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Static pressure correction in high Reynolds number fully developed turbulent pipe flow

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Abstract
Measurements are reported of the error in wall static pressure reading due to the finite size of the pressure tapping. The experiments were performed in incompressible turbulent pipe flow over a wide range of Reynolds numbers, and the results indicate that the correction term (as a fraction of the wall stress) continues to increase as the hole Reynolds number $d^+ = u_\tau d/\nu$ increases, contrary to previous studies. For small holes relative to the pipe diameter the results follow a single curve, but for larger holes the data diverge from this universal behaviour at a point that depends on the ratio of the hole diameter to the pipe diameter.

Keywords: static pressure, pressure tapping

Nomenclature

D	pipe diameter
d	diameter of static pressure tapping
d^+	non-dimensional diameter du_τ/ν
d_c	manometer connection diameter
l	tapping depth
u_τ	friction velocity $(\tau_w/\rho)^{0.5}$
Δp	difference between measured and true pressure at the wall
ϵ	burr height
μ	fluid dynamic viscosity
ν	fluid kinematic viscosity
Π	non-dimensional pressure error $\Delta p/\tau_w$
ρ	fluid density
τ_w	wall shear stress

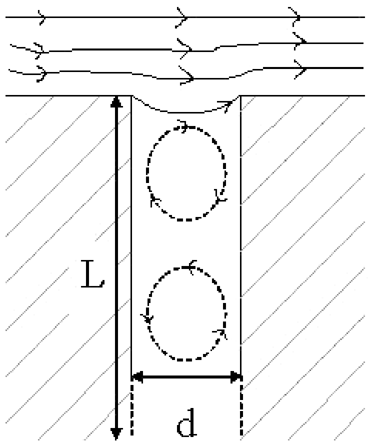

Figure 1. Flow structure within the static pressure tapping.

1. Introduction

To measure static pressure in a flowing fluid, a wall static tapping is often used, consisting of a small hole drilled in the wall connected to a pressure gauge. The presence of the hole affects the flow so that the streamlines are deflected into the hole and a system of eddies, often called cavity vortices, are generated within the tapping (figure 1). As a consequence, a pressure will be recorded by the tapping that is higher than the 'true' value at the wall. This problem is well known, and it has been the focus of several major investigations, including those by Allen and Hooper (1932), Ray (1956), Thom and Appelt (1957), Rayle (1959) and Livesey *et al* (1962). A summary of the complete literature is given in Chue (1975). Among the works of most interest are those by Shaw (1960), Franklin and Wallace (1970) and Ducruet and Dyment (1984).

We expect that the pressure error Δp will depend on the hole diameter d, the hole depth l (figure 1), the diameter of the connection to the manometer d_c, the wall shear stress τ_w, the fluid density ρ and the dynamic viscosity μ. The characteristic length scale of the facility, in this case the pipe diameter D, may be important for large holes. Thus

$$\Delta p = f(d, D, \tau_w, \rho, \mu, l, d_c) \tag{1}$$

and

$$\Pi = \frac{\Delta p}{\tau_w} = f\left(\frac{du_\tau}{\nu}, \frac{d}{D}, \frac{l}{d}, \frac{d_c}{d}\right) \tag{2}$$

where u_τ is the friction velocity given by $\sqrt{\tau_w/\rho}$, ν is the kinematic viscosity and Π is the non-dimensional pressure error.

We assume first that d/D, l/d and d_c/d are held constant in order to explore how the pressure error depends on hole Reynolds number, $d^+ = u_\tau d/\nu$. As Shaw (1960) noted, for very small d

$$\Pi = \frac{\Delta p}{\tau_w} = \text{const} = 0 \tag{3}$$

since the streamline deflection becomes smaller as $d \to 0$ (and $d^+ \to 0$) and hence $\Delta p \to 0$ also. Although this limit is generally accepted as being correct, Kistler and Tan (1967) suggested that the mechanism for the pressure rise within the hole was such that, even for small holes, the measured pressure would always be higher than the true static pressure. However the error introduced by this effect would be asymptotically small.

Shaw (1960) also proposed that far from the wall, dynamic, and possibly turbulent, effects dominate the flow behaviour and thus for large d we have

$$\Pi = \frac{\Delta p}{\tau_w} = f\left(\frac{d}{D}\right) \tag{4}$$

where we see that the ratio d/D may be important. Shaw performed his experiments in a pipe of 50 mm diameter at pipe flow Reynolds numbers up to about 1.7×10^5. The absolute error at each Reynolds number was obtained by extrapolating the relative errors for all tappings to zero diameter and offsetting the data by this amount, which implicitly assumes that the absolute error follows a unique curve for small values of d^+. Shaw found that the non-dimensional pressure error, Π, increased with increasing d^+ but reached an asymptotic limit of approximately three at the highest value of d^+ (=750). In fact, a closer inspection of his data reveals a dependence on d, or more specifically d/D, that becomes more obvious as d^+ increases (see figure 2). Shaw, however, dismissed these trends for all but the largest tapping and concluded that a single curve could be found that describes all the results.

Franklin and Wallace (1970) studied the effects of hole Reynolds number up to $d^+ = 2000$ in a wind tunnel wall boundary layer. They employed flush-mounted transducers to determine the reference pressure reading (corresponding to zero hole diameter). When plotted on equivalent axes their results are very close to those of Shaw (1960) with a slightly higher asymptotic value of pressure error (3.7 compared to 3.0). Ducruet and Dyment (1984) also investigated the effects of hole Reynolds number in a boundary layer, including the effects of variations in streamwise velocity gradient and wall curvature. Their results again tend to those of Shaw (1960) for large d^+.

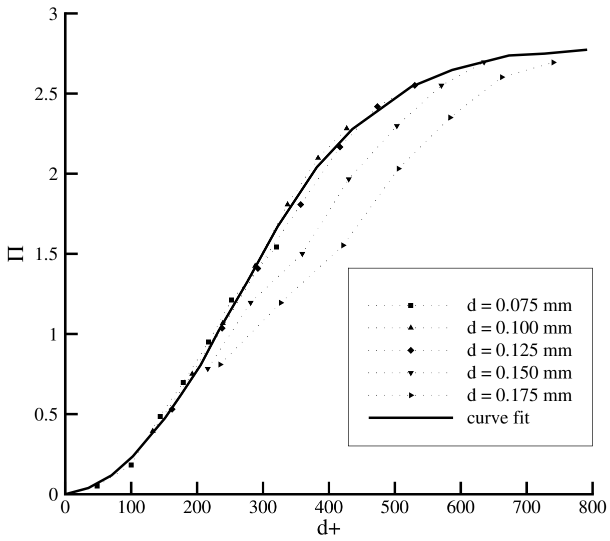

Figure 2. Results of Shaw (1960) for different diameter tappings in a 2 inch diameter pipe. Shaw's 'universal' curve is shown as a solid curve. Other curves are for guidance only.

As far as hole geometry effects are concerned, we see that as d is increased, the hole Reynolds number and the ratio of the hole to the pipe diameter d/D both increase. Eventually the hole must become large enough to change the flow field itself. Shaw (1960) suggested that this occurred at a value of d/D of about 0.1.

The depth-to-diameter ratio also plays an important role since it dictates the eddy system set up within the cavity. It has been shown in past investigations that the error increases with l/d ratio, and that the error is always positive (that is the measured value is always higher than the true value) but when l/d approaches 1.5–2 Shaw found that there is no further change with l/d, and this may represent the 'deep' limit for all Reynolds numbers. Chue (1975) pointed out that the connection to the manometer is important for tappings with a small l/d ratio: a wide cavity behind the tapping reduces the error and for a very shallow tapping can even lead to a negative pressure error, while a contraction in diameter from the tapping to the manometer connection can increase the error (Livesey *et al* 1962).

The present investigation was driven by the need to make accurate static pressure measurements at pipe flow Reynolds numbers up to 35×10^6, with a maximum $d^+ > 6400$, and $d/D = 0.006$ (Zagarola and Smits 1998). First, we had reasons to doubt the earlier conclusions by Shaw that the ratio d/D was not important for values less than 0.1, and second, the behaviour of static pressure tappings at Reynolds numbers that were an order of magnitude greater was unknown. It was decided, therefore, to perform a new investigation of static pressure errors for Reynolds numbers up to $d^+ = 8000$. As we will show, it was found that the error does not reach an asymptotic limit, but continues to increase with d^+, and demonstrates a significant d/D dependence.

2. Experimental facility and procedures

The experiments were performed in the Princeton/DARPA/ONR Superpipe, a facility constructed to enable the study

Table 1. Dimensions of tappings.

	d (mm)	d/D
A	2.381	0.0184
B	2.083	0.0161
C	1.588	0.0123
D	1.191	0.0092
E (×2)	0.794	0.0061
R (reference, ×4)	0.572	0.0044
F	0.254	0.0020

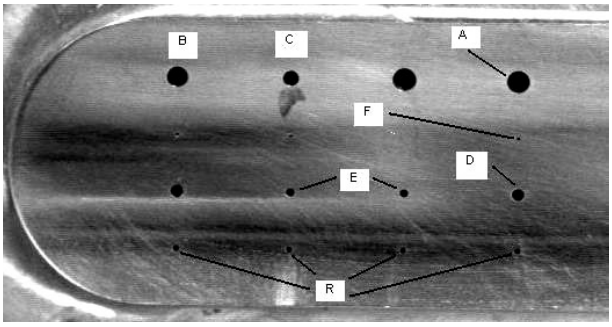

Figure 3. Photograph of test piece.

of fully developed turbulent pipe flow over a wide range of Reynolds numbers. The working fluid is air at ambient temperature and pressures up to 187 atm, allowing a variation in the kinematic viscosity by a factor up to 160. Reynolds numbers in the range $Re_D = 31\times10^3$–35×10^6 can be achieved in this manner. The maximum Mach number encountered in the facility is approximately 0.07. The test pipe has a nominal diameter of 129.36 ± 0.08 mm, and a length of $202D$. The facility is described in detail by Zagarola and Smits (1998) and Zagarola (1996).

The current study was performed at a location approximately $200D$ downstream from the entrance to the pipe. Pressure tappings with diameter ranging from 0.254 to 2.381 mm (or $d/D = 0.0020$–0.0184) were drilled into the blank test piece. The 0.572 mm tappings were designated as reference values d_{ref}. For the first set of tappings, three rows of holes were drilled, 12.7 mm apart to minimize interference between the tappings, with one tapping of reference diameter in each row to verify the reference pressure measurement. In addition, there were two holes of diameter 0.794 mm in the set in order to check the error in pressure reading associated with nominally identical tappings. The tappings used in the final experiment are given in table 1 and shown in figure 3. The test piece, which sits flush with the pipe surface in a slot machined to an interference fit, was approximately 9.21 cm long and approximately 27.6° of the circumference. The rms base roughness of this insert was approximately 0.15 μm, similar to the rest of the pipe.

All the tappings were examined under an optical microscope with 10× magnification. The design of the test facility meant that the tappings were drilled inwards from the polished measurement surface, thus reducing the expected level of burring and avoiding additional rounding of the hole edge due to polishing or honing after drilling. Nevertheless, it was found to be extremely difficult to drill the smallest hole with smooth edges, and the largest hole displayed some burring

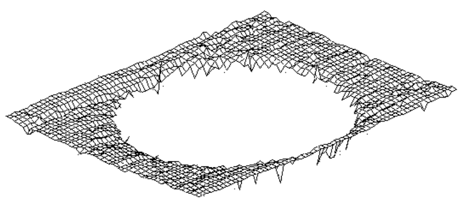

Figure 4. Sample magnification of 0.794 mm tapping.

at the edge. Since sanding has been found to round the edges of the tappings to some extent (Franklin and Wallace 1970) and a radius on the edge alters the separation of the flow from the cavity edge (Savory *et al* 1996) which can affect the pressure error magnitude (Rayle 1959), new holes were drilled in an additional row of tappings. The holes were observed to be round and perpendicular to the surface. A Zygo white light scanning interferometer was then used to examine the profile of the holes. The only burr observed was to the side of one of the largest holes, but the amplitude, ϵ, was less than 1.5 μm, giving $\epsilon/d_{ref} = 0.63 \times 10^{-3}$. Extrapolating the results of Shaw's (1960) study of burr effects, this ϵ/d corresponds to a negligible additional pressure error. Nevertheless, the results from this hole were removed from the data set. The maximum ratio of edge radius to hole diameter was estimated to be less than 0.001. Rayle (1959) found that an edge radius of $D/4$ led to an error of 0.2%, so the effect of edge radius on the current study can be considered to be negligible. A sample surface profile is shown for one of the 0.794 mm tappings in figure 4. The insert was thoroughly cleaned before each use, since a speck of dust sitting on the edge of a tapping would have the same effect as a similarly sized burr, as observed by Shaw.

Each hole was drilled to a depth of $4d$ and backed into a hole of diameter large enough to receive tubing of d internal diameter. In this way, the overall l/d was effectively infinite. All the tappings were connected to the transducer through a Scanivalve in an identical fashion. The overall reference tapping was connected directly to the transducer.

Validyne pressure transducers DP15-30 and DP15-22 with a combined range of 0–8.6 kPa were used to measure differential pressures with a resolution of 0.25% full scale. For each pipe Reynolds number, the pressure drop along the pipe and the pressure error for each tapping relative to the reference pressure were recorded. Special care was taken to eliminate transducer drift since this has an important effect on the accuracy of the pressure error measurement. The transducer signals were filtered using a Krohn–Hite filter model 3988 in low-pass mode at 10 Hz and sampled at 500 Hz for 20 s, which was found to be sufficient to achieve convergence at all Reynolds numbers.

The absolute error for the reference hole was established at the lowest Reynolds number by extrapolating the relative error (which is zero for the reference diameter tapping and therefore negative for the smallest tapping F) to zero hole diameter. The scaled data at this Reynolds number were curve fitted and this curve was then used to establish the absolute error at the reference hole Reynolds number d^+_{ref} at the next pipe Reynolds number, Re_D. The reference hole Reynolds number always lay within the range of hole Reynolds numbers described by the lower Reynolds number curve. This procedure was continued to the highest Reynolds numbers. It was therefore assumed that

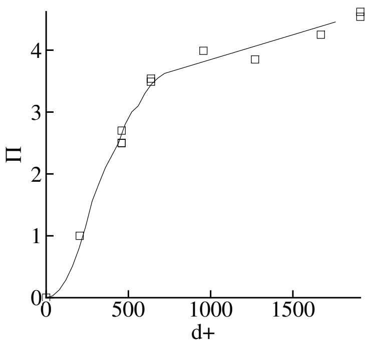

Figure 5. Distribution of non-dimensional pressure error data, Π (□), around curve fit (——), $Re_D = 3 \times 10^6$.

the low Reynolds number data were described by a universal curve. This proved to be correct, as the results will show. In this manner, the error due to extrapolation of data at high d^+ to zero hole diameter was avoided. It should be noted that even when the error for the larger tappings diverged from the curve that describes the lower Reynolds number results, at least two data points lay on the curve (including the reference tapping).

3. Static pressure errors

Figure 5 shows a sample distribution of data and the corresponding curve fit for $Re_D = 3 \times 10^6$. The maximum deviation of the Π data from the curve was observed to be 0.3 and in general the difference was less than half that value. Zagarola (1996) estimated that the errors in τ_w and Δp were ±0.83 and ±0.40%, respectively, or less than 1% of $\Delta p/\tau_w$. Additional errors will be introduced due to the non-ideal tapping geometry, since we know that small deviations can have large effects. Comparing two tappings of nominally the same diameter, the maximum difference in measured pressure error was found to be $\Delta\Pi = 0.35$ at $Re_D = 14 \times 10^6$, although this value was smaller at low Reynolds numbers. Thus the interference between tappings was confirmed to be negligible.

The variation of non-dimensional pressure with hole Reynolds number is shown in figure 6 for all tappings and flow Reynolds number greater than 5×10^5. The low Reynolds number data ($180 \times 10^3 < Re_D < 750 \times 10^3$) lie on the universal curve that exists for $d^+ < 500$. The shape of the curve for each Reynolds number is similar, but achieving a high d^+ by increasing the flow Reynolds number leads to a different result than achieving a high d^+ by increasing the hole diameter at the same flow Reynolds number. This is in contrast to Shaw (1960) who concluded that a single curve described the behaviour for all $d/D < 0.0945$ (the curve of Shaw is shown in figure 6 for comparison). The data follow a common curve up to some value of d^+, and then diverge at some point depending on the value of d/D. The higher d/D, the lower the divergence value of d^+. This observation is discussed further below. We find that, for the range of experiments performed here, the maximum error continues to increase with Reynolds number. For the largest tapping diameter at the highest pipe Reynolds number $Re_D = 14 \times 10^6$ the error has a maximum value of $\Delta p/\tau_w = 7.4$, about twice the maximum value observed in previous work performed at lower Reynolds numbers.

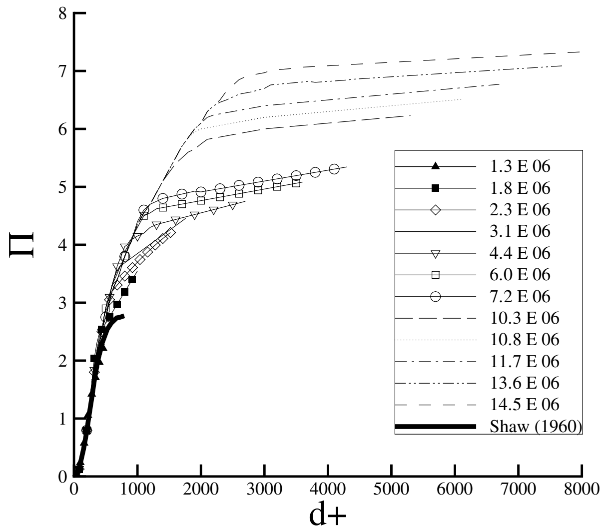

Figure 6. Variation of non-dimensional pressure error, Π, for different pipe Reynolds numbers Re_D.

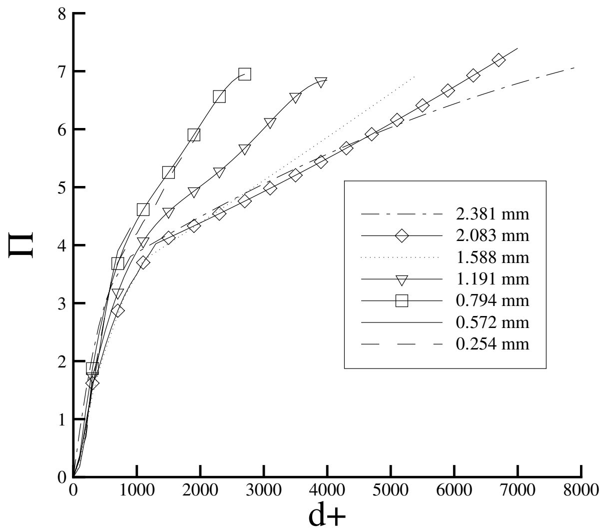

Figure 7. Variation of non-dimensional pressure error, Π, with tapping diameter.

The variation of non-dimensional pressure for each tapping diameter is shown in figure 7. There is agreement between all the tappings for d^+ up to approximately 500. Beyond this value the pressure error for larger tappings is smaller than obtained using a smaller diameter hole at the same d^+.

4. Discussion and comparison with previous work

Figure 6 suggests that there is a universal dependence of non-dimensional pressure error on hole Reynolds number, d^+, as long as d^+ is small. If the flow Reynolds number is held constant and measurements of pressure error are made with tappings of increasing diameter (that is, d^+ is increased by increasing d), a value of d^+ will be reached at which the pressure errors diverge from this universal curve: the tapping is 'too large' for the wall scaling to hold. Similarly, if a tapping of a certain diameter is used and the flow Reynolds number is increased, there will be a Reynolds number at which the pressure error diverges from the universal curve. The larger the diameter of the tapping, or more specifically the larger the value of d/D, the smaller the value of d^+ at which the divergence takes place.

Shaw's (1960) data reveal the same trend (see figure 2). His data are entirely consistent with those shown here, although they were in general obtained at lower Re_D by using larger values of d/D ($0.0080 < d/D < 0.0945$). The same trends occur, and different curves for each tapping diameter may be observed, although as indicated earlier Shaw ignored these trends in making his conclusions. His data also show that for the same d^+, but for a smaller d/D, the pressure error Π is higher, and it seems clear that the value of d/D must be considered in analysing the results. While it is obvious that large values of d/D could change the global flow pattern in the pipe, or at least the flow over the tapping, it is not clear at what value of d/D these effects become important.

These studies do not directly address the mechanism that is responsible for producing the pressure error. In fact, little is known regarding the flow induced within the tapping and in its immediate neighbourhood. There is an obvious analogy with the lid-driven or shear-driven cavity flows, and there are many numerical and experimental studies of shear-driven rectangular cavities from which the basic flow can be deduced. Stokes flow was assumed by Roshko (1955), Burggraf (1966), Kistler and Tan (1967), Pan and Acrivos (1967), Shen and Floryan (1985) and Gustafson and Halasi (1986), but studies at high Reynolds numbers were done by Nallasamy and Prasad (1977). Unfortunately, there is very little information on the flow within a cylindrical cavity, for either lid- or shear-driven flows. What literature there is deals almost exclusively with cavity Reynolds numbers in the Stokes flow regime, with the exception of the study by Savory *et al* (1996). For example, Pozrikidis (1994) and Shankar (1997) performed numerical studies of Stokes flow in cylindrical cavities: Pozrikidis examined shear flow over a plane wall containing the cavity while Shankar used a lid-driven cylindrical cavity. The basic flow structure in a centreline plane has been shown in figure 1 (Savory *et al* 1996).

Part of the difficulty in making the analogy with a lid-driven cavity flow is that the driving velocity for a cavity under a shear flow is unknown. Livesey *et al* (1962) postulated that the pressure error in a tapping was proportional to the dynamic pressure averaged over some fraction of a tapping diameter from the wall. He found that the pressure averaged over a distance $d^+/20$ was a good match to his data. Thus the driving velocity for a lid-driven cavity model might be taken to be the velocity calculated from a dynamic pressure averaged over a y distance that depends on the tapping size. A simpler model would assume that the driving velocity is equivalent to the velocity at some fraction of the hole diameter away from the wall, where the fraction could be Reynolds number dependent. It may be speculated that a local hole Reynolds number defined using a driving velocity would give a more obvious criterion on where the pressure error deviates from the universal curve.

The lid-driven cavity may also give some insight into the flow structure within the tapping. For example, Shankar (1997) showed that for a cylindrical cavity of infinite depth driven by the lid such that the flow inside was within the Stokes regime, an infinite series of eddies was formed along the depth of the cavity. The strength of the eddies decreased rapidly with distance from the lid, and the eddy closest to the lid was shown to extend to a depth of approximately 1.5 hole diameters. For cavities of finite depth, the number of eddies depended on the depth. In all cases, small and complex secondary eddies were observed in the corners of the cavity, where the recirculating flow of the large primary eddy separated from the wall. For cavity depths less than approximately $1.5d$, only one primary eddy was observed. As the depth was increased, the eddy grew to fill the cavity, but when the depth was increased to just above $1.5d$, the primary eddy stopped expanding and the secondary eddies merged, leading to two primary eddies and new secondary eddies. These flow patterns were also observed by Pozrikidis (1994) for shear-driven flow. Savory *et al* (1996) observed the primary eddy at higher Reynolds numbers but in cavities with rounded edges.

This observation fits nicely with Shaw's (1960) conclusion that the non-dimensional error increases with l/d for $l/d < 1.5$ and then remains fixed (for a given d^+). At this point in the lid-driven cavity the flow structure near the top of the cavity is fixed, and any subsequent eddies are significantly weaker; this may provide an explanation of why the pressure error remains constant even if the cavity is made deeper. However, as the Reynolds number within the cavity increases beyond the Stokes regime, the streamline pattern need no longer be symmetrical. Studies of the two-dimensional lid-driven rectangular cavity by Pan and Acrivos (1967) suggest that the core of the eddy will move slowly downwards, and that the eddy will never reach an inviscid limit but continue to grow as the Reynolds number increases (this was shown to be true for cavity Reynolds number up to 4000 for infinite depth). Further visualization or numerical studies are necessary to confirm that $l/d = 1.5$ is a valid criterion for constant error as the Reynolds number increases, but the suggestion looks promising.

The divergence of the pressure error from wall scaling at higher Reynolds numbers may be related to the presence of a shear layer formed by the separation of the turbulent pipe flow from the upstream edge of the tapping. It is possible that instabilities may develop in the shear layer that cause it to flap, and the cavity would then no longer remain closed. For inviscid flow, the resonant frequency would be the organ pipe natural frequency of the tapping, but for viscous flow it is probable that any instability is damped until a critical condition is exceeded. Covert (1970), for example, found a critical Strouhal number based on effective natural frequency of the cavity for a laminar shear layer over a deep rectangular cavity and Sarohia (1977) found a critical value of $(d\sqrt{Re_\delta}/\delta)$ for oscillations of a laminar shear layer (of thickness δ at the separation point) over a shallow rectangular cavity.

Developing the ideas of Covert, a cylindrical cavity may display a critical value of Strouhal number, $St = fd/U$, where f is the natural frequency of the cavity, d is the diameter of a neutrally stable cavity and U is the effective driving velocity, corresponding to neutral stability of the shear layer. If the driving velocity were increased above this neutral limit, the shear layer would become unstable and the cavity flow would effectively enter a new regime. It is expected that the instability would grow until the energy extracted from the mean flow was equal to the dissipation inside the cavity, at which point the pressure error may asymptote to a final value. Experimentally, the pressure reading for larger holes at high pipe Reynolds numbers displays larger fluctuations, but the connection with possible shear layer instabilities remains to be established.

Alternatively, visualizations by Ligrani *et al* (2001) of the flow over a dimpled surface show that a pair of counter-rotating vortices is formed above two recirculation zones within each dimple. This mechanism may also be applicable to the tapping problem, hinting at some three-dimensional aspects of the flow. The larger the tapping with respect to the pipe diameter, the larger the curvature of the stagnation stream surface introduced by the wall curvature alone and hence, perhaps, the lower the Reynolds number at which these vortices would develop. This may help to explain why the effect of diameter observed in the present study and that of Shaw in pipes was not apparent at low d^+ in the boundary layer study of Franklin and Wallace (1970).

Finally, we note that this correction will be important in all high Reynolds number facilities where velocity results are calculated from an impact tube and wall static tapping, and not simply pressurized facilities like the Superpipe, since for a given pressure error Π,

$$\frac{\Delta p}{p_{meas}} = \frac{\Pi \rho u_\tau^2}{0.5\rho u_{meas}^2} = \frac{2A}{u_{meas}^{+2}} \tag{5}$$

and

$$\frac{u^+}{u_{meas}^+} = \left(1 + \frac{2\Pi}{u_{meas}^{+2}}\right)^{1/2} \tag{6}$$

where $u^+ = U/u_\tau$, which increases with distance from the wall. Thus the error in velocity is maximum for measurements near the wall, where u^+ is small, and for large Π. Figure 6 has shown that the pressure error Π continues to grow as the Reynolds number increases, therefore the velocity error for a given u^+ also continues to increase with Reynolds number and is important for high Reynolds number experiments.

5. Conclusions

Investigation of the pressure error introduced by a static pressure tapping of finite size at high Reynolds number shows that the error continues to increase with increasing hole Reynolds number d^+ beyond the asymptotic limit of approximately three suggested by previous researchers. A maximum error of about $\Pi = \Delta p/\tau_w = 7.4$ was observed for the largest tapping diameter at the highest pipe Reynolds number $Re_D = 14 \times 10^6$ ($d^+ = 8000$). For high d^+, the error is not identical for large and small diameter holes: the larger the ratio of tapping diameter to pipe diameter, the smaller the pressure error. The mechanism for this dependence on d/D is not clear. Further visualization studies would be required to ascertain the flow structure within the tapping as the Reynolds number is increased.

As a practical guide, it is suggested that if a Pitot tube and static tapping are used to make dynamic pressure measurements in pipe flow, the static tapping should have (1) large and constant l/d, at least $l/d > 2$ to ensure that the flow structure within the cavity is fully developed and not changing with Reynolds number, and (2) a small ratio of diameter to pipe diameter, to prevent the tapping fundamentally altering the external flow. Impact tubes may be used to obtain measurements closer to the wall than would be possible with a Pitot-static probe, but it should be noted that the effect of the static pressure error is most important at small distances from the wall and hence care must be taken to use the appropriate static correction. Although the maximum pressure error was observed to be less than 1% of the dynamic pressure on the pipe centreline in all cases, the error has a significant effect on the conclusions drawn from the high Reynolds number mean velocity data taken in the Princeton Superpipe. This has been reported in a separate publication (McKeon *et al* 2002).

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