The Preston tube as a means of measuring skin friction

By M. R. HEAD AND I. RECHENBERG*
Department of Engineering, University of Cambridge

(Received 29 March 1962)

Preston's method of measuring skin friction, which makes use of a Pitot tube resting on the surface, depends upon the assumption of a region of flow similarity, adjacent to the wall, common to fully developed turbulent pipe flow and the turbulent boundary layer. Experiments performed elsewhere have cast considerable doubt on the validity of this assumption, and the present investigation was undertaken to establish whether or not it is justified.

Experiments were carried out in a short length of large-diameter pipe which could either form part of a very much longer pipe, giving fully developed turbulent pipe flow, or could be preceded by a conventional contraction and screens, giving a developing turbulent boundary layer.

Final results showed that for a given skin friction the Pitot tube reading was the same for both boundary layer and pipe flows, thus vindicating Preston's method and confirming the existence of a universal region of wall similarity. Initial experimental difficulties were found to be due to unexpectedly large circumferential variations in skin friction in the growing boundary layer.

1. Introduction

Some eight years ago Preston (1954) published a method of measuring skin friction which promised to be both accurate and convenient. It depended upon the assumption that close to the wall in turbulent shear flow there exists a region in which the flow is substantially determined by the surface shear stress and the relevant properties of the fluid, independent of the nature of the outer turbulent flow and such quantities as pressure gradient and surface curvature.

By the application of dimensional analysis this assumption leads directly to the so-called universal inner law, or law of the wall, for the distribution of mean velocity in the wall region. This inner law is commonly expressed as

$$u/U_\tau = f(U_\tau y/\nu),$$

where $U_\tau = (\tau_0/\rho)^{\frac{1}{2}}$ and the function f is finally determined by experiment, though dimensional arguments and mixing length theory have been used to show that in the fully turbulent region (i.e. outside the laminar sublayer and transition zone) it should be logarithmic, as is found to be the case.

Instead of the mean velocity at a point close to the wall we may consider in the dimensional analysis the difference between the pressure recorded by a

---

* On leave from Hermann Föttinger-Institut für Strömungstechnik Technische Universität, Berlin.

Pitot resting on the wall and the local static pressure. If we call this pressure difference Δp and the Pitot diameter d, then the analysis shows that

$$\Delta p/\tau_0 = g(U_\tau d/\nu)$$

or, alternatively,

$$\frac{\tau_0 d^2}{\rho\nu^2} = h\left(\frac{\Delta p d^2}{\rho\nu^2}\right).$$

Clearly, either of these expressions gives us the means of determining skin friction, since for a Pitot tube of given geometry either of the functions g and h can be simply and accurately determined from pipe experiments, where the skin friction follows directly from the measurement of pressure drop. The Pitot tubes used by Preston were of circular section with a ratio of internal to external diameter of 0·6, and the calibration curve representing the function h was determined from measurements with four Pitot tubes of different diameters in a 2 in. pipe.

At the time when Preston proposed his method there was a considerable body of evidence to indicate that the function f defining the law of the wall was universal for fully developed turbulent flow in pipes and channels, but only the experiments of Ludwieg & Tillmann (1950) to show directly that it applied also in the wall region of the turbulent boundary layer. The evidence from pipe flow was in itself, however, such as to suggest that the similarity might well extend to the boundary layer, since between high and low Reynolds number pipe flows there is a very considerable variation in the ratio of pipe radius to laminar sublayer thickness, and in shear stress gradient across the pipe (in terms of $U_\tau y/\nu$). Thus it would appear that the universality of the inner law is substantially unaffected by transverse curvature of the surface, the magnitude of the favourable pressure gradient or the absolute thickness of the turbulent flow. Moreover, Preston's own experiments with Pitot tubes on the wall offered what at the time appeared to be conclusive evidence in favour of universality in the wall region of pipe and boundary-layer flows. Not only was the calibration curve (i.e. the function h) as determined in the pipe found to be independent of the Pitot tube diameter, as was to be expected, but also, when a series of Pitot tubes of widely different diameters were used at any particular station in the boundary layer, the values of skin friction determined by the use of this calibration curve were found to be identical.

Soon after Preston's method was published experiments were undertaken at the N.P.L. (Staff of the Aerodynamics Division 1958) to check its usefulness. Measurements were made of the skin friction along a flat plate using Pitots resting on the surface and Preston's calibration curve. These values were compared with the corresponding values obtained by differentiation of the overall surface friction determined by the wake-traverse method. An appreciable discrepancy was found, indicating that the surface Pitots underestimated the skin friction by some 14 %. On the other hand, experiments by Hsu (1955) at the David Taylor Model Basin, carried out at about the same time, appeared to confirm the accuracy of Preston's method. Boundary-layer velocity profiles were measured in both zero and adverse pressure gradients, and the corresponding Preston tube readings recorded. In zero pressure gradient Landweber's numerical results relating R_θ and c_f were used to obtain skin friction values from the measured profiles, and in adverse pressure gradients Ludwieg and Tillmann's formula relating c_f, R_θ and H was used in the same way. The skin-friction values thus obtained were found to be in excellent agreement with those given by Preston's method.

At Preston's suggestion further experiments were then undertaken at Cambridge by Dutton (1956). Boundary-layer velocity profiles were measured along the centre line of a flat plate, and the measured rate of growth of momentum thickness was compared with that found by the use of the momentum equation with skin-friction values found by Preston's method. Five such comparisons were made; three showed excellent agreement and, of the remaining two, one gave the experimental values too high and the other too low by about the same margin. Although this method of measuring (or checking) skin friction is not a particularly accurate one, the experiments were conducted with great care, and it was considered that consistent discrepancies in the region of 5 or 10 % should have been readily apparent. These results appeared to confirm the accuracy of Preston's method but subsequent experiments were again to throw considerable doubt upon it.

At the N.P.L., Bradshaw and Gregory (Staff of the Aerodynamics Division 1958) carried out further experiments, in which the values of skin friction given by a Preston tube were compared with the corresponding values obtained by using a Stanton tube calibrated in a rectangular duct. An 11 % discrepancy was observed. Again, in America, Smith & Walker (1958) measured skin friction on a flat plate both directly by the use of a floating element and by means of Preston tubes and obtained a result almost identical to that of Bradshaw and Gregory. They further concluded from their experimental results that the constants A and B appearing in the logarithmic portion of the inner law were functions of Reynolds number.

At this stage then the experimental evidence, though conflicting, seemed to weigh heavily against the validity of Preston's method for measuring skin friction (at least in the form originally proposed) and against the existence of a universal inner law for pipe and boundary-layer flows. Yet the concept of a universal inner law and general similarity in the wall region was intuitively so appealing and provided such a notable and much needed simplification to the theory of turbulent shear flows that it seemed that it should be abandoned only if the evidence against it were quite clear-cut and decisive. The experiments to be described were intended to provide just such direct evidence either for or against the validity of Preston's method and the assumption of universal wall similarity upon which it was based.

2. General description of experiments

The idea behind the present experiments was a simple one; if a given Preston tube gave the same readings in pipe and boundary-layer flows for the same values of the skin friction then the method would be justified, and if not, not. Preston's original calibration of the surface Pitots in the pipe might still of course be open to question but this could be treated as a separate issue. The answer to the experimental difficulty of determining just when the values of skin friction in pipe and boundary-layer flows were identical appeared to lie in performing both sets of experiments in a short length of large-diameter pipe in which a Preston tube and a Stanton tube could be fitted side by side, the Stanton tube, if sufficiently small, giving an accurate measure of skin friction. This test section could be preceded either by a long pipe of the same diamter, giving fully developed pipe flow at the measuring station, or by a conventional contraction with screens, giving a developing turbulent boundary layer of relatively small thickness. The method of conducting the tests would simply be to determine, for each type of flow, the Stanton and Preston tube readings corresponding to different rates of flow. If then, on plotting Preston tube readings against Stanton tube readings for each type of flow, it were found that the two sets of points lay on a single curve then Preston's method could be said to have been justified. If, on the other hand, two different curves were obtained, one for the pipe and one for the boundary layer, then obviously the assumption of universal wall similarity could not be maintained.

The advantages of carrying out the experiment in this way were that the Stanton and Preston tubes were not disturbed in proceeding from the pipe to the boundary-layer experiments, and that there was no necessity for an absolute calibration of the Stanton tube; all that was required was that it should lie well within the laminar sublayer so that it could be accepted as giving a reliable measure of the skin friction. It could of course be objected that the boundary-layer measurements were carried out on a wall with transverse curvature instead of on a plane surface; but since the radius of curvature of the pipe was large compared with the boundary-layer thickness and since experiments could be carried out with different ratios of boundary-layer thickness to pipe radius this did not seem to be an objection of great importance.

3. Experimental arrangement

Figure 1 shows the general layout and some of the details of the original experimental arrangement, which was assembled largely from existing components. Certain relatively minor modifications were subsequently introduced and will be discussed in later sections. The test section, which was 8 ft. long, consisted of an 8 in. diameter drawn copper tube with $\frac{1}{8}$ in. wall thickness, maintained accurately circular in section by a series of steel clamps. The tube which preceded the test section for the pipe experiments was of light-gauge galvanized sheet steel and had been used as ventilation trunking. The Preston and Stanton tubes could be fitted at either of two stations in the test section and were $\frac{3}{4}$ in. apart with their mouths in line with two static pressure tappings. The shaped entry, which could be fitted either directly to the test section or at entry to the extended pipe, was of fibreglass and resin and had a 9:1 contraction ratio. At the downstream end of the contraction a serrated transition ring was fitted. The centrifugal pump at exit gave a maximum velocity through the pipe in the region of 120 ft./sec, the flow being controlled by a shutter at the pump outlet.

The surface Pitot tube used in the initial experiments had an external diameter of 0·0544 in. and was one of those originally used by Preston. In later experiments tubes of different diameters were used, the diameters being indicated on the appropriate figures. With the Preston tubes, unless they were of very small diameter, a normal laboratory manometer gave sufficient reading accuracy, though for convenience a Betz manometer was used in the later experiments. Stanton tube readings were invariably made using a micromanometer which was probably accurate to ± 0·01 mm. During the initial stages of the investigation, isolated readings were checked with the leads to the manometers reversed, in order to determine whether asymmetry of the manometers and of the pressure connexions to them had any appreciable effect on the mean readings recorded in turbulent flow. As no change in the magnitudes of the readings could be detected it was concluded that the effect was negligible.

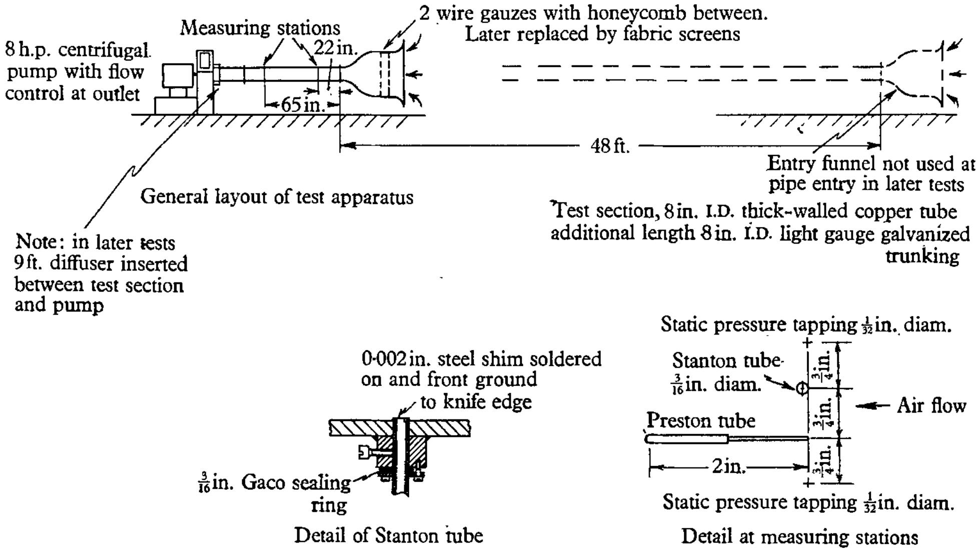


FIGURE 1. Layout and some details of experimental arrangement.

The general procedure followed in using the Stanton tube was to adjust its height to give a convenient reading at maximum velocity and to clamp it in this position. Measurement of its height above the surface by the use of feeler gauges could only be approximate but should probably be accurate to ± 0·001 in.

4. Detailed account of experiments

Initial experiments were carried out by the first author early in 1959. Excellent agreement between pipe and boundary-layer measurements was obtained at the first measuring station 22 in. along the test section; but when, as a check, the experiment was repeated at the second station 65 in. along the test section, two quite separate curves were obtained for pipe and boundary-layer flows and the observed discrepancy was similar to that which the N.P.L. and Smith & Walker's results would have predicted. Such conflicting results from an apparently straightforward experiment which could have been expected to give a decisive answer was disconcerting, and as no remotely plausible explanation could be advanced the experiment was set aside until a detailed investigation could be undertaken. The opportunity arose when the second author arrived in England in February 1961 and the experiments were then resumed.

The test arrangement was improved by fitting a 9 ft. long diffuser downstream of the test section, and for the pipe experiments an additional 8 ft. length of drawn copper tube was provided between the test section and the sheet metal trunking, so increasing the length of accurately circular and smooth pipe upstream of the measuring stations. It should perhaps be pointed out that the sheet metal trunking, while being nominally of the same internal diameter as the copper tube, was not accurately circular nor were the joints between sections particularly smooth. It seemed unlikely that this should be of importance, and indeed if the results of the initial experiments had been consistent it is unlikely that these imperfections would have received any attention. In the circumstances, however, it seemed important to eliminate even the most unlikely sources of inconsistent behaviour. To ensure that swirl originating in the centrifugal fan could not influence conditions upstream a honeycomb was fitted in the diffuser downstream of the test section, and, to improve conditions in the developing boundary layer, a more accurate serrated transition ring was made and fitted at outlet from the contraction. The arrangement of Stanton and Preston tubes and static pressure tappings in the test section was unaltered.

First results, at the measuring station 22 in. from entry to the test section, showed fair but by no means perfect agreement between pipe and boundary-layer flows. To find out whether there were appreciable departures from axial symmetry, four Preston tubes $\frac{1}{4}$ in. in diameter were fitted at 90° intervals around the pipe at the same 22 in. distance downstream of entry. It was evident that the flow was far from being axisymmetric in the case of the developing boundary layer since the readings of the four tubes differed by up to 20 %. It seemed likely that the irregularities were associated with variations in the inlet flow, and accordingly the gauze screens and honeycomb were removed and replaced by fabric screens of higher resistance. Several different materials were tried, the best results being obtained with four layers of brushed nylon fabric, supported on a single wire gauze screen. The differences between the readings of the four tubes were now substantially reduced and on repeating the original experiment at the 22 in. station it was found that the Preston tube readings in pipe and boundary layer were extremely close. Readings at 65 in., however, still showed marked disagreement and when eight equally spaced Pitots were fitted around the circumference at this second station the readings which they gave again differed by almost 20 %. Different screens were tried, and whilst the irregularities could be altered it did not appear that they could be greatly reduced. Different transition devices were also tested but without producing any noticeable improvement in the flow.

At the time then, all that seemed to be established was the extreme difficulty, if not the impossibility, of achieving axisymmetric conditions in the growing boundary layer. By means of a surface-film technique using yellow pigment suspended in light machine oil (Maltby & Keating 1960) a visible record was obtained of the mean flow direction at the surface. This indicated that in spite of the lack of axial symmetry the flow was in fact as nearly as could be determined parallel to the axis.

One possibility remained to be explored. All the inconsistencies so far observed might be explained if the skin friction varied sufficiently rapidly around the circumference of the pipe in either the pipe or boundary-layer flows, though the magnitude of the observed discrepancies (which amounted in some cases to as much as 20 %), combined with the fact that the Stanton and Preston tubes were separated by only $\frac{3}{4}$ in. (in a total pipe circumference of approximately 25 in.) made it seem unlikely this should be the case.

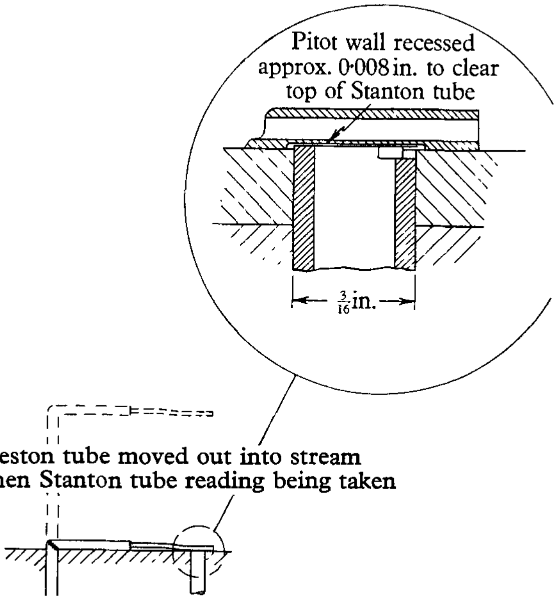


FIGURE 2. Arrangement of Stanton and Preston tubes at same circumferential position. The same arrangement was used with the sublayer fence.

It was initially suggested that runs in pipe and boundary layer should be repeated, first with the Stanton and Preston tubes in their existing positions, then with these positions reversed. If any observed discrepancy between pipe and boundary-layer results were then also reversed it would appear almost certain that variations in skin friction around the circumference of the pipe, occurring in a repeatable fashion, were the cause of the difficulties which had been encountered. But before this proposed experiment could be carried out, a more direct solution to the problem presented itself; it consisted simply in making the Stanton and Preston tube measurements at virtually the same position in the pipe. The scheme, as illustrated in figure 2, was made possible by the extremely small height of the Stanton tube compared with the diameter of the Preston tube. The experimental procedure, though still quite straightforward, was at first complicated by the the necessity for carrying out separate runs to obtain the corresponding readings of the Preston and Stanton tubes. This presented no great difficulty, as fixed openings of the shutter fitted to the outlet of the pump were found to produce repeatable flow conditions as determined by the pressure drop along the test section and by a three-quarter-radius Pitot fitted at its downstream end. The test procedure was, however, considerably simplified when it was found unnecessary to remove the Preston tube from the test section when the Stanton tube readings were being taken. These readings were shown to be unaffected by the presence of the Preston tube so long as it was pushed well out into the flow, away from the wall. Thus the readings of both Preston and Stanton tubes could be obtained on a single run.

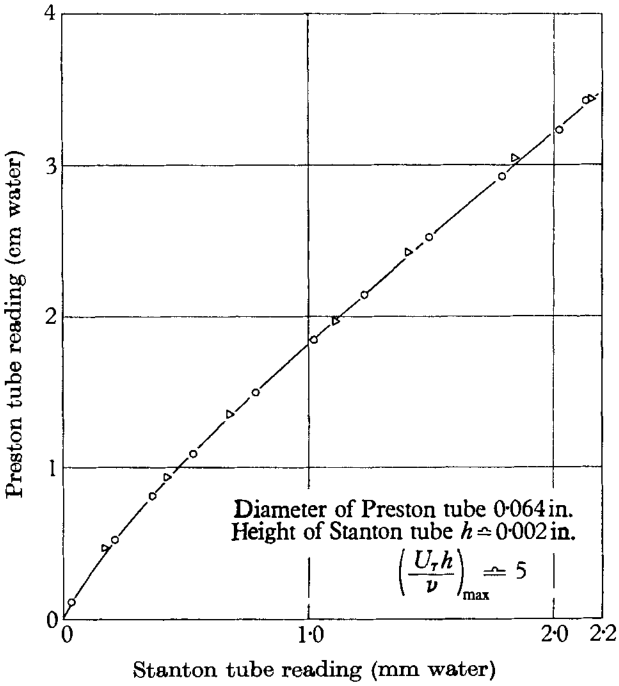


FIGURE 3. Comparison between readings in pipe and boundary-layer flows. First station at 65 in. ○, Fully developed pipe flow; △, boundary-layer flow.

As earlier experiments had shown that no advantage in steadiness or uniformity was to be derived from fitting the contraction and screens at entry to the extended pipe, its use for fully developed turbulent pipe flow was discontinued in these tests, though it was, of course, retained for the experiments on the developing turbulent boundary layer.

The results obtained with the new test arrangement were immediately rewarding, as figure 3 shows. It will be seen that there is almost perfect agreement between the results for fully developed pipe flow and the growing boundary layer. The experiment was repeated at a second station the same distance (65 in.) along the test section but displaced some 8 in. around the circumference. The readings of the Stanton tube were for some reason irregular and unrepeatable, and whilst in retrospect it seems almost certain that this was due to nothing more fundamental than possibly alcohol in the connecting leads, it was decided to try an alternative device to the Stanton tube. This was the so-called sublayer fence illustrated in figure 4 and first described in a more elaborate form by Konstantinov & Dragnysh (1960). It appeared to offer substantial advantages over the Stanton tube. First, it was self-contained so that no additional static pressure tapping in the surface was required. Secondly, it could be expected to give a reading almost double that of a Stanton tube of the same height. The disadvantages are fairly obvious; it is rather more difficult to construct, and unlike the Stanton tube in the form used in the present investigation its height

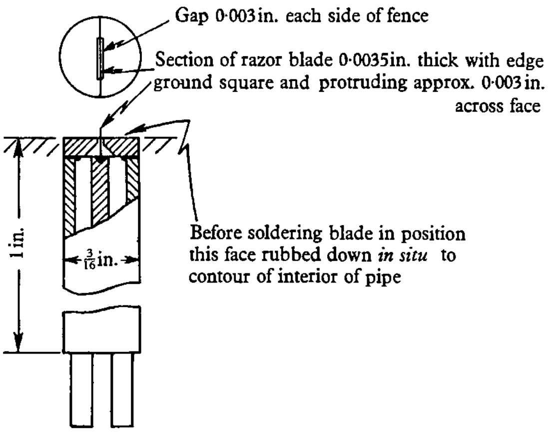


FIGURE 4. Construction of sublayer fence.

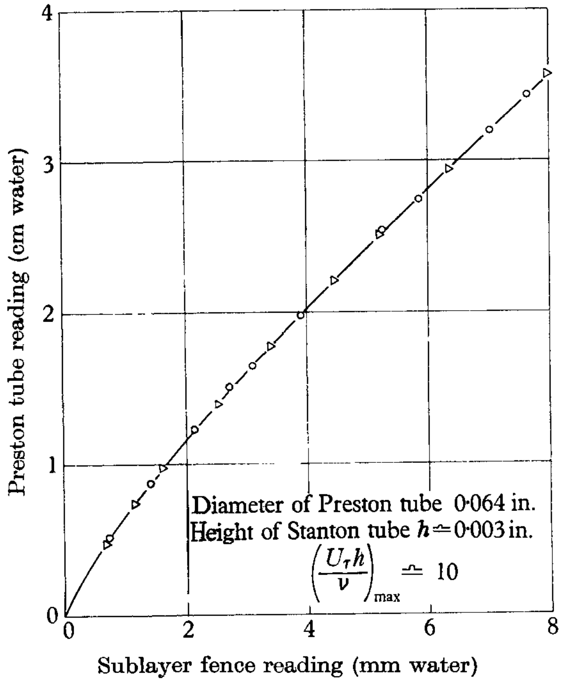


FIGURE 5. Comparison between readings in pipe and boundary-layer flows. Second station at 65 in. ○, Fully developed pipe flow; △, boundary-layer flow.

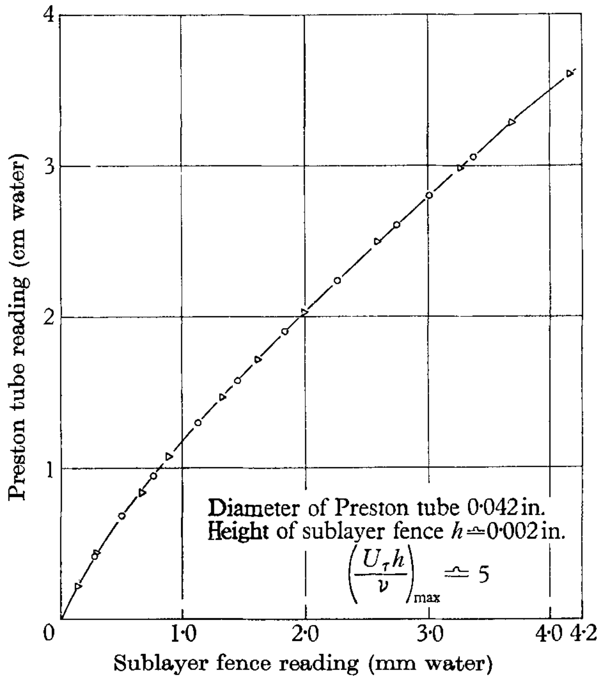


FIGURE 6. Comparison between readings in pipe and boundary-layer flows. Station at 22 in. ○, Fully developed pipe flow; △, boundary-layer flow.

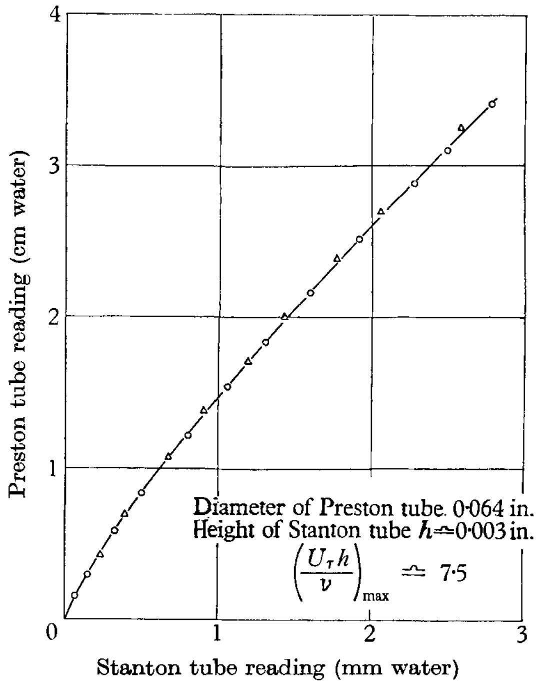


FIGURE 7. Comparison between readings in pipe and boundary layer flows. Second station at 65 in. ○, Fully developed pipe flow. △, Boundary-layer flow.

cannot be simply adjusted *in situ* to give a convenient reading. With the fence replacing the Stanton tube at this second station the results shown in figure 5 were obtained. It will be seen that the two sets of points from pipe and boundary-layer flows are in virtually perfect agreement. The experiment was then repeated at the station 22 in. from entry with a similar result, as shown by figure 6.

Thus at all three stations quite decisive evidence had been obtained in favour of the essential validity of Preston's method. To dispel any possible doubts concerning the measurements at the second station, where the Stanton tube had initially given erratic and unrepeatable readings, the experiment was later repeated, again using the Stanton tube, with the satisfactory result shown in figure 7.

The results now appeared quite conclusive and it seemed almost certain that earlier difficulties had arisen solely because of unexpectedly large variations in skin friction occurring around the circumference of the pipe. What was in fact unexpected was not so much the magnitude of the variations but the fact that they apparently occurred over such a very small extent of the circumference. To check that such variations in skin friction were present the experiments described in the following section were undertaken.

5. Circumferential variations in skin friction in the developing turbulent boundary layer

For these experiments the flange at the inlet to the test section was unsoldered so that the contraction, complete with screens and transition device, could be freely rotated on the tube relative to the fixed measuring positions. Measurements were made in turn at the 22 in. and one of the 65 in. stations, the inlet being progressively rotated in each case in steps of approximately 0·12 in. The results are shown in figure 8. From this figure it will be observed that the major variations occurring at the 22 in. station are quite faithfully reproduced at the 65 in. station, though some of the smaller scale variations have disappeared. It will be noted too that the presence or absence of the transition device (in this case a flat serrated strip) had only a negligible effect on the skin friction, indicating that at this velocity, which was the maximum attainable, transition probably occurred ahead of the strip. It is also to be concluded from these results that the pattern of skin friction downstream was, so to speak, tied to the entry, since the 22 in. and 65 in. stations were not in line and the correspondence of the results at the two positions which is to be observed in the figure was obtained by taking into account the angular displacement of the two positions. It should perhaps be pointed out that the variations in Preston tube readings can be taken as giving a fair approximation to the variations in skin friction since, according to Preston's calibration, $\tau_0 \propto \Delta p^{\frac{7}{8}}$.

These measurements are certainly sufficient to explain the inconsistencies observed in the earlier experiments, and may go some distance towards explaining the conflicting results obtained by different experimenters in the past. It is of course possible that the boundary-layer development on a flat plate is different from that in a circular tube, but it is recalled that in past experiments on a flat plate, performed in a wind tunnel in this laboratory, marked differences have been observed in turbulent boundary-layer velocity profiles measured on and off the tunnel centreline, and it has been established that these differences are associated with the condition of the screens in the contraction. We may also note that Schubauer (1957) observed that transition, either free or excited by a vibrating ribbon, occurred in quite regular streets, the pattern of which was determined by the condition of the screens upstream. However, even with these results borne in mind, it is somewhat surprising that such marked variations in skin friction as have been recorded here should persist virtually unchanged with distance downstream. This is obviously a topic which will repay further investigation.

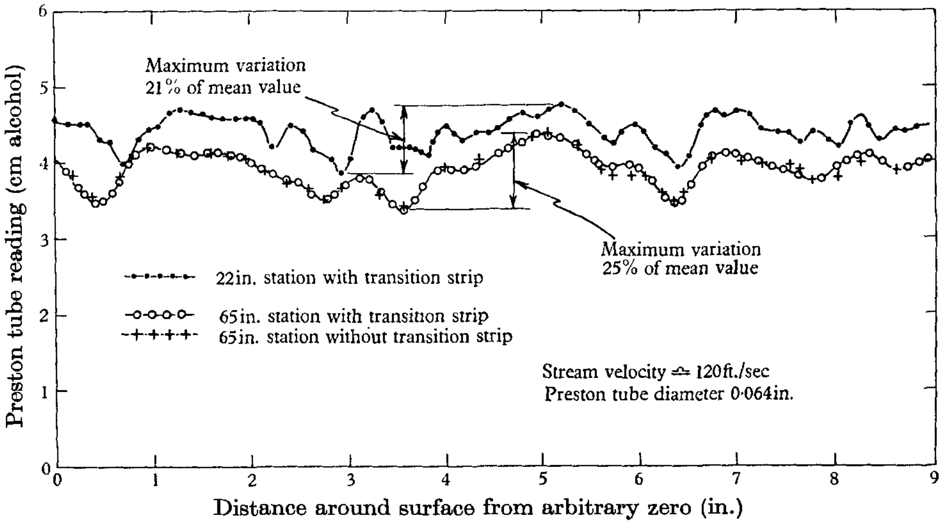


Figure 8. Variations of skin friction around circumference of pipe in growing boundary layer.

6. Tests of the Preston tube in adverse pressure gradients

The experiments described in §4 may be taken as providing substantial justification of Preston's method and the hypothesis of wall similarity, but two objections may be raised. First, the experiments were all carried out on a surface with transverse curvature, and secondly, the experiments were limited to the case of a favourable pressure gradient. As mentioned earlier the first objection is believed to have been answered, though perhaps not conclusively, by making measurements at a station where the boundary-layer thickness was small compared with the pipe radius, and by repeating the measurements further downstream where the boundary layer was considerably thicker.

To provide an answer to the second objection a limited series of experiments were performed in adverse pressure gradient conditions. The experimental arrangement is shown in figure 9. A plywood ring with a rubber sealing strip was fitted in the pipe downstream of the forward (22 in.) measuring station. By moving the ring along the test section the pressure gradient and the skin friction at the measuring station could be adjusted as required. Indeed, by making a series of measurements with the position of the ring systematically varied, a good approximation to the distribution of skin friction ahead of the ring could be obtained, though it will be recognized that moving the ring with the measuring station fixed could not give quite the same result as the reverse procedure, because of the varying distance of the ring from the entry and the consequent change in boundary-layer thickness ahead of the ring. Thus figure 10 cannot strictly be regarded as giving the distributions of static pressure and skin friction ahead of the ring though it may be expected to give a fair approximation to it. The results illustrated in the figure were obtained by first calibrating the Preston tube and the sublayer fence in pipe flow, using the pressure drop over 50 in. of the test section to obtain the skin friction. Preston tube and fence readings were then taken in the developing boundary layer with the position of the ring systematically varied. Because the sublayer fence was $\frac{3}{32}$ in. downstream of the mouth of the Preston tube and the static pressure tappings it was necessary to observe this displacement in plotting the results.

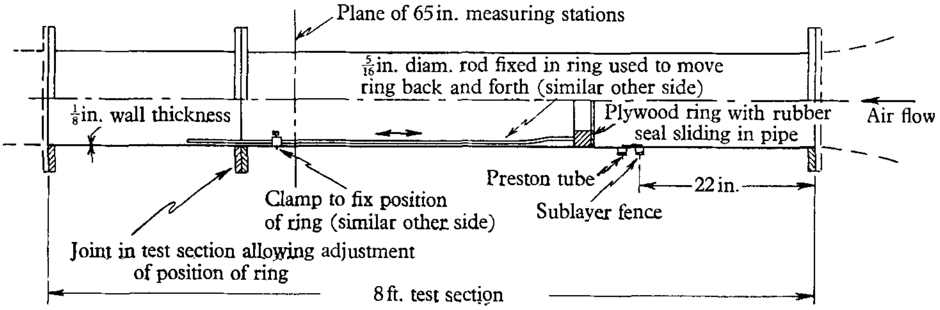


FIGURE 9. Arrangement of ring in pipe to produce adverse pressure gradient at forward measuring station. The steel clamping rings, used to maintain an accurately circular section, are not shown.

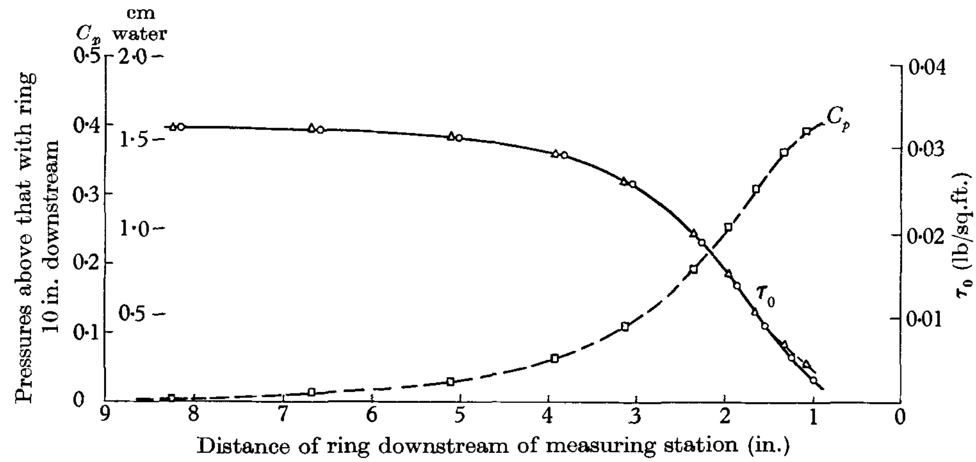


FIGURE 10. Variation of static pressure and skin friction with downstream distance of ring. Values of C_p are based on a stream velocity of 83 ft. per sec., the approximate value with the ring 10 in. downstream. ○, Sublayer fence; △, Preston tube; □, static pressure.

From figure 10 it will be seen that the values of skin friction given by the fence and the Preston tube are in excellent agreement except very close to separation, so that Preston's method of measurement is evidently valid in adverse pressure gradients with this restriction. It may be noted that conditions in this experiment were particularly severe in that the flow was heavily curved and large variations in static pressure and skin friction occurred in distances comparable with the boundary-layer thickness. Indeed, it would not have occasioned great surprise if Preston's method had failed in these circumstances: the fact that it did not except very close to separation gives added confidence in the method.

7. Calibration of the Preston tube

One of the advantages of the present series of experiments (except for that described in the previous section) was that only comparative readings of Preston tube and sublayer fence (or Stanton tube) were required and that no absolute calibration of either instrument was called for. Nevertheless, it was thought desirable to check the calibration of the Preston tube, to see whether a systematic error in Preston's original calibration could be used to account for the results

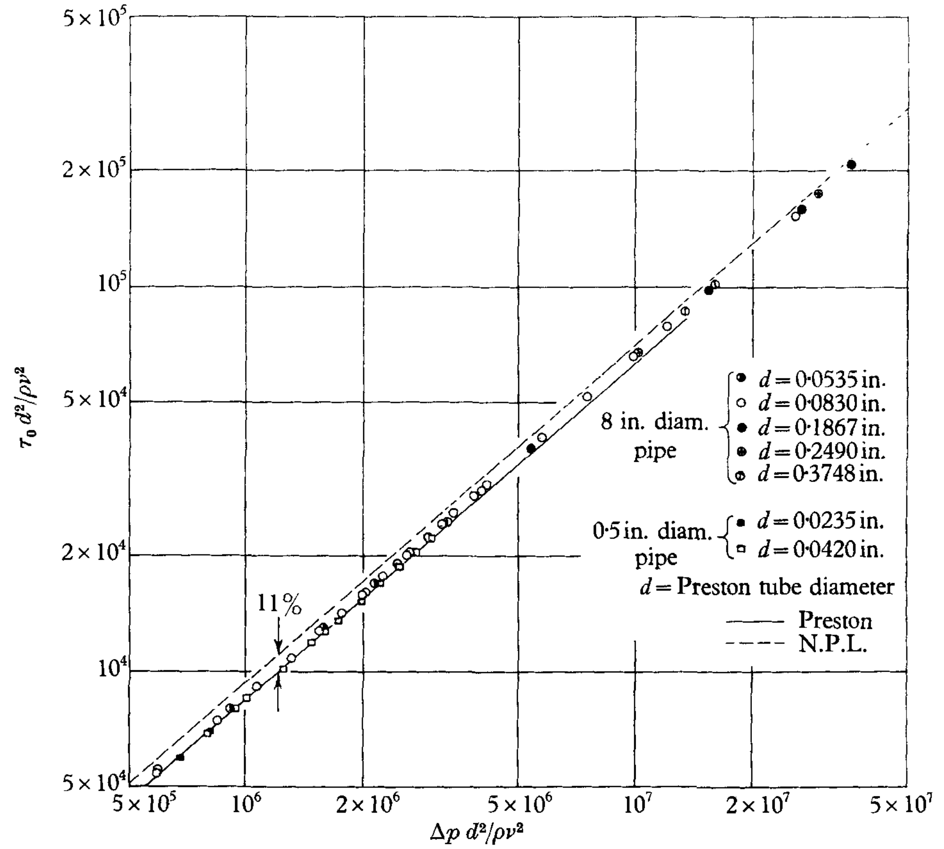


FIGURE 11. Calibration of Preston tube.

obtained by Smith & Walker and the N.P.L. It seemed unlikely that such should be the case but it remained a possibility which could not be dismissed.

Two sets of calibrations were carried out, one in the large pipe, by measuring the pressure drop along the test section ahead of the Preston tube which was fitted at one of the 65 in. stations, and one in a pipe of very much smaller diameter. The results given here, which are shown in figure 11, cover only the range of greatest practical interest; a more extensive investigation was in fact carried out and will be reported fully elsewhere. For all the points shown on the figure the maximum Mach number was very little greater than 0·1 and as the measured pressure differences were small no compressibility corrections were applied.

In each of the pipes the results for Pitot tubes of different diameters are seen to agree very closely, but there appears to be a consistent discrepancy of perhaps 2 or 3 % between the results for the two pipes, those for the $\frac{1}{2}$ in. pipe being, in fact, in almost perfect agreement with Preston's calibration. Although the lack of agreement between the two sets of results makes one hesitate to draw any very precise conclusion, it is perhaps reasonable to suggest that Preston's calibration may be a few percent in error, perhaps as much as 7 % at high Pitot tube Reynolds numbers. It is of course possible that the differences in calibration may arise through variations in skin friction around the pipe circumference but exploratory experiments have so far failed to reveal variations of appreciable magnitude in the fully developed pipe flow.

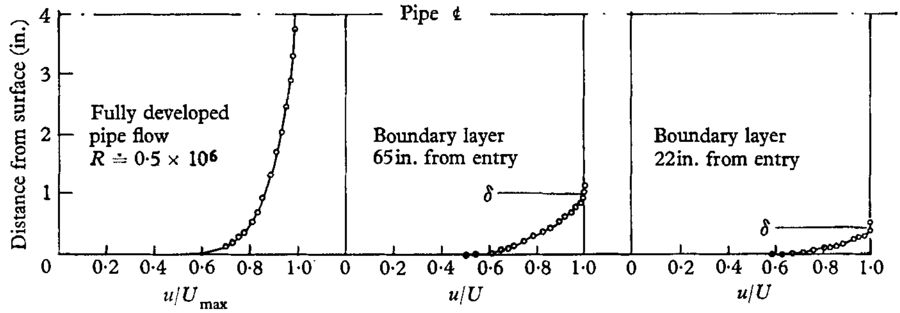
8. Velocity profiles

To conclude the investigation, mean velocity profiles were measured for the fully developed pipe flow and for the growing boundary layer at the 22 in. and 65 in. stations. The measurements were confined to the highest speed and were intended only to confirm that the velocity distributions were typical of fully developed turbulent pipe flow and of the turbulent boundary layer respectively. The results are shown in figure 12 and indicate boundary-layer thicknesses of approximately 1 in. and 0·4 in. at the 65 in. and 22 in. stations, respectively.

9. Discussion and conclusions

The present experiments appear to have demonstrated conclusively that Preston's method of measuring skin friction is basically sound, and that close to the wall there exists a region of flow similarity common to boundary layers and fully developed pipe flow. It has further been shown that at least in certain circumstances very substantial and almost periodic variations in skin friction may occur at right angles to the flow direction in the developing turbulent boundary layer. Such variations might explain random differences in the results obtained by different experimenters in the past, although they can scarcely be held to account for the consistent discrepancies observed by Smith & Walker and the staff at the N.P.L. The present calibration of the Preston tube, while certainly not definitive, does go some distance towards closing the gap, but it is felt that further investigation is required before the issue can be considered settled.

It will of course be noted that the presence of large and more or less regular spanwise variations in skin friction considerably complicates the measurement of surface shear, and in these circumstances the Preston tube, because of the ease with which it can be traversed across the surface, is likely to be extremely useful.



Comparison of measured profiles

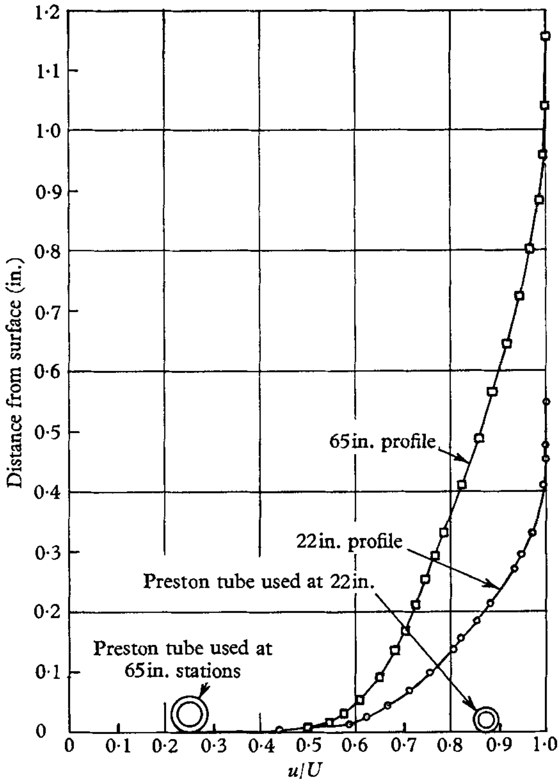


FIGURE 12. Measured velocity profiles, with Preston tubes shown to same scale.

In conclusion it may be remarked that Landweber (1960), from a re-analysis of existing boundary-layer and pipe measurements, confirms the universality of the inner law (though only for values of $U_\tau y/\nu < 100$) and suggests a calibration curve for the Preston tube which appears to be in good agreement with that given here.

REFERENCES

DUTTON, R. A. 1956 The accuracy of the measurement of turbulent skin friction by means of surface pitot-tubes and the distribution of skin friction on a flat plate. *Aero. Res. Counc., Lond., Rep. & Mem.* no. 3058.

HSU, E. Y. 1955 The measurement of local turbulent skin friction by means of surface tubes. *David W. Taylor Model Basin Rep.* no. 957.

KONSTANTINOV, N. I. & DRAGNYSH, G. I. 1960 The measurement of friction stress on a surface. (Trans.) *D.S.I.R. RTS* 1499.

LANDWEBER, L. 1960 Reanalysis of boundary-layer data on a flat plate. *Written discussion for Ninth International Towing Tank Conference, Paris,* 1960. Iowa Institute of Hydraulic Research, State University of Iowa.

LUDWIEG, H. & TILLMANN, W. 1950 Investigations of the wall shearing stress in turbulent boundary layers. (Trans.) *Nat. Adv. Comm. Aero., Wash., Tech. Mem.* no. 1285.

MALTBY, R. L. & KEATING, R. F. A. 1960 Flow visualization in low-speed wind tunnels: Current British practice. *Aero. Res. Counc., Lond., Rep.* no. 22, 373.

PRESTON, J. H. 1954 The determination of turbulent skin friction by means of pitot tubes. *J. Roy. Aero. Soc.* **58**, 109.

SCHUBAUER, G. B. 1957 Mechanism of transition at subsonic speeds. *I.U.T.A.M. Symposium, Freiburg/BR* (Published by Springer-Verlag, Berlin, 1958).

SMITH, D. S. & WALKER, J. H. 1958 Skin friction measurements in incompressible flow. *Nat. Adv. Comm. Aero., Wash., Tech. Note* no. 4231.

STAFF OF THE AERODYNAMICS DIVISION, N.P.L. 1958 On the measurement of local surface friction on a flat plate by means of Preston tubes. *Aero. Res. Counc., Lond., Rep. & Mem.* no. 3185.