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Preston Tube Measurements in Turbulent Boundary Layers and Fully Developed Pipe Flow

By

D.H. Ferriss, B.Sc.

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Preston Tube Measurements in Turbulent Boundary Layers and Fully Developed Pipe Flow

- By -
D. H. Ferriss, B.Sc.

February, 1965

SUMMARY

Measurements made with Preston tubes in a square pipe and in accurately two-dimensional boundary layers have confirmed Head and Rechenberg's finding that there is a region of similarity close to the wall for each type of flow. The Preston tube calibration was found to be in good agreement with that of Head, which implies that three-dimensionality of the type found by Head and Rechenberg does not alter the Preston tube calibration.

The tests have emphasized the need for dimensional accuracy in manufacture of the pipe.

Introduction/

Replaces N.P.L. Aero. Report No. 1142 - A.R.C.26 678.

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Introduction

In 1954 Preston[1] showed that, within the limits of experimental accuracy, the dynamic pressure indicated by a pitot tube of a given geometrical shape, immersed in the wall law region of turbulent pipe flow, was a universal function of the surface shear stress. Preston's measurements in turbulent boundary layers also showed that a unique value of surface shear stress was predicted by tubes of different sizes, even in an adverse pressure gradient ($H = 1{\cdot}85$, $c_f \simeq 0{\cdot}0008$), although it was not conclusively proved that this unique value was the correct one. These results, together with those of Ludwig and Tillmann[2], provided strong evidence in favour of the universal "law of the wall".

Since 1954, however, several investigators have made measurements in boundary layers using other methods of measuring surface shear stress, in order to obtain a direct calibration of Preston tubes. Experiments performed at N.P.L.[3] and at N.A.C.A. Ames Laboratory[4] showed that Preston's pipe calibration predicted a value of surface shear stress about 11 percent too low in the boundary layer in zero pressure gradient. These experiments appeared to deny the existence of a universal inner law for turbulent pipe and boundary-layer flows. On the other hand, experiments undertaken at David Taylor Model Basin[5] and by Dutton in Cambridge[6] appeared to confirm Preston's method to within an accuracy much better than 10 percent. In 1962, Head and Rechenberg[7] published a further set of experimental results in favour of the existence of a universal calibration for pipe and boundary-layer flows; their results are within 1 or 2 percent of Preston's calibration curve, and about 9 percent different from those published by the N.P.L. Head and Rechenberg's report also traces the history of this controversy in more detail than is given above. Head and Rechenberg also found, significantly, that the surface shear stress in their boundary layer varied in the spanwise direction by as much as ±10 percent of the mean value. To overcome this, they took care to mount the Preston tube at exactly the same station as the Stanton tube (sub-layer pitot tube) used to measure surface shear stress; details as to how they obtained both Preston and Stanton tube readings at this station with only one run are given in their paper. They also used a sub-layer fence (as did the author of this report) again verifying the validity of Preston's method.

Variations of skin friction in the spanwise direction would clearly go a long way towards explaining the conflicting results of previous experiments. In the light of this observation, the author feels that any further calibration of Preston tubes should only be performed in boundary layers largely free from such three-dimensional effects, or alternatively that care should be exercised to ensure that the skin friction calibration device and the Preston tube are mounted at the same station, as they were in Head and Rechenberg's experiment.

Spanwise skin friction variations of about ±10 percent have been observed in the Boundary Layer Tunnel of the Aerodynamics Division at N.P.L. Experiments showed that these variations were caused by a spatial instability of the flow through the wind-tunnel screens, and could be much reduced by using screens of open area ratio greater than about $0{\cdot}57$. Information on this point can be found in Ref. 8. The experiments described here were performed in the Boundary Layer Tunnel after modification with comparatively small spanwise variations (±4 percent) and in fully developed pipe flow in a square pipe, and are therefore a check on the work of Head and Rechenberg.

The/

The "Law of the Wall"

The usual derivation of the law of the wall is to assume that the flow sufficiently near to the surface below a turbulent wall layer is determined entirely by conditions at the wall and is independent of the outer flow except insofar as the latter determines the conditions at the wall. Then the velocity profile in the region of this "law of the wall" is found by a straightforward dimensional analysis to be

$$\frac{U}{u_\tau} = f_1\left(\frac{u_\tau y}{\nu}\right) \quad \text{where} \quad u_\tau = \sqrt{\tau_w/\rho} .$$

Since the mean velocity profile and the shear stress are connected by the equations of motion, it is clear that if the mean velocity profile is hypothesized to be exactly universal then the Reynolds stresses should be exactly universal also: similarly the arguments used on the mean velocity profile should be equally applicable to the shear stress, the turbulent motion, and the pressure fluctuations. It is well known, however, that turbulent eddies and pressure fluctuations are not local phenomena, but that eddies may extend over most of the thickness of the shear layer and that the pressure fluctuations at the surface receive contributions from the whole turbulent field; thus the law of the wall cannot be regarded as being mathematically exact but it is at best a good engineering approximation. It follows that some caution is necessary in relying on the law of the wall, and this point was borne in mind when the various experiments subsequent to Preston's were undertaken.

If we now consider a region of the shear layer further out from the surface where the Reynolds shear stress is much larger than the viscous shear stress, the direct effect of viscosity on the motion may be neglected. It is interesting to note here that we have a clearer idea of the errors involved in this approximation than in the case of the assumptions leading to the law of the wall. For this region the dimensional arguments lead to

$$\frac{U_1 - U}{u_\tau} = f_2(y/\delta).$$

Now if the region where the viscous shear stress is negligible overlaps the region where the law of the wall is valid, then the two expressions for U/u_τ must be simultaneously valid. It follows that for this region of overlap

$$\frac{U_1}{u_\tau} = f_1\left(\frac{u_\tau y}{\nu}\right) + f_2(y/\delta)$$

or that the sum of the functions is a constant, i.e., independent of y. Consequently, the functions f_1 and f_2 are either constants or they are functions complementary to each other independent of the scale of y. This indicates a logarithmic form for both functions, viz.,

$$\frac{U}{u_\tau} = A \log\left(\frac{u_\tau y}{\nu}\right) + B \quad .$$

and/

and
$$\frac{U_1 - U}{u_\tau} = - A \log (y/\delta) + C$$

and so
$$\frac{U_1}{u_\tau} = B + C + A \log \left(\frac{u_\tau \delta}{\nu} \right) .$$

The last expression is the skin friction coefficient - Reynolds number formula. As a result of both Head and Rechenberg's experiments, and those to be described below, the universal logarithmic form is now established to an accuracy of 2 percent or better, but a dimensional analysis shows that the logarithmic region of the velocity profile in a boundary layer is confined to the region where $\tau \simeq \tau_W$; consequently the region of validity decreases as the pressure gradient increases in severity and eventually shrinks to zero.

If now a pitot tube is placed in the region where the relation $U/u_\tau = f_1(u_\tau y/\nu)$ is valid, it can be shown that the pressure difference Δp between its reading and that of a nearby static hole is given by

$$\frac{\Delta p d^2}{\rho \nu^2} = f_3 \left(\frac{\tau_W d^2}{\rho \nu^2} \right) .$$

This relation follows from a dimensional analysis using the same assumptions as are used in the derivation of the law of the wall. Most of the results of this experiment are non-dimensionalised in this way and plotted in log-log form. If, however, a pitot tube is placed in a region so near the wall that $U/u_\tau = u_\tau y/\nu$, then its reading will be given by

$$\frac{\Delta p d^2}{\rho \nu^2} = f_4 \left(\frac{\tau_W d^2}{\rho \nu^2} \right)$$

independent of the assumptions used to obtain the law of the wall. This region is called the linear sub-layer, and here the viscous stresses are very much greater than the Reynolds stresses. This is the region in which the flat Stanton tubes and sub-layer fences are used.

Apparatus

Preston tubes of different diameters were made up by mounting short lengths of hypodermic tubing onto $3\frac{1}{2}$ inch diameter brass discs. These discs enabled the tubes to be conveniently fitted to the floor of the working section of the Boundary Layer Tunnel or alternatively to the square pipe as desired. Reasonable but not excessive care was taken to ensure that the mouths of the surface pitot tubes were free from burrs and deformities and that the tubes were lying along the surface as closely as was reasonably possible. Consequently, the discrepancies found between the calibrations of different tubes are typical of those that may be expected from 'home-made' tubes. Each disc was fitted with two static pressure tappings, one each side of the tube mouth and on a level with it. The distance between the tappings was 3 inches, and as there was no measurable difference of pressure between the two holes, only one was used in the experiment.

Preston took a great deal of trouble in his original experiment to ensure that the ratio of internal diameter to external diameter was

0·600 ± ½ per cent, by grinding until the required accuracy was attained. However, experiments performed by the staff of N.P.L.[3] indicated that this ratio is not important. They tested tubes of internal to external diameter ratio of 0·55, 0·60 and 0·70 and found no distinguishable difference between them. Consequently the author used stock hypodermic tubing; for the range of external diameter taken, the internal to external diameter ratio varied between 0·70 and 0·75.

Most of the Preston tube measurements were made on a multi-tube alcohol manometer inclined at 15 degrees to the horizontal. The maximum pressure difference across the sub-layer fence was only about 0·2 in. of water, so it was neither convenient nor accurate to read this on the inclined manometer. A small null reading oil-filled manometer was used to make these measurements; an account of this instrument is given in Ref. 10.

The original pipe used in the experiment was 6 feet long and constructed of ¼-inch aluminium strips screwed together. A plate was let into the side to take the 3½-inch diameter discs. The final design for the pipe however is given in Fig. 1; the main point of difference is the addition of a new working section made by machining a 1-inch square groove in a 2-inch by 2¾-inch piece of aluminium alloy (NORAL BS1477/HP15WP, which does not distort during machining), and capping this groove with an aluminium plate.

The sub-layer fence is shown in Fig. 2 and was constructed by sealing a steel shim into a slot cut into the end of a ½-inch diameter brass rod. Holes let into the sides of the slot served as pressure tappings. The whole was then mounted into a 3½-inch diameter brass disc.

Details of the Boundary Layer Tunnel are given in Ref. 9.

Experimental Procedure and Initial Difficulties Encountered

The procedure followed was nominally quite straightforward. A Preston tube traverse across one wall of the square pipe showed that the average skin friction across the wall was within 1 percent of the value indicated by the tube when the latter was positioned at the centre of the wall. Consequently, the sub-layer fence was fitted into the centre of one side of the square pipe and calibrated against the skin friction calculated from the pressure drop measured along the pipe. The fence was then removed and fitted into the Boundary Layer Tunnel to determine the surface shear stress as a function of tunnel reference pressure. A repeat calibration of the fence was then performed in the pipe to check that dust from the tunnel had not interfered with the fence and affected its calibration. The Preston tubes were then fitted one at a time into the pipe and their readings related to the calculated skin friction. Each tube was then mounted in the Boundary Layer Tunnel at the station previously occupied by the sub-layer fence and the readings related to skin friction in the tunnel by way of the skin friction versus reference pressure calibration. This procedure was followed in two different boundary-layer flows; one with zero pressure gradient ($c_f = 0{\cdot}0027$, $R_x \sim 6{\cdot}5 \times 10^6$), and the other in an equilibrium layer with adverse pressure gradient ($c_f = 0{\cdot}00125$, $R_x \sim 4{\cdot}6 \times 10^6$, $U_1 \alpha\ x^{-0{\cdot}255}$). The relations found between Preston tube reading and skin friction are compared for the two boundary-layer flows and the pipe flow.

As indicated in the heading of this section, difficulties were encountered as the experiment progressed. The author wishes to recount these at some length as it may help any future investigator embarking on a similar experiment. The difficulties are especially pertinent to experiments conducted in rectangular made-up channels using skin friction measuring devices.

The experiment was first performed in a boundary layer with zero pressure gradient at a station $8\frac{1}{2}$ feet behind the line of origin (in this case, a trip-wire at the entry of the working section of the tunnel) at free stream speeds up to 130 ft/sec. Good agreement was obtained between the Preston tube readings plotted against skin friction for the case of the boundary layer and those obtained for the square pipe, but it was found that for the same Preston tube reading the skin friction given by these curves was of the order of 12 percent <u>lower</u> than that forecast by Preston's original calibration, that is, in the opposite sense to the discrepancies in the earlier N.P.L. work. The calculations were checked, and the experiment repeated, with the same result. The author considered that it was significant that both types of flow gave almost the same calibration for the tubes and that it appeared that the skin friction values were all reduced by an almost constant factor.

It was decided to re-check that the pressure drop along the pipe was linear and that the average pressure drop per unit length of pipe agreed with the first determination of this quantity. This was found to be so and it was decided then to try another pipe. A Preston tube was mounted in a 1-inch diameter circular pipe 12 feet long and a few measurements made. The tube calibration against skin friction calculated from the pressure drop in this case was within 3 percent of Preston's calibration. A tube was then mounted in a 24-inch by 1-inch duct 18 feet long, and further measurements made here also agreed reasonably well with Preston's calibration, although the agreement was not as good as that in the circular pipe. Although the experimental results obtained from these two pieces of equipment were sketchy, and consequently not given in this report, they are mentioned here as they threw definite suspicion on the square pipe used to calibrate the sub-layer fence. A slight curvature of the square pipe was evident on close examination but measurements made after this had been corrected showed the same discrepancy as before. At this stage the pipe was partly dismantled and examined for burrs around static holes, etc., and any other noticeable peculiarities that might explain the anomalous behaviour. A step of two or three thousandths of an inch was discovered about 4 inches upstream of the tube station at the joint between the plate used to hold the discs and the pipe itself. Another step was discovered the same distance downstream at the second joint. These were rubbed down and smoothed, the pipe assembled and leak tested and some more measurements made. These gave a Preston tube - skin friction calibration considerably different from the previous one. At this stage, the author considered that the section of the square pipe around the tube station was generally unsatisfactory, and decided to have the pipe almost completely re-made. Consequently, the existing pipe was shortened a few inches, and a one inch square channel added to be used as the working section. This modified pipe proved quite satisfactory, and is shown in diagrammatic form in Fig. 1. The considerable time and trouble taken with a piece of equipment which appeared to be so simple demonstrates how very difficult it is to make a built-up duct of rectangular section that has sufficiently uniform internal dimensions. Indeed, a relatively small change in internal dimension of the pipe has a very significant effect on the measured skin friction. This can be shown quite easily by a simple calculation; the Appendix to this report shows that a taper of 1 in 1000 can produce an error of about 13 percent in the skin friction calculated from the pressure drop. It was not surprising then, that spurious skin friction values were obtained in the original pipe that had steps in the region of the working section. It is possible that similar errors may have existed in the second set of experiments described in Ref. 3, in which a 12-inch by 2-inch rectangular duct was used to calibrate Stanton tubes.

Presentation of Results

Fig. 3 shows the pressures at the static holes along the modified pipe. It can be seen that there is a definite non-linearity in the region where the new section is joined to the old; this is despite the utmost care taken to ensure that the area of cross-section of the original pipe was as close as possible to that of the channel, so as to minimise acceleration of the flow. The linearity over the last twenty inches of pipe, however, is very good and the actual position for the fence and tubes is indicated in Fig. 3, well within this well behaved region, 84 inches from entry. The reference pressure used when running the pipe was the difference between atmospheric pressure and the pressure at the static hole 75 inches from entry.

Fig. 4 shows a calibration of the sub-layer fence in the square pipe. To show the repeatability of the measurements, two runs are plotted, one before and one after the fence had been used in the Boundary Layer Tunnel.

In Fig. 5 the sub-layer fence readings are plotted against tunnel reference pressure; from this graph and the one in Fig. 4 one can obtain the relation between skin friction and reference pressure.

Non-dimensional values of Preston tube readings are plotted against corresponding skin friction values for the boundary layer with zero pressure gradient in Fig. 6; Fig. 7 is a similar plot for the tubes in the square pipe, while Fig. 8 shows the adverse pressure gradient results. Examination of these graphs reveals more scatter in the tunnel results; this is probably due to more unsteadiness in the tunnel readings generally, and the fact that the speed of the tunnel was not as steady as that in the pipe owing to small fluctuations in the power supply. The pipe was supplied from compressed air and not subject to this effect.

Figs. 6, 7 and 8 show slight discrepancies between the Preston tubes of different sizes; this effect is more marked in the tunnel results and tends to confuse the comparison between both types of flow. To compare further, however, the fully developed pipe flow and the tunnel flow, plots of the logarithm of Preston tube reading divided by skin friction were plotted against non-dimensionalised skin friction for each separate tube. These graphs are shown in Figs. 9 to 12 inclusive. This is a more sensitive plot than the log-log plot of non-dimensionalised skin friction versus Preston tube reading used by previous investigators and employed in Figs. 6 to 8. Examination of Figs. 6 to 12 clearly indicates the similarity between the types of flow. It can be seen from Figs. 9 to 12, however, that more noticeable consistent differences exist between different sizes of tube in the case of the adverse pressure gradient. The most probable explanation of this is the effect of the high turbulence intensity on the tubes, which must also have had some effect on the Stanton fence calibration in this boundary layer. In view of this, it is likely that the quantitative results taken in the adverse pressure gradient boundary layer are in error. The discrepancies are sufficiently small however to be ignored for most purposes, as the surface shear stress coefficient is itself small in strong adverse pressure gradients. Also, the turbulent intensity in this equilibrium layer is higher than in an aerofoil boundary layer. Further work is being done on the behaviour of surface tubes in highly turbulent flows.

The results suggest then, that the Preston tube is adequate for determining the overall skin friction drag of any body, but that the accuracy of determination of local surface shear stress may be poorer when the boundary layer is strongly retarded.

Conclusions/

Conclusions

This series of experiments has confirmed Head and Rechenberg's conclusion that, within the limits of experimental accuracy, the calibration of Preston tubes, and therefore the logarithmic profile, is the same in pipe flow and in boundary-layer flow. The major possible source of error in Head and Rechenberg's experiment, spanwise variation of skin friction, was much reduced in the present experiment. The fact that Head and Rechenberg's results were apparently unaffected by these variations is a useful confirmation of the validity of the inner law in three-dimensional boundary layers.

The experimental results provide some evidence to suggest that surface skin friction measurements made with Preston tubes in strong adverse pressure gradients may suffer in accuracy, but that for most engineering purposes this effect can be ignored, except near separation.

The calibration of the Preston tube itself was found to be in good agreement with that of Head.

Preston found:-

$$\log_{10}\left(\frac{\tau_w d^2}{\rho \nu^2}\right) = 0{\cdot}875 \log_{10}\frac{(P-p)d^2}{\rho\nu^2} - 1{\cdot}321 \qquad 3{\cdot}6 < \log_{10}\left(\frac{\tau_w d^2}{\rho\nu^2}\right) < 4{\cdot}9.$$

A line through Head's results in his paper gives:-

$$\log_{10}\left(\frac{\tau_w d^2}{\rho \nu^2}\right) = 0{\cdot}889 \log_{10}\frac{(P-p)d^2}{\rho\nu^2} - 1{\cdot}400 \qquad 3{\cdot}7 < \log_{10}\left(\frac{\tau_w d^2}{\rho\nu^2}\right) < 5{\cdot}3$$

while the present set of experiments gave:-

$$\log_{10}\left(\frac{\tau_w d^2}{\rho \nu^2}\right) = 0{\cdot}881 \log_{10}\frac{(P-p)d^2}{\rho\nu^2} - 1{\cdot}350 \qquad 3{\cdot}4 < \log_{10}\left(\frac{\tau_w d^2}{\rho\nu^2}\right) < 4{\cdot}8.$$

One of the salient features of the experiment as a whole is the difficulty in constructing a pipe of square cross section with sufficiently uniform dimensions to be used to calibrate skin friction measuring devices. If a round pipe is used, in which case this difficulty is obviated, an instrument such as a sub-layer fence has to be ground down to fit the geometry of the pipe, and cannot be used in the boundary layer on a flat surface.

Acknowledgements

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Notation/

Notation

H	form parameter of velocity profile; displacement thickness divided by momentum thickness
ρ	density of fluid
ν	kinematic viscosity of fluid
x	distance along the surface, in the direction of flow
y	distance normal to surface
R_x	Reynolds number of layer, based on distance from origin of tube station
τ_w	local skin friction
U	mean velocity component parallel to surface at distance y
u_τ	equal to $\sqrt{(\tau_w/\rho)}$
U_1	velocity at edge of boundary layer
d	outside diameter of Preston tube
δ	boundary-layer thickness
c_f	equal to $\tau_w/\frac{1}{2}\rho U_1^2$
λ	equal to $\rho\nu^2/\rho_0\nu_0^2$, where ρ_0 and ν_0 are values of ρ and ν for air at 76 cms of mercury barometric pressure and at 15° Centigrade.

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APPENDIX/

APPENDIX

This Appendix shows the effect on measured skin friction in a circular pipe whose diameter changes by 0·001d per diameter measured along the pipe. No attempt is made to make the argument rigorous; the intention is to indicate the order of magnitude of the error incurred.

Let A be the area of cross section; $\bar{u}$ the average velocity across the section; d the diameter of the pipe; then we have

$$p + \tfrac{1}{2}\rho\bar{u}^2 = \text{const.}$$

$$\text{so} \quad \Delta p + \rho\bar{u}\,\Delta\bar{u} = 0 \quad \text{approximately,} \qquad \ldots (1)$$

where Δ represents a difference across the piece of pipe of length d along which the diameter changes by 0·001d.

$$\text{Also we have} \quad A\bar{u} = \text{const.}$$

$$\text{and so} \quad \Delta A.\bar{u} + A.\Delta\bar{u} = 0 \quad \text{approximately.} \qquad \ldots (2)$$

$$\text{From (1) and (2)} \quad \Delta p = \rho\bar{u}^2 \frac{\Delta A}{A}. \qquad \ldots (3)$$

For the circular pipe we have

$$\tau_w = \frac{d}{4}\frac{dp}{dx}$$

$$\text{and so} \quad \Delta\tau_w = \frac{\Delta d}{4}\frac{dp}{dx} + \frac{d}{4}\,.\,\Delta\left(\frac{dp}{dx}\right) \quad \text{approximately,}$$

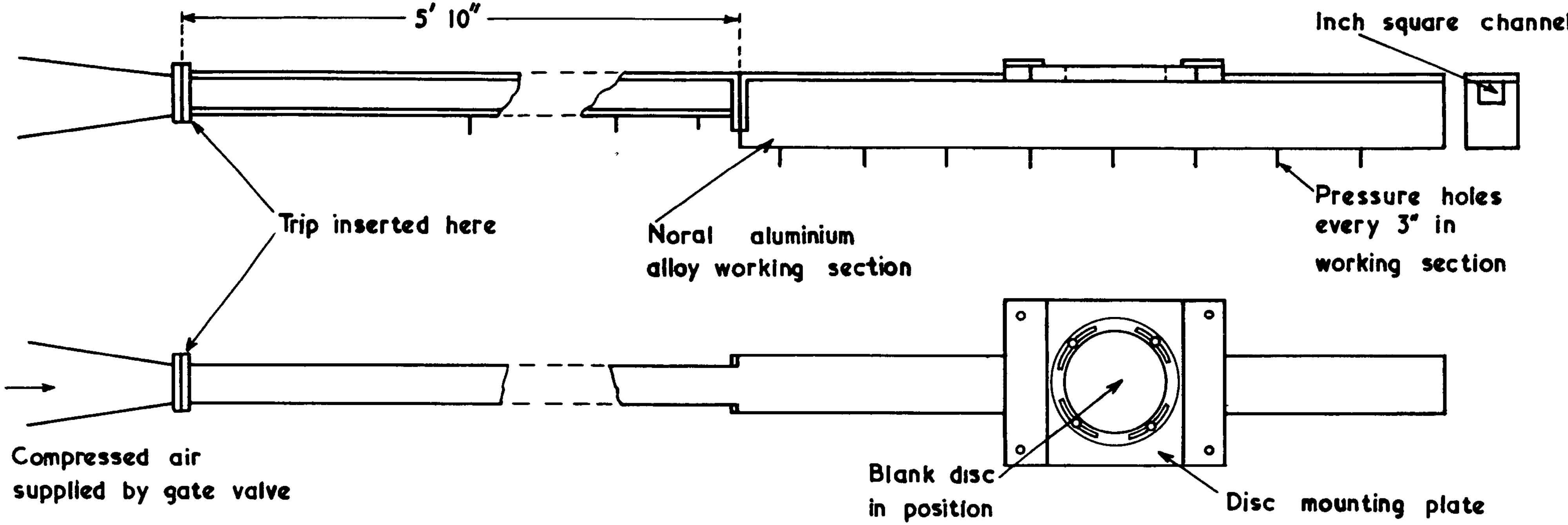
$$= \frac{\Delta d}{4}\frac{dp}{dx} + \tfrac{1}{2}\,.\,\tfrac{1}{2}\rho\bar{u}^2\frac{\Delta A}{A} \quad \text{from (3)}$$

$$\text{and so} \quad \frac{\Delta\tau_w}{\tau_w} = \frac{\Delta d}{d} + \tfrac{1}{2}\,.\,\tfrac{1}{2}\frac{\rho\bar{u}^2}{\tau_w}\frac{\Delta A}{A}.$$

But $\dfrac{\Delta A}{A} = \dfrac{2\Delta d}{d}$; and if we put $\dfrac{\Delta d}{d} = 0\cdot001$ we obtain

$$\frac{\Delta\tau_w}{\tau_w} = 0\cdot001\left(1 + \frac{\tfrac{1}{2}\rho\bar{u}^2}{\tau_w}\right).$$

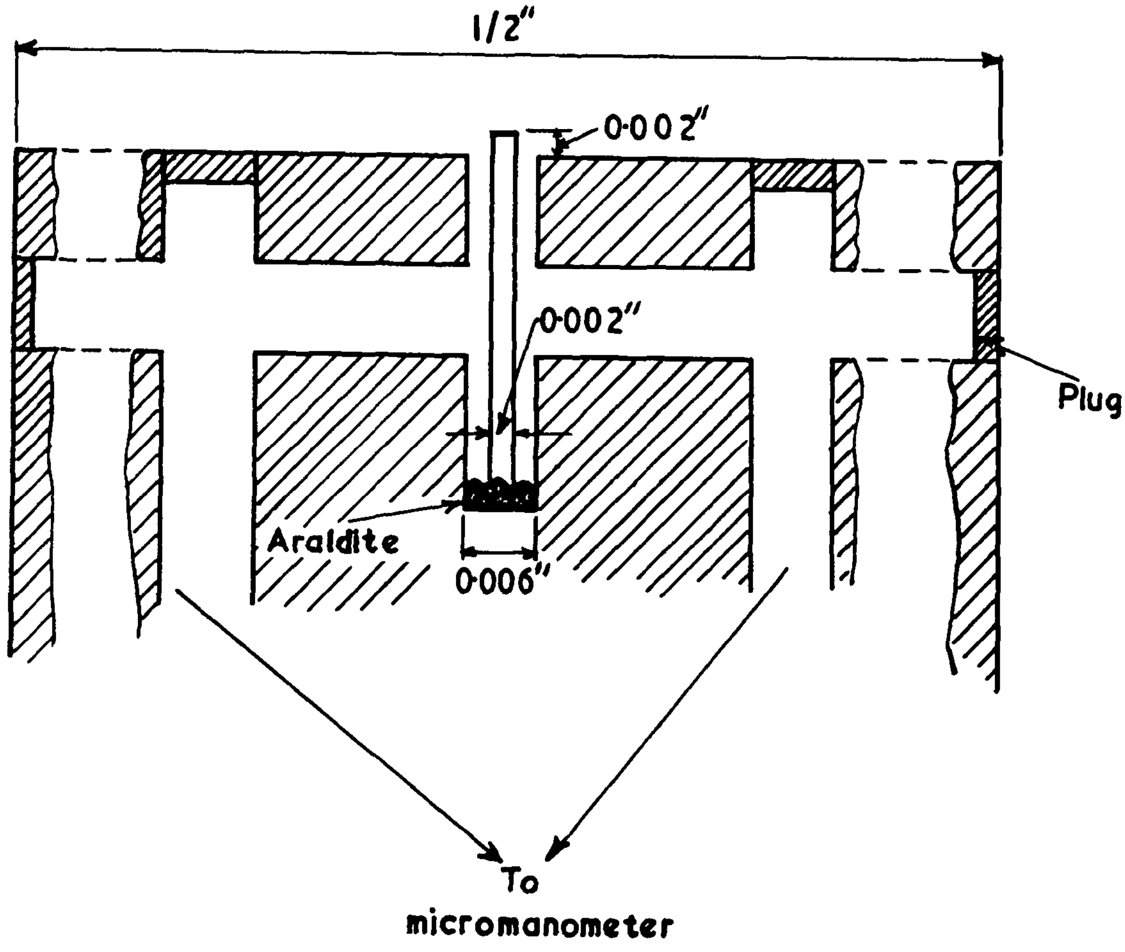
Typically, at a Reynolds number based on the pipe diameter and the average velocity in the pipe of 10^4, $\tfrac{1}{2}\rho\bar{u}^2/\tau_w \approx 130$ and so $\Delta\tau_w/\tau_w$ is about 13 percent.



Construction of square pipe

FIG. 1.

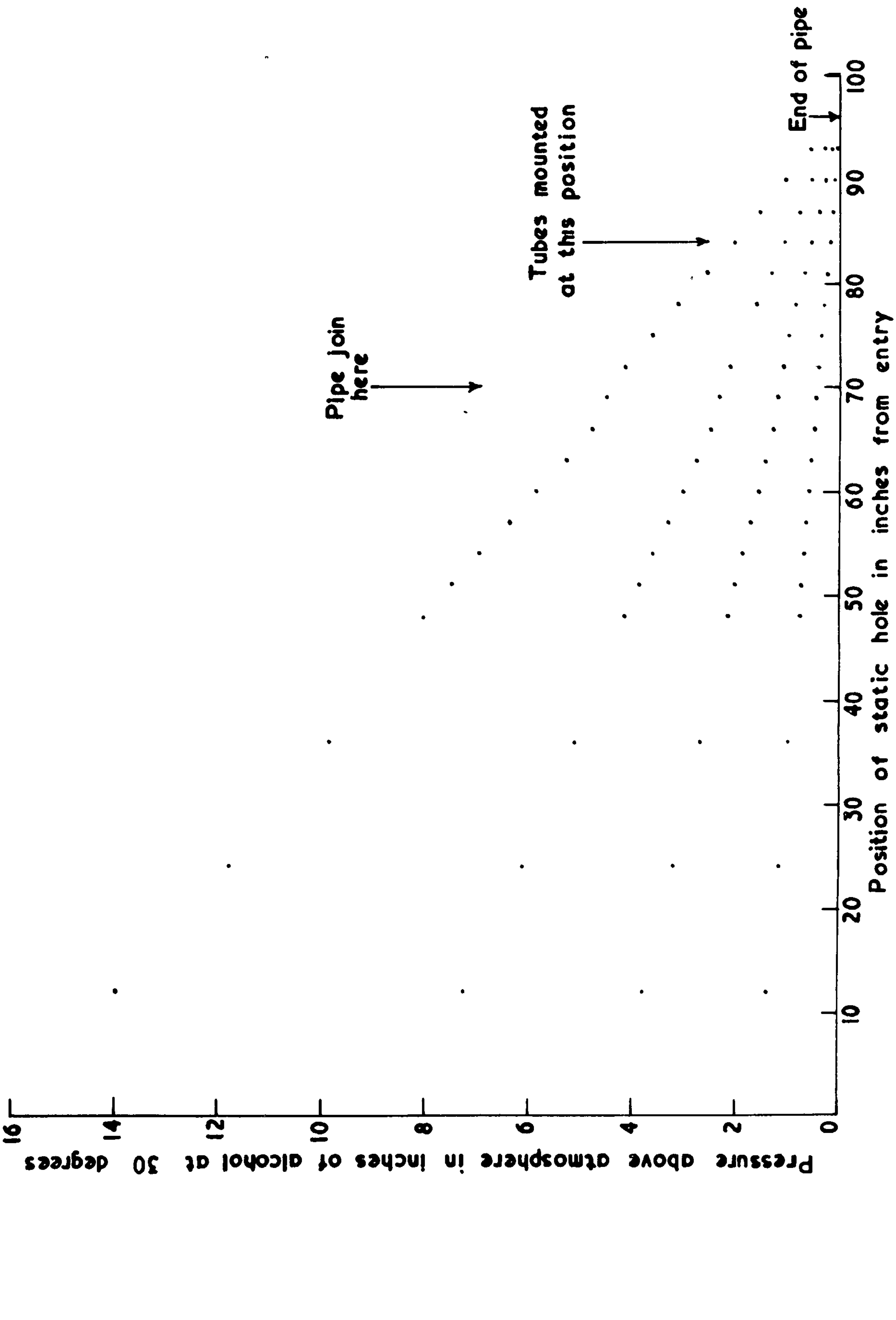
FIG. 2



The above is a vertical section through the centre of the fence

Construction of sub-layer fence

FIG. 3



Pressure drop along square pipe

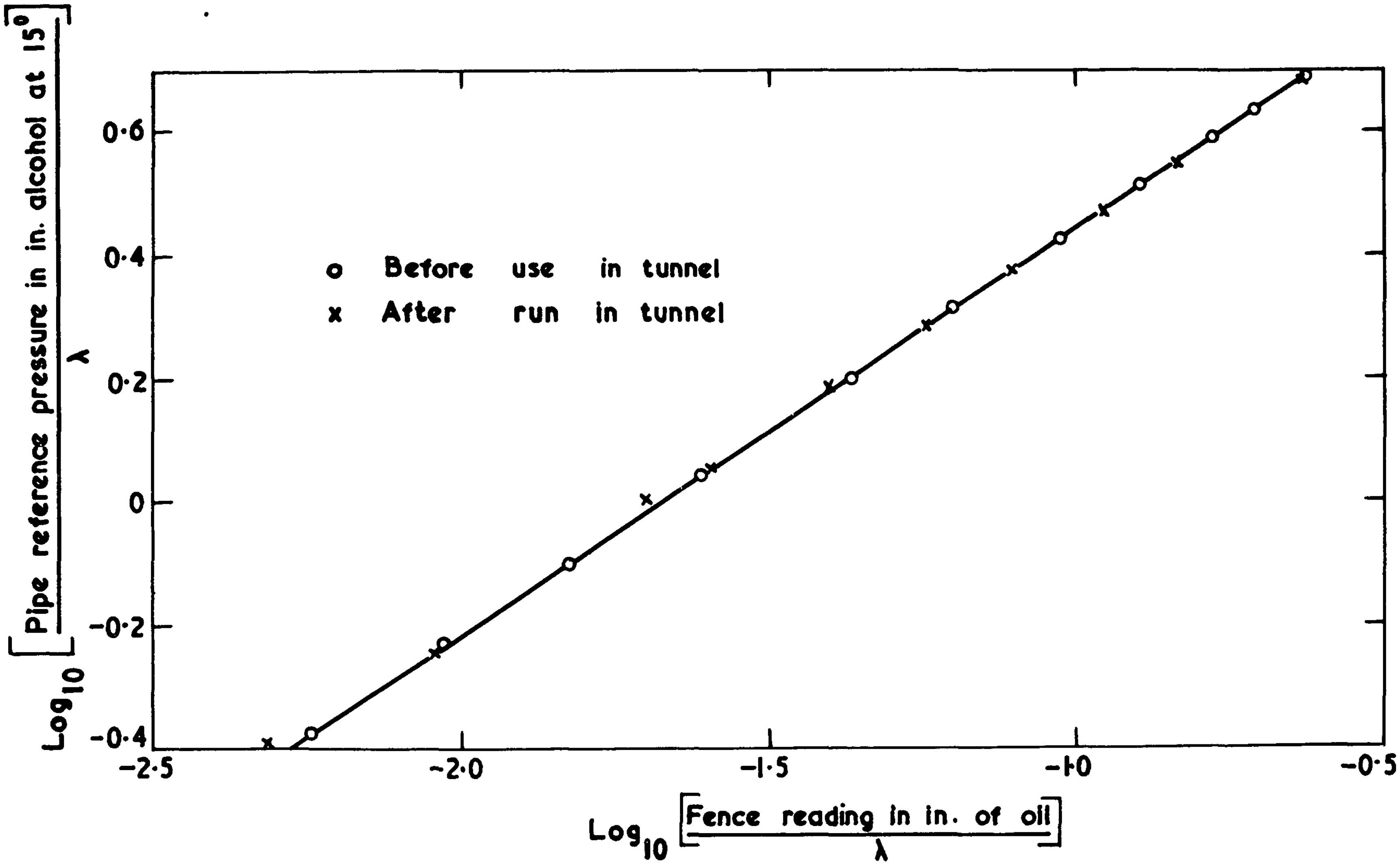
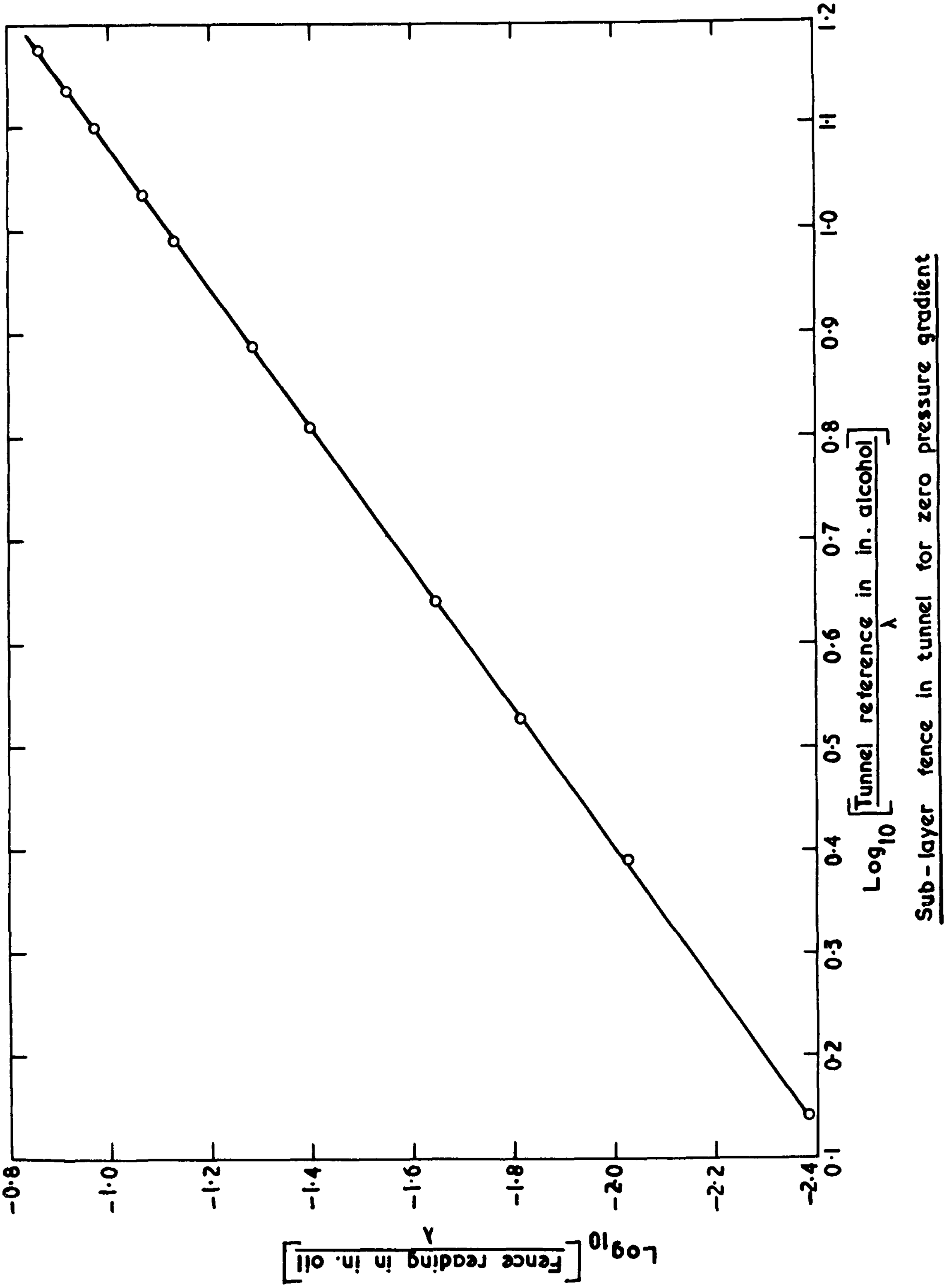


FIG. 4

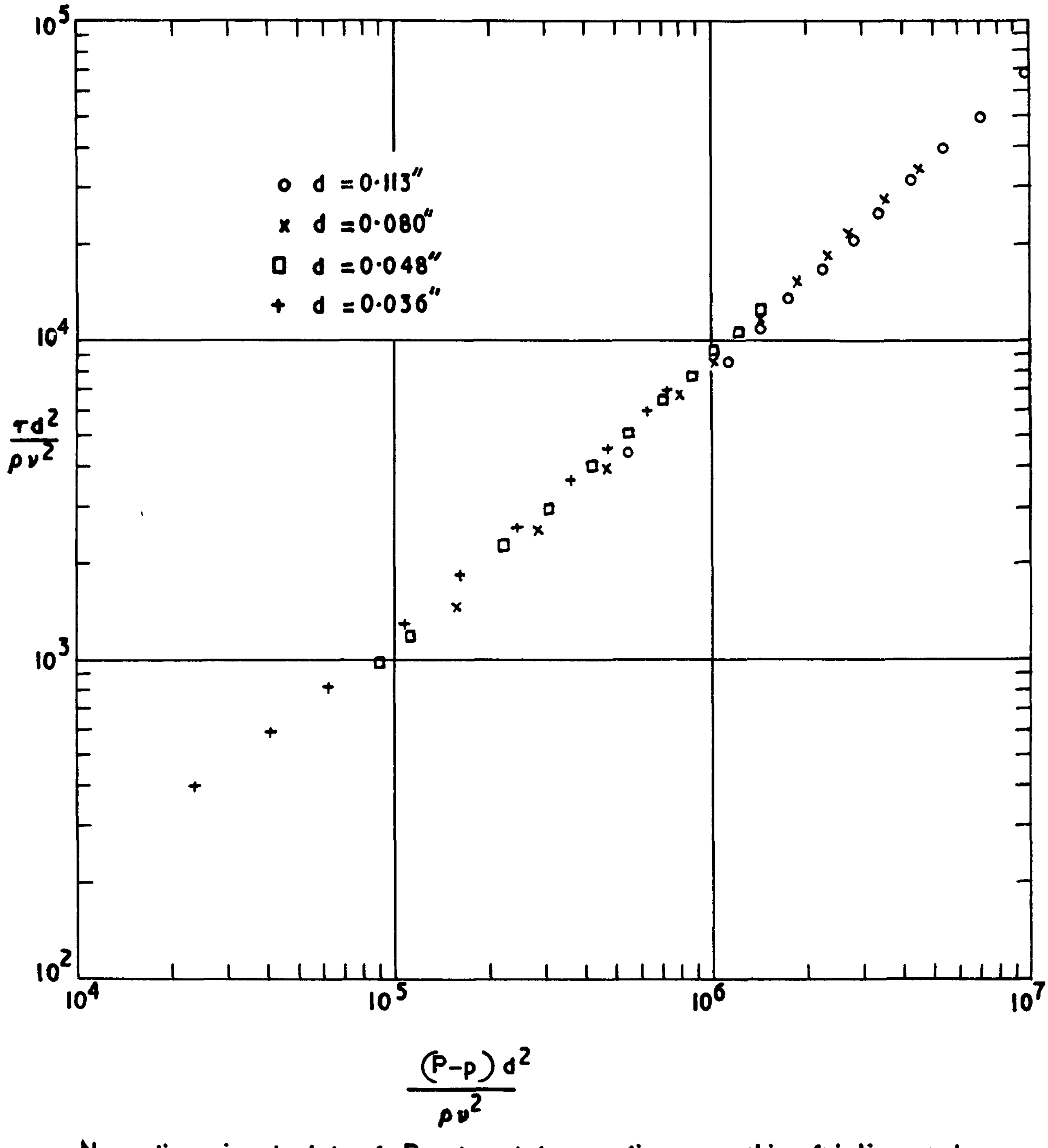
Calibration of sub-layer fence in the square pipe

FIG. 5



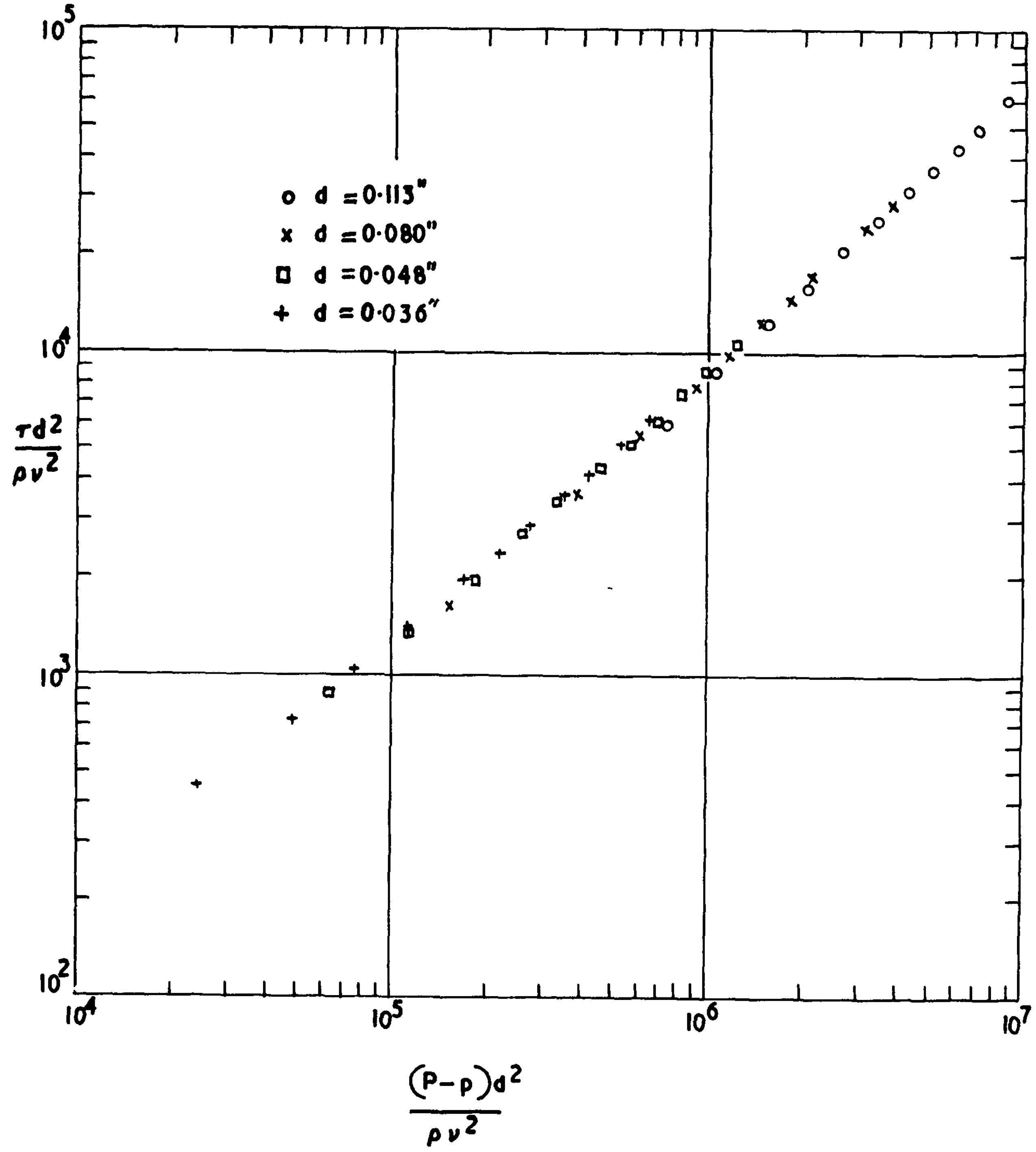
Log10 [Fence reading in in. oil / λ]
-0·8
-1·0
-1·2
-1·4
-1·6
-1·8
-2·0
-2·2
-2·4
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
Log10 [Tunnel reference in in. alcohol / λ]
Sub-layer fence in tunnel for zero pressure gradient

FIG.6



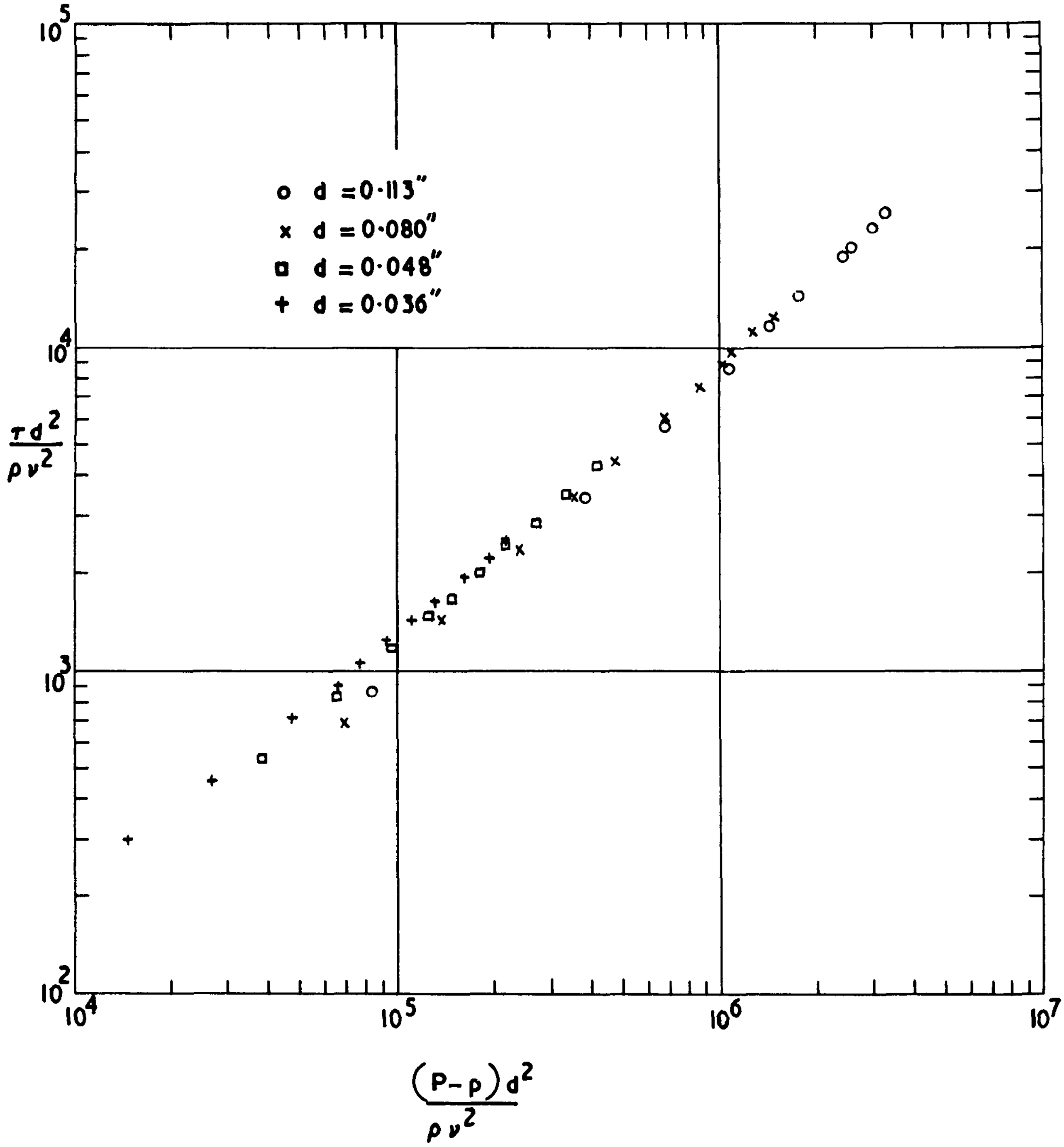
Non - dimensional plot of Preston tube readings vs. skin friction values for zero pressure gradient in tunnel.

FIG. 7

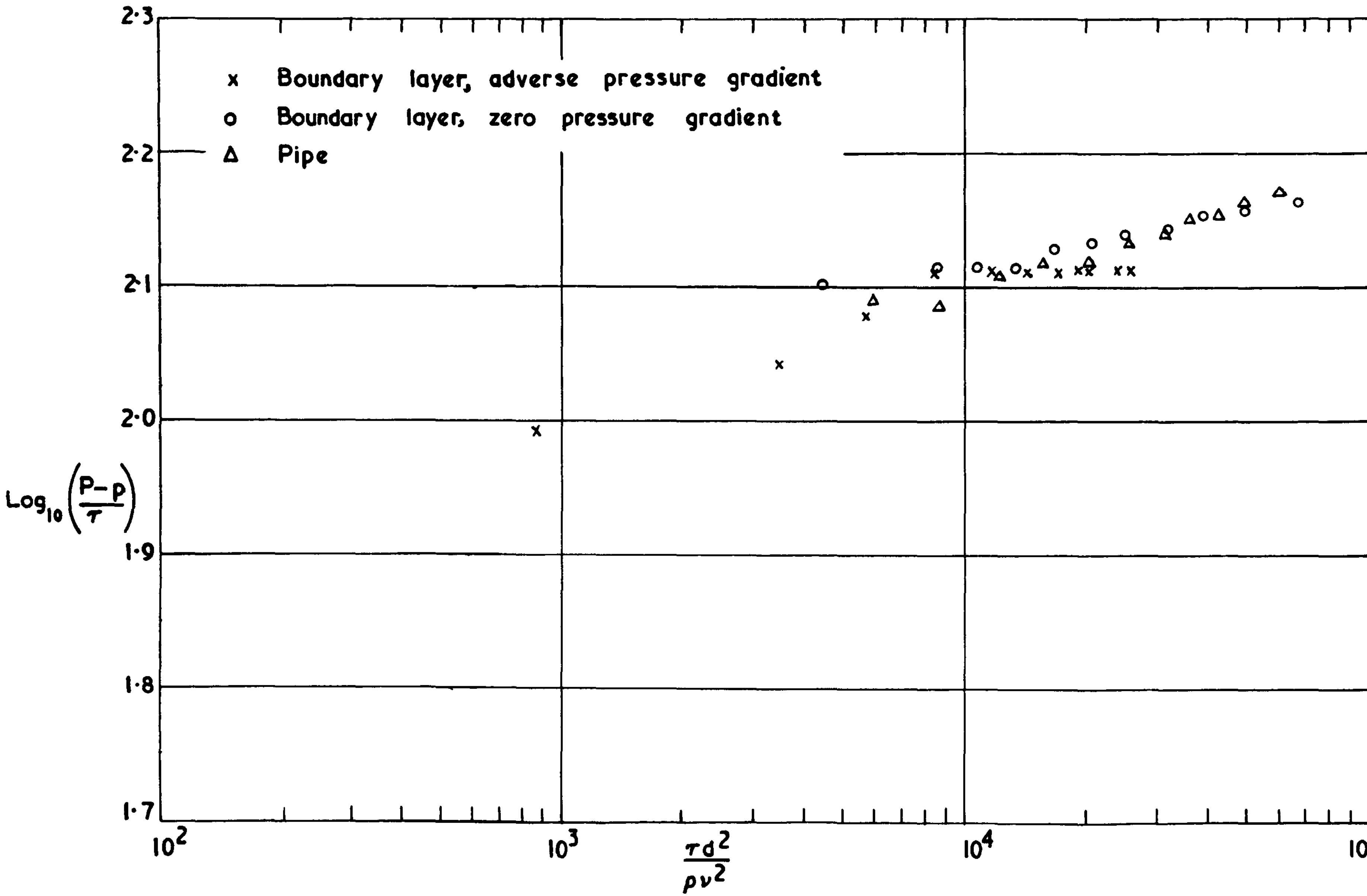


Non-dimensional plot of Preston tube readings vs. skin friction values in the square pipe

FIG. 8



Non-dimensional plot of Preston tube readings vs. skin friction values for adverse pressure gradient in tunnel



Re-plot of 0·113" Preston tube readings for different flows

FIG. 9

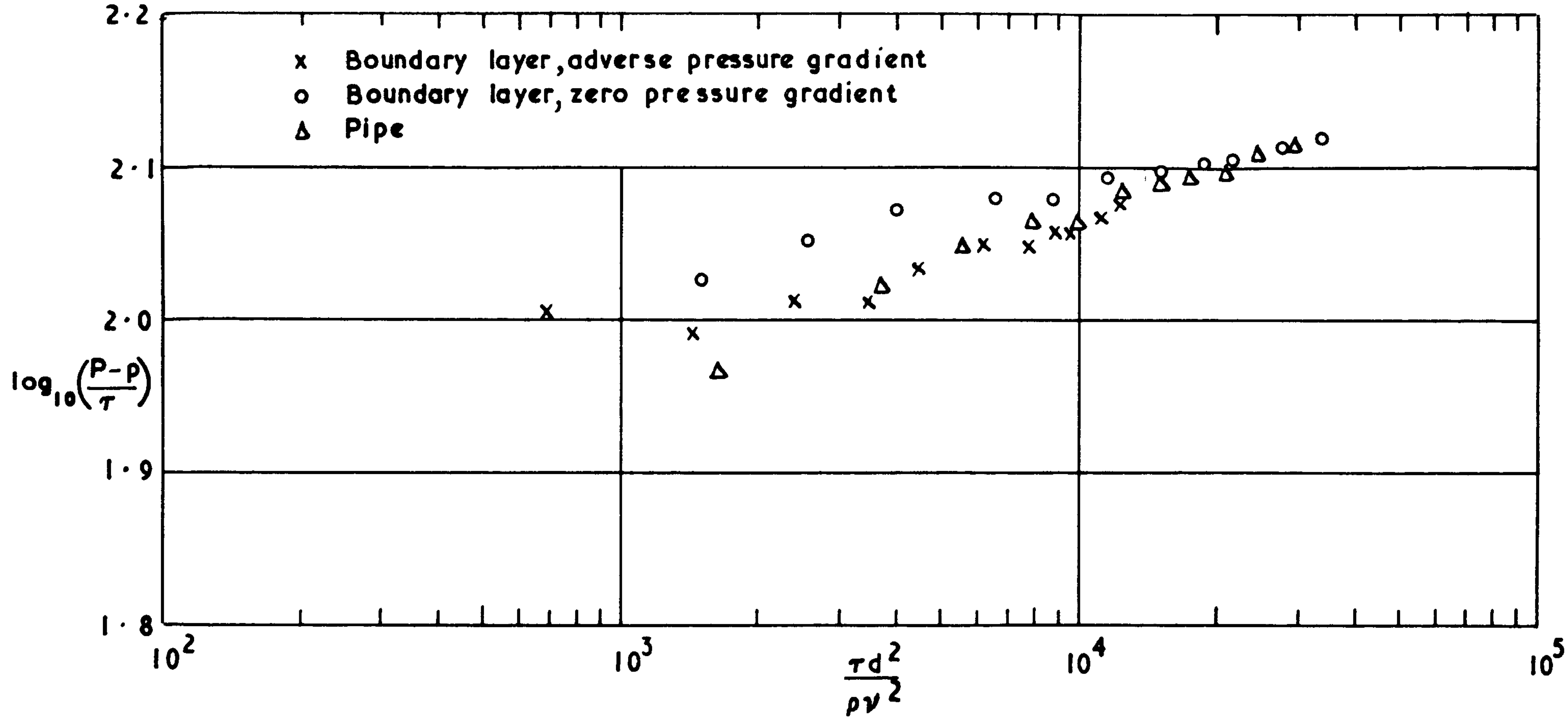


FIG. 10

Re-plot of 0·080" Preston tube readings for different flows

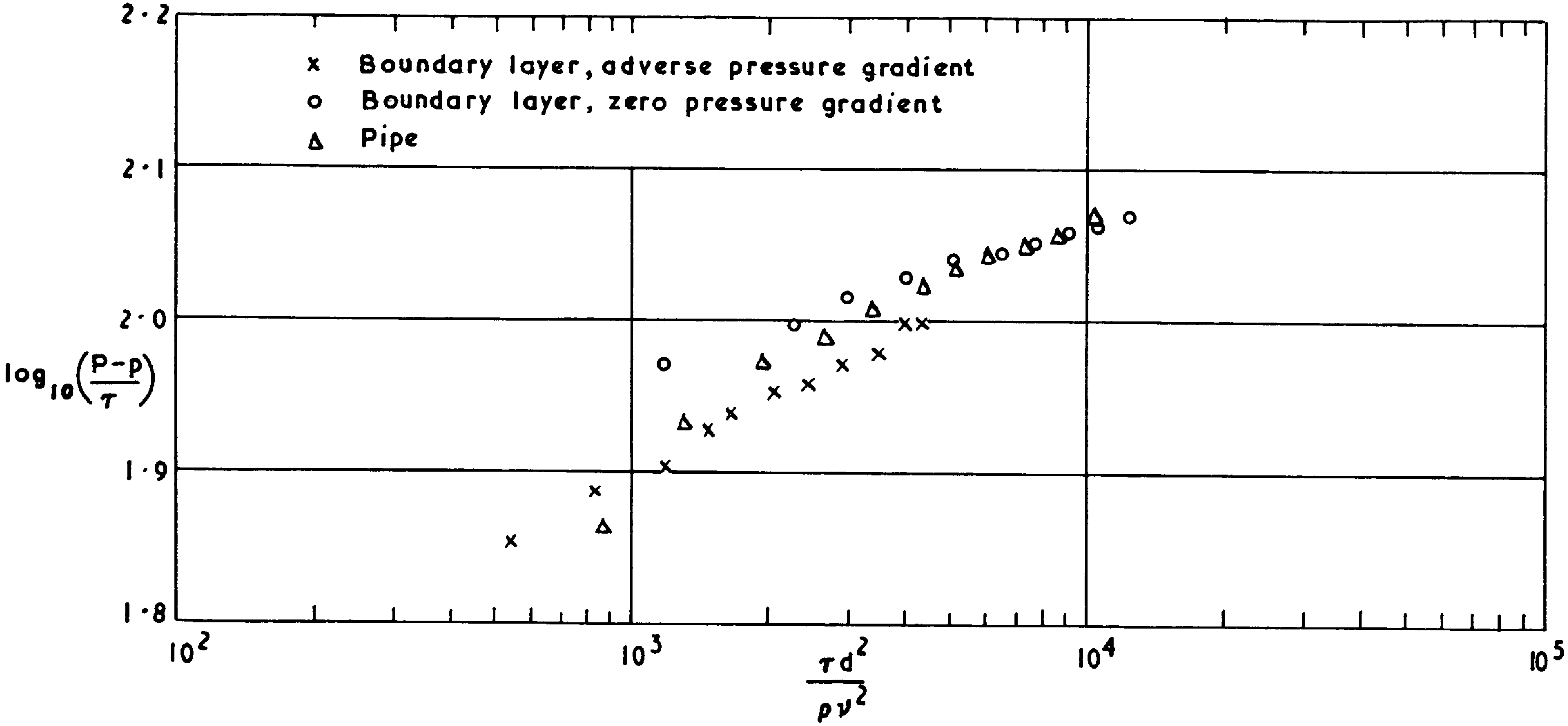
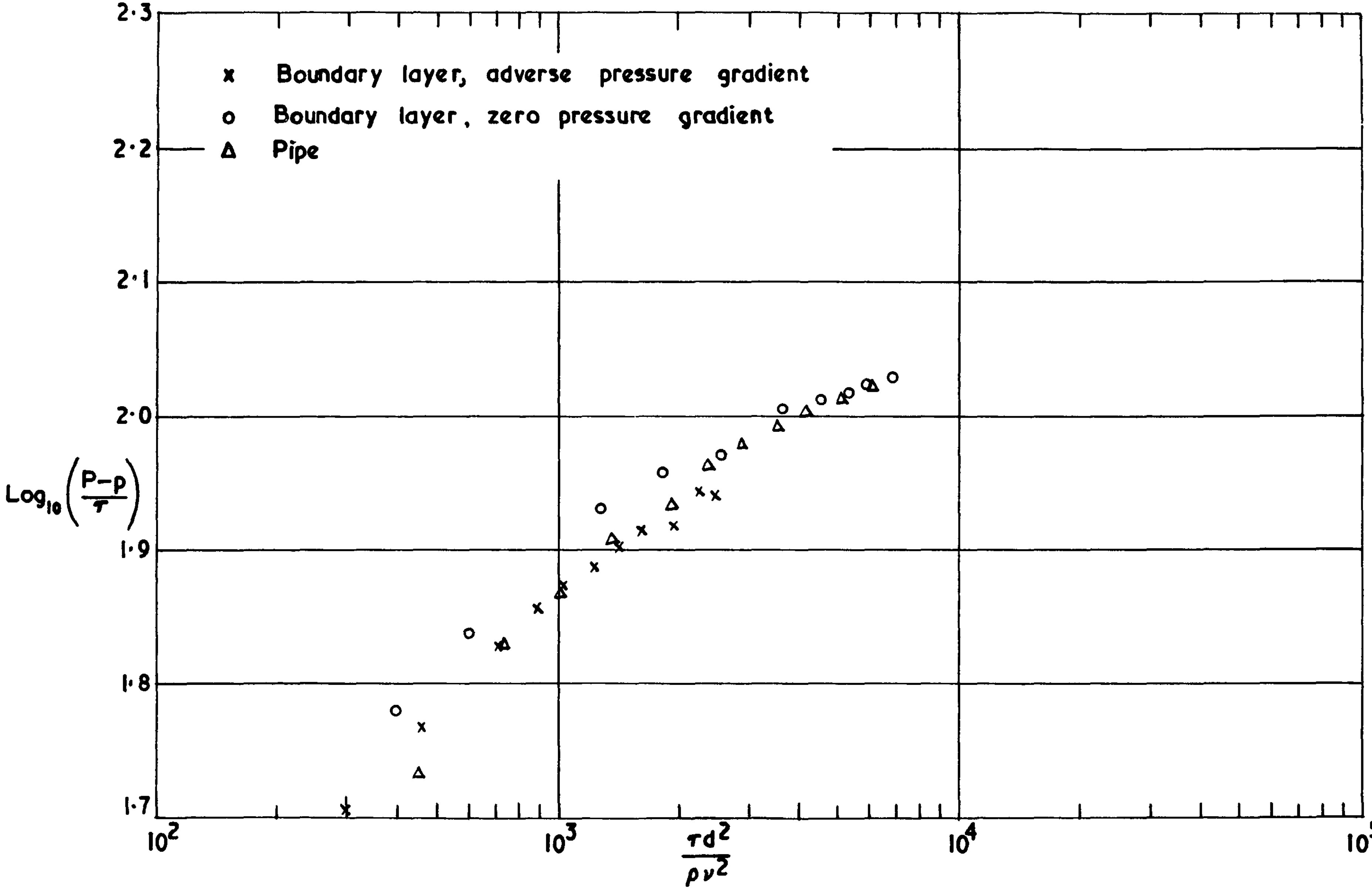


FIG. 11

Re-plot of 0·048" Preston tube readings for different flows



Re-plot of 0·036" Preston tube readings for different flows

FIG. 12

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February, 1965
D. H. Ferriss, B. Sc.

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The tests have emphasized the need for dimensional accuracy in manufacture of the pipe.

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