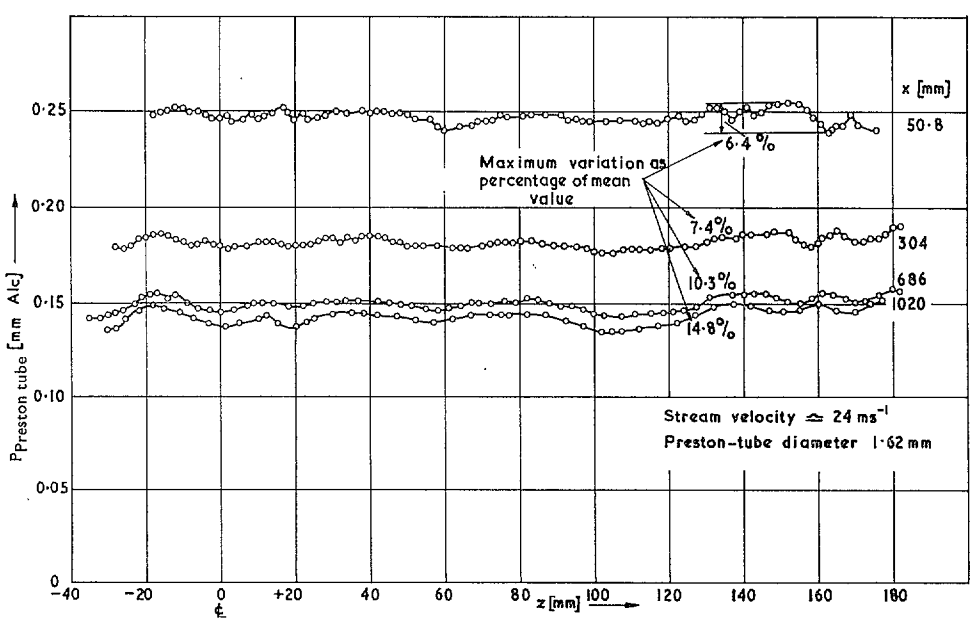

FIG. 2. Spanwise distribution of dynamic pressure close to the surface of a flat plate.

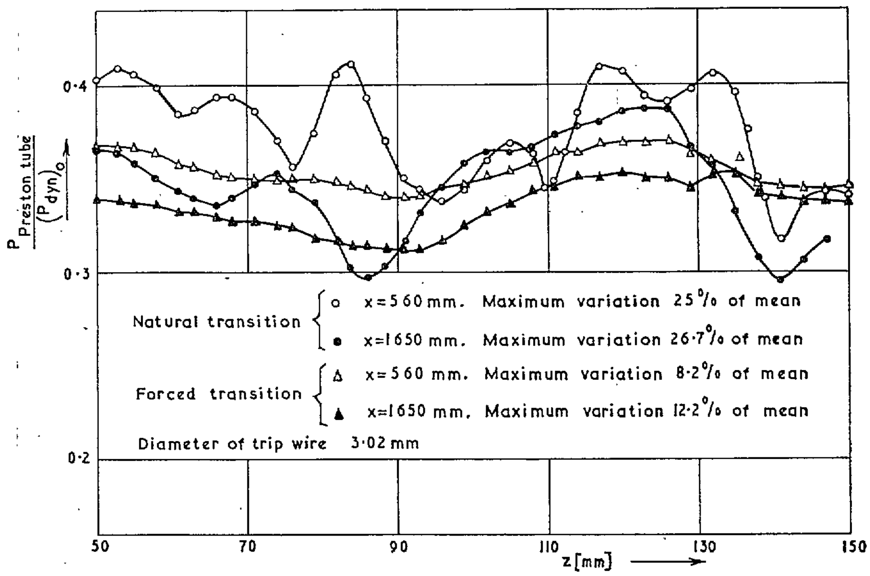

FIG. 3. Transverse distribution of dynamic pressure close to the wall in a pipe with natural and forced transition.

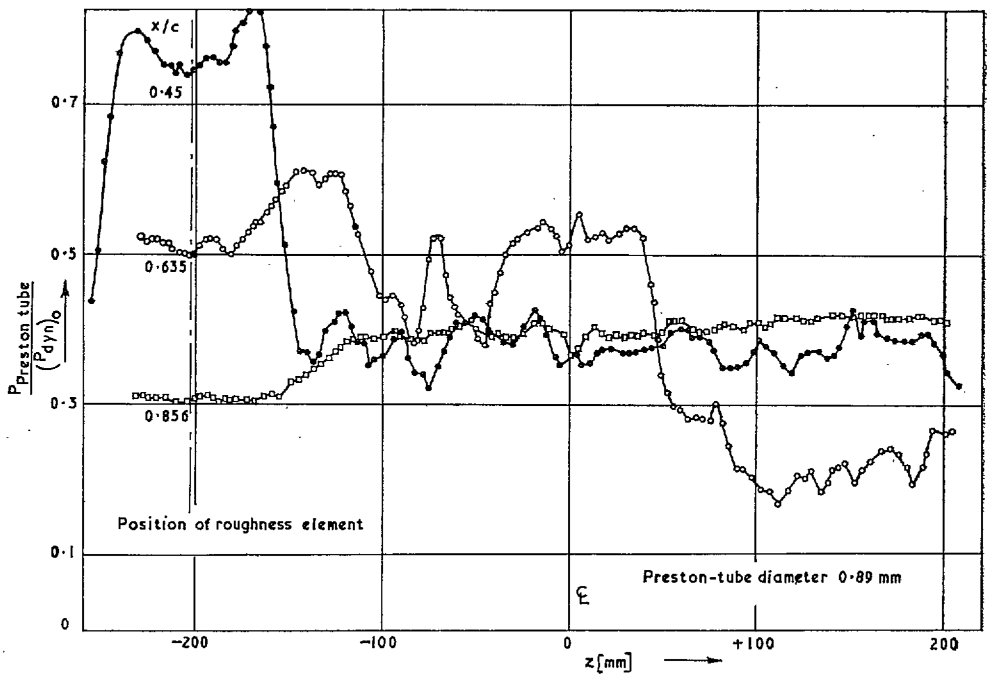

FIG. 4. Spanwise distribution of dynamic pressure close to the surface of a NACA 64010 aerofoil with free transition.

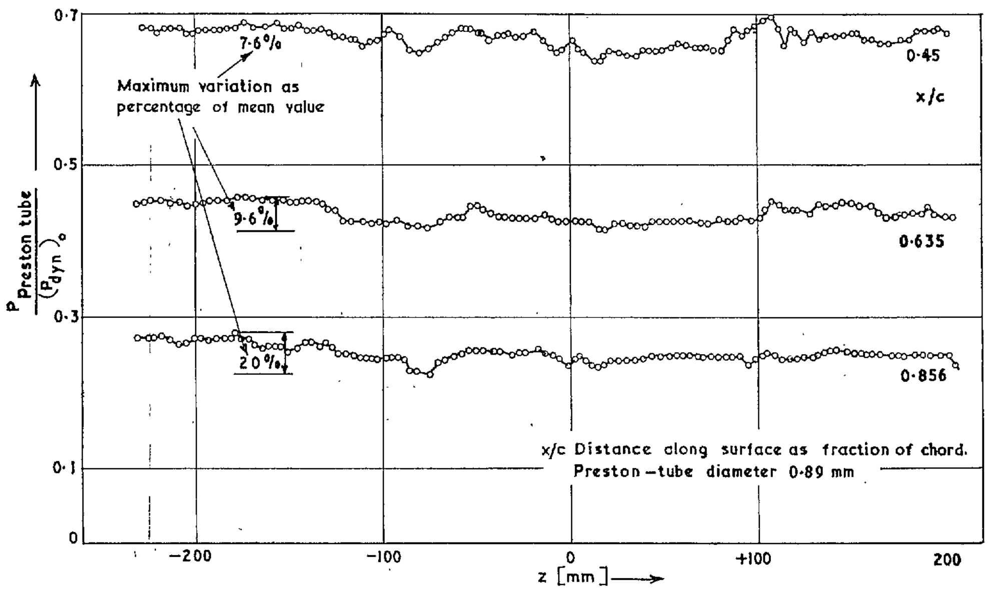

FIG. 5. Spanwise distribution of dynamic pressure close to the surface of a NACA 64010 aerofoil with forced transition.

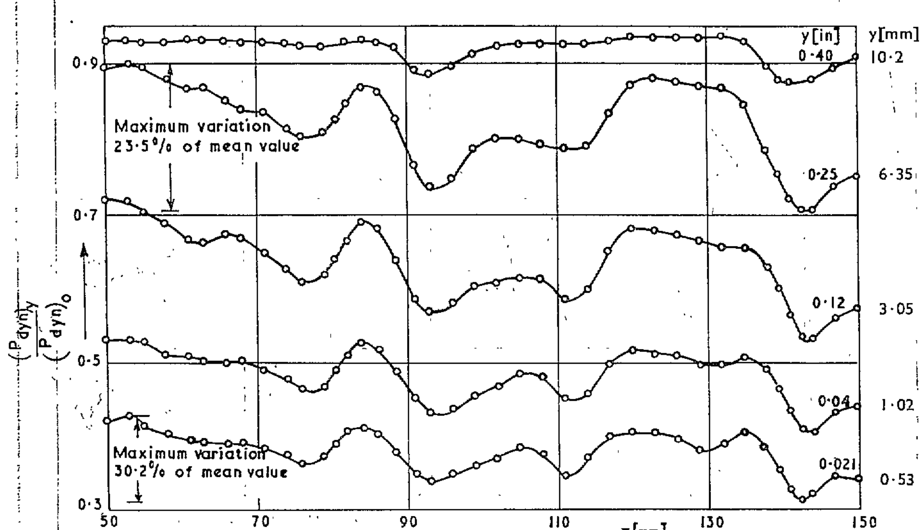

FIG. 6. Transverse distribution of dynamic pressure across a turbulent boundary layer in a circular pipe.

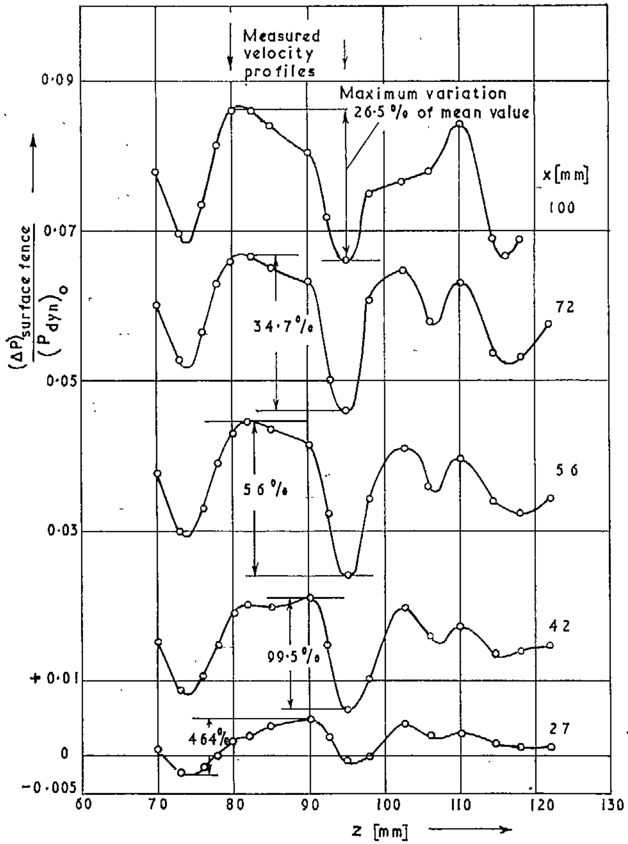

FIG. 7. Transverse distribution of 'skin friction' as shown by a surface fence in a pipe in a region of rising pressure ahead of a step.

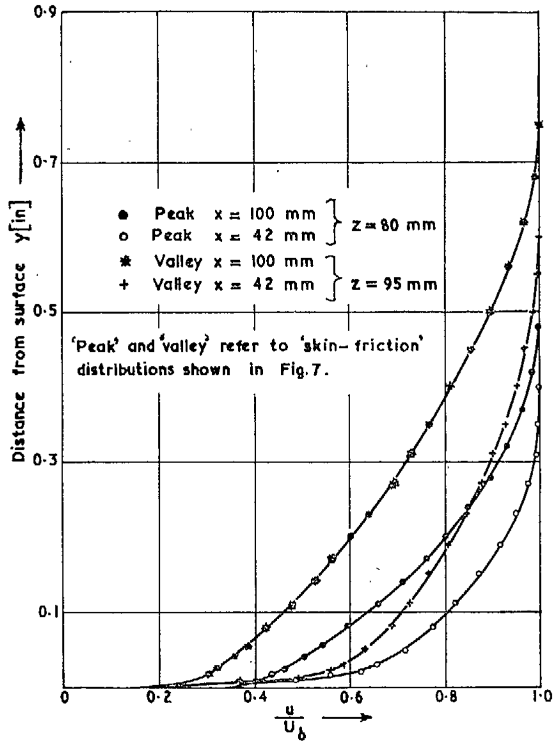

FIG. 8. Velocity profiles at peak and valley at two distances x ahead of a step.

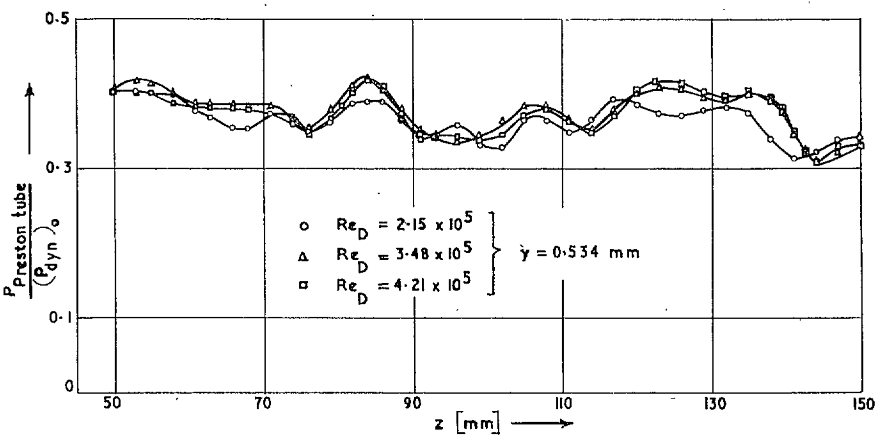

FIG. 9. Transverse distribution of dynamic pressure close to the wall of a pipe at three different Reynolds numbers.

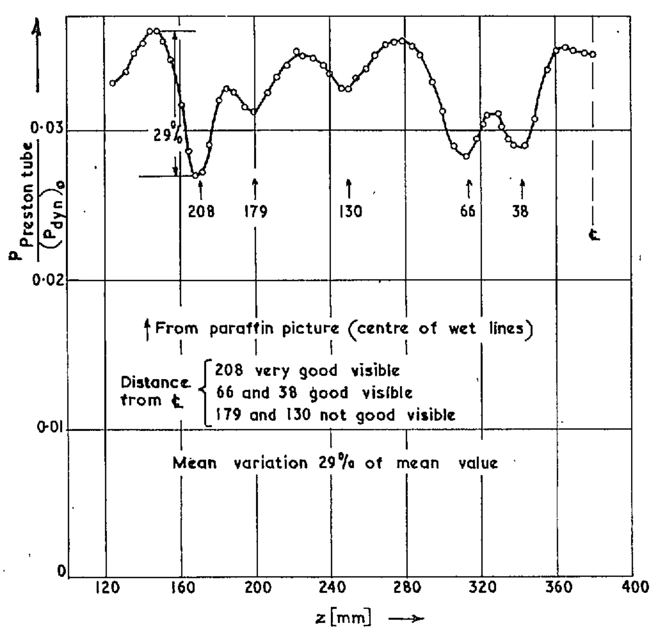

FIG. 10. Transverse distribution of dynamic pressure close to the wall of a wind tunnel.

(89085)

13

C

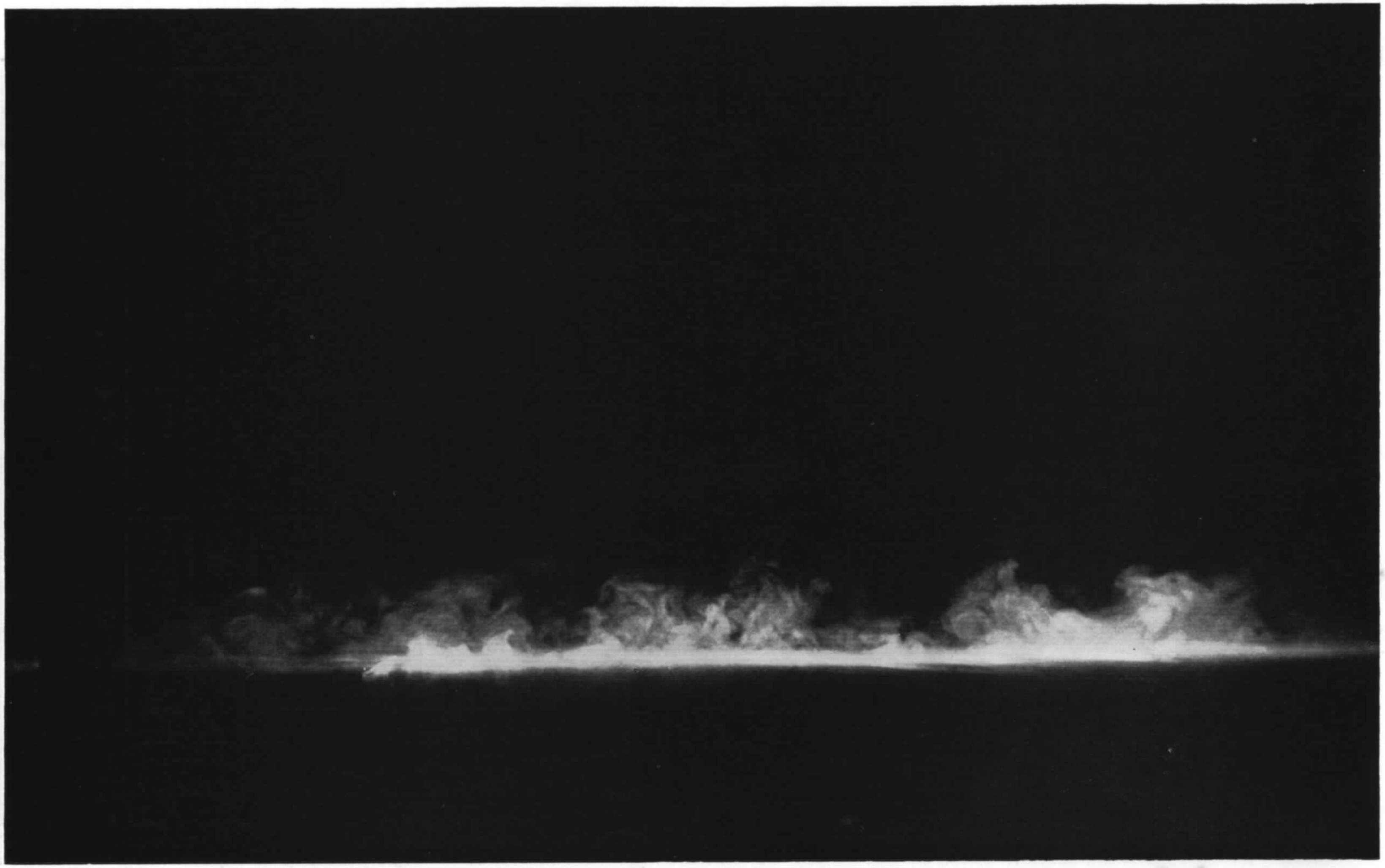

FIG. 11.

Fig. 12.

(89085) Wt. 65/1418 K.5 4/64 Hw.

FIG. 13.

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