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Errors in static pressure measurements due to protruding pressure taps

By H. ZOGG AND H. THOMANN

Institute of Aerodynamics, Swiss Federal Institute of Technology, Zurich

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Errors in static pressure measurements caused by taps which protrude beyond the wall and disturb the boundary layer locally are investigated experimentally. The resulting error is presented as a function of the wall shearing stress, the protrusion height and the probe diameter in a representation similar to the calibration curve of Preston tubes. If suitably plotted, the present results can be made to fit this calibration curve to within the experimental accuracy, in spite of the differences between the geometries being compared.

1. Introduction

Static pressures in flows are commonly measured by holes drilled in a bounding surface. Often a short piece of pipe tubing is inserted into the hole for connexion with some manometric system. This assembly is referred to as a pressure tap. There are several ways in which errors may occur in the application of this method. One type of error results from the presence of the hole in the surface. Recently, the results of a thorough study of this effect have been published by Franklin & Wallace (1970); for further references this article may be consulted.

The object of the present report is to investigate a second type of error which occurs if the static pressure tap is not flush with the wall. This situation might arise, for example, if the pressure tap were inadvertently mounted poorly, or if the wall surface were subliming, eroding or ablating. Knowledge of the error resulting from a protruding tap could also be used for specifying tolerances for the installation of pressure taps.

The error due to a protruding pressure tap was determined experimentally for incompressible turbulent flow. The data are presented in the same non-dimensional form as the calibration curve for the Preston tube (Patel 1965) and this reduces the results to a single-parameter family of curves, as long as the tap remains in the part of the boundary layer in which the universal law of the wall is valid. An interesting feature of the results is the strong resemblance to the calibration curve of the Preston tube.

2. Apparatus and experimental procedure

The experiments were performed in a wooden duct of rectangular cross-section (0·2 × 0·1 m). The hydraulic roughness of the surface was 0·027 mm. To ensure fully developed turbulent flow the measurements were made 110 hydraulic diameters downstream from the inlet. The protruding tap was mounted in

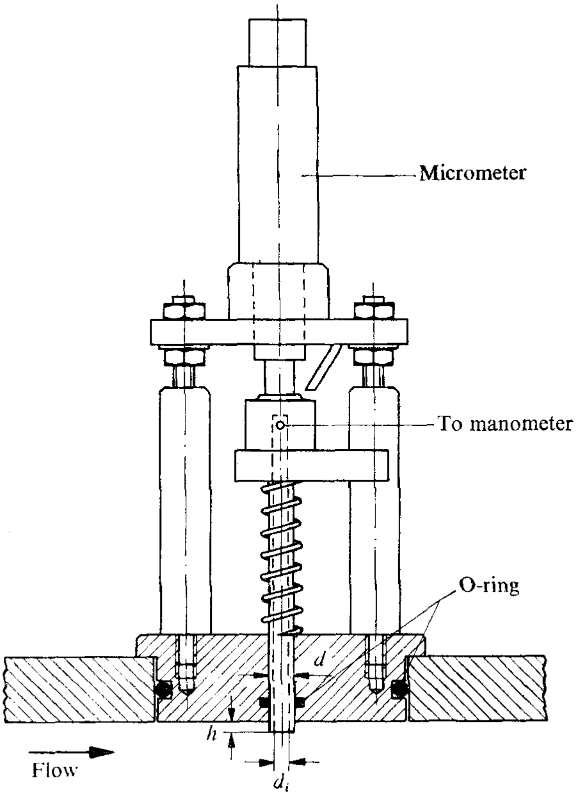

FIGURE 1. Sketch of the static pressure probe.

the middle of one of the wider duct walls. Atmospheric air was drawn through the duct by a radial flow fan. Static pressure probes of six different diameters were examined. The outer probe diameters d were 1 mm, 2 mm, 2·5 mm, 5 mm, 10 mm and 20 mm and the inner diameter d_i was 0·6 times the outer diameter. The height of protrusion of the taps was set so that the ratio h/d was 0·1, 0·2, 0·3 or 0·5. The depth l of the hole was 2 to 40 times d_i, so that it did not affect the readings. The geometry of the tap is shown in figure 1, which also displays details of the mounting.

The reference static pressure p_r was measured by three pressure taps 1 mm in diameter placed in the same cross-sectional plane as the tap under test and in the middle of the three remaining duct walls. The difference between the average pressure of these reference taps and the pressure p_e sensed by the protruding tap, $\Delta p_e = p_r - p_e$, was measured to an accuracy of $\pm 1\,\mathrm{N/m^2}$.

The local skin friction τ was measured by applying the method of Preston (1954) and using the calibration curve of Patel (1965). This value was compared with a mean value of skin friction calculated from the pressure gradient. Both values were found to be in good agreement if the variation of τ on the duct wall was taken into account. The mean velocity in the duct was varied from 10 to 55 m/s, corresponding to Reynolds numbers based on the hydraulic diameter from $8{\cdot}5 \times 10^4$ to $5{\cdot}2 \times 10^5$.

3. Analysis and presentation of results

The presentation of the data is facilitated by using geometric and dynamic similarity properties of the system. Geometric similarity exists if the ratio h/d (figure 1) is constant, as the ratio of the diameters d_i/d was constant during all measurements. Dynamic similarity is expressed by a non-dimensional equation for the pressure difference Δp_e:

$$\Delta p_e h^2/4\rho\nu^2 = f_1(\tau h^2/4\rho\nu^2, h/d). \tag{1}$$

A representation of this type is well known from similar considerations, for example, for the Preston tube (Preston 1954) or the 'static-hole error' (Shaw 1960; Franklin & Wallace 1970). The function f_1 is universal as long as the tap is located well within the part of the turbulent boundary layer which is described by the universal law of the wall. This fact has been firmly established by numerous investigations (see for instance Patel 1965). The boundary y_0 of the universal part of the boundary layer in the case of zero or moderate pressure gradient is approximately given by $u_\tau y_0/\nu = 300$, where $u_\tau = (\tau/\rho)^{\frac{1}{2}}$ denotes the friction velocity and ρ and ν are the local values of the fluid density and kinematic viscosity respectively. The characteristic length was chosen as h rather than d because h is better suited for comparison with the thickness of the boundary layer.

The main results of the investigation are shown in figure 2. The pressure error Δp_e is plotted against the wall shearing stress τ, both being in non-dimensional form. The ratio h/d appears as a parameter. This diagram shows the universal character of the relation between the pressure error and wall shearing stress, as the results corresponding to taps of different diameters lie on a single curve. $\Delta p_e = p_r - p_e$ is positive, as expected. For $\tau h^2/4\rho\nu^2 > 10^3$, the relationship between the non-dimensional shear and pressure error can be expressed by a power law with an exponent $\alpha_1 = 1{\cdot}12$. For $\tau h^2/4\rho\nu^2 < 80$ the curves coincide for the values of h/d investigated and in this region the relation can be expressed in terms of a power law with an exponent $\alpha_2 = 1{\cdot}92$. It is evident from the curves that the pressure error increases with both τ and h/d.

Comparison of the different curves reveals an interesting feature. Within the experimental accuracy these curves can be brought to coincidence by shifting both axes, i.e. by scaling both variables by a suitable factor, as shown in figure 3. This could not be expected from considerations of dimensional analysis, as different geometries are compared. It is even more striking that they are also congruent with the calibration curve of the Preston tube. This curve, as published by Patel (1965), is also plotted in figure 3. However the congruence cannot be exact, as can be concluded, for instance, from the experimental results of MacMillan (1956), who investigated displacement effects of Pitot tubes.

As an indication of the accuracy of the apparatus, the pressure difference Δp_e was also measured for zero protrusion height. High accuracy could not be expected, as the apparatus had not been designed for investigating the error caused by the hole diameter only, whose magnitude is smaller by at least a factor of three than that for the studied protruding tap. In spite of this, the error

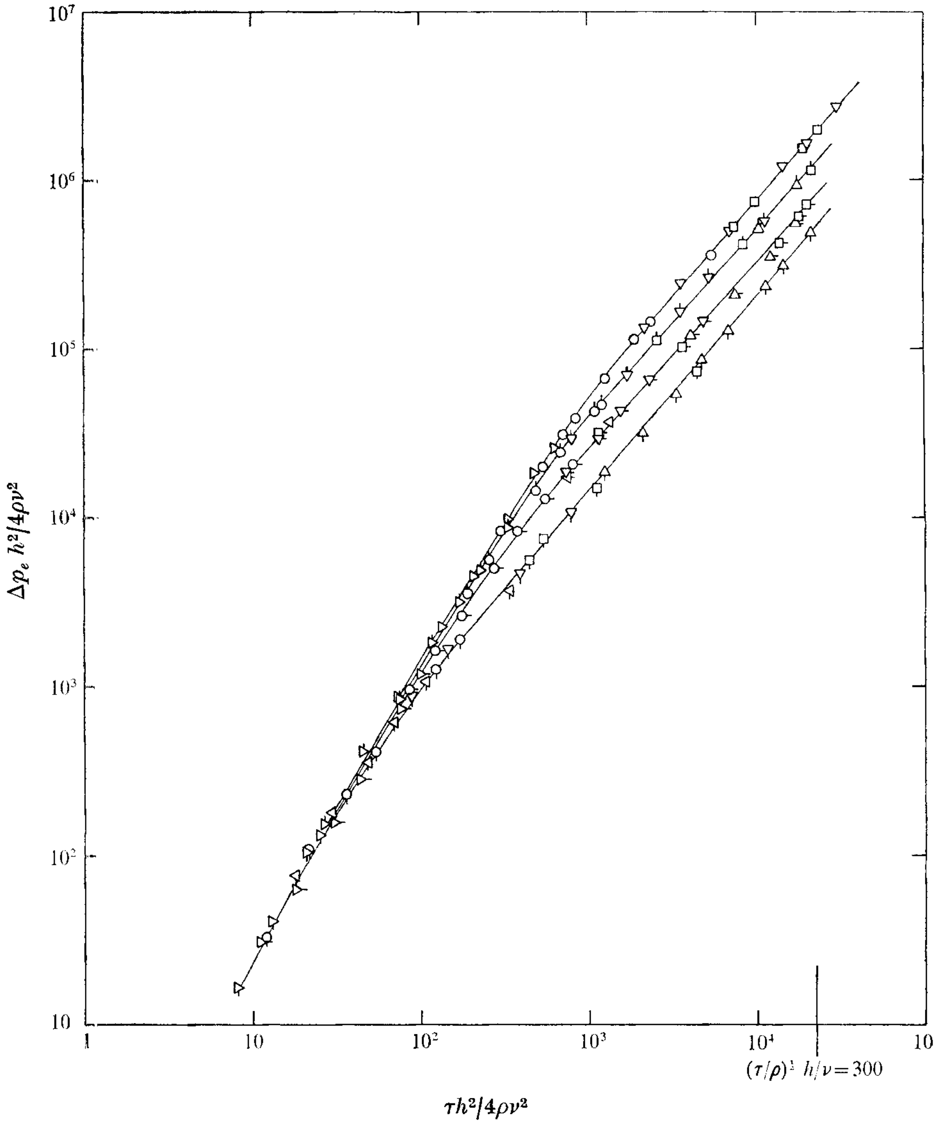

FIGURE 2. Non-dimensional error curve.

d (mm)	$h/d =$ 0·1	$h/d =$ 0·2	$h/d =$ 0·3	$h/d =$ 0·5
20	△	△	△	△
10	□	□	□	□
5	▽	▽	▽	▽
2·5	◁	◁	◁	◁
2	○	○	○	○
1	▷	▷	▷	▷

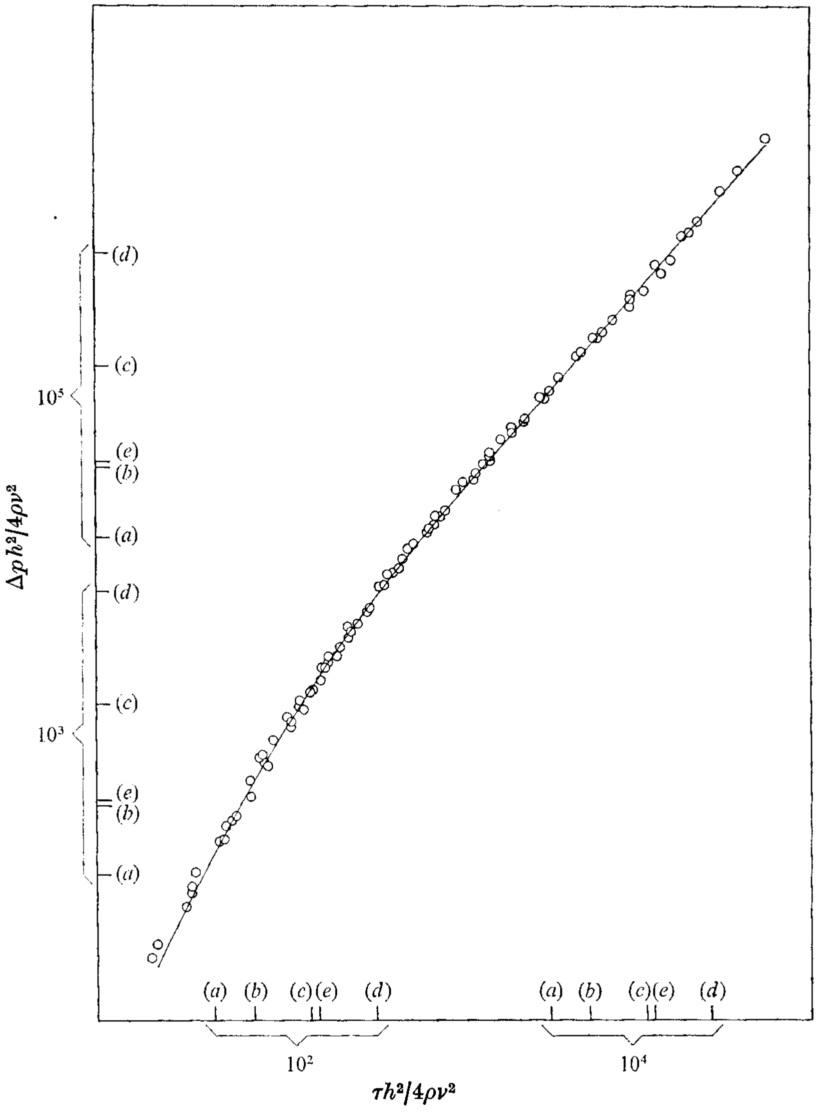

FIGURE 3. Comparison of error curves of protruding taps (data points) and Preston calibration curve (solid line). For the Preston probe, h denotes the outer diameter of the pipe. The different logarithmic scales are given by (*a*) $h/d = 0{\cdot}5$, (*b*) $h/d = 0{\cdot}3$, (*c*) $h/d = 0{\cdot}2$, (*d*) $h/d = 0{\cdot}1$, (*e*) Preston tube.

curve was similar to that published by Franklin & Wallace (1970), although the measured errors were up to twice as large. Yet it was satisfying that these results had the correct sign and the right order of magnitude.

4. Conclusions

The main results of the present investigation are the error curves for protruding pressure taps shown in figure 2 and the fact that the error can be expressed by universal functions, as long as the tap does not protrude beyond the universal part of a turbulent boundary layer. The pressure sensed by the protruding tap is smaller than the wall static pressure. An interesting property of the curves is that, within experimental accuracy, they can be made to coincide with each other and with the Preston calibration curve by a suitable scaling.

Although the experiments were carried out for only one ratio of the inner to the outer diameter of the taps ($d_i/d = 0{\cdot}6$), it is expected that this ratio does not have a great influence on the pressure error. This could be checked in further investigations. Another point of interest would be to study the region close to the wall in which the error due to the protruding tap is balanced by the static-hole error (which is different in sign).

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