Chapter 3

AN EVALUATION AND IMPROVEMENT OF A PRESSURE TRANSUDER UNDER DIFFERENT FLOW CONDITIONS

3.1 Introduction

Pressure transducers are widely being used for measurements of sea level. In the past, sea level measurements were made; to aid navigation in shallow coastal regions; for hydrographic survey applications; and for preparation of tide tables. An accuracy of 10 cm was considered to be sufficient for these applications. In recent years, in the wake of increasing threat of mean sea level rise from greenhouse effect and other causes, a greater emphasis has been placed on a more accurate measurement of sea level. In this context it is appropriate to examine the accuracy that can be obtained from sea level measuring devices such as pressure transducers. Even an ideal pressure transducer tends to be influenced by the dynamic nature of the measurement site (Joseph et al, 1993). An important parameter which deteriorates the performance of a pressure transducer is the water flow at the measurement site. Experiments by Carson et al, (1975) indicated that attaching a free-streaming flexible tube to the inlet of a pressure transducer reduces the flow effects. However, in practice, it is difficult to maintain a stable datum with such a system. In this paper the experimental performance of a pressure transducer deployed in a flow field has been examined. Some design solutions to improve its performance in a flow field have also been investigated.
together with justifications based on known principles of fluid dynamics.

### 3.2 Response of pressure transducer to a flow field

The output of a pressure transducer, deployed for sea level measurements, is influenced by the fluid flow in its vicinity. Thus the presence of a pressure transducer housing and its support devices may distort the flow field so that the pressure sensed is different from the hydrostatic pressure at the inlet of the pressure transducer. According to Bernoulli’s arguments, if the fluid velocity $V$ outside the boundary layer of a body changes from its initial value $V_1$ to a considerably different value $V_2$ over a small distance, the pressure $P$ changes rapidly from $P_1$ to $P_2$ over the same distance. The relation between pressure and flow velocity is given by Bernoulli’s equation (Landau et al, 1984):

$$\frac{V_1^2 - V_2^2}{2} = \frac{P_2 - P_1}{\rho}$$  \hspace{1cm} (3.1)

where $\rho$ is the density of water at the body. On account of the velocity at the surface of the body being zero, the pressure difference $\Delta P$ can be expressed as:

$$\Delta P = \frac{\rho V^2}{2}$$  \hspace{1cm} (3.2)

The minus sign indicates that an accelerating flow at the inlet of a pressure transducer results in a decrease in pressure and vice versa compared to the hydrostatic pressure at the inlet. In practice, $\Delta P$ is strongly dependent on the geometry of the pressure intake mechanism. This complexity in the response of a pressure
transducer to the flow in the vicinity of its inlet is taken care of by introducing a constant factor \( k \) in relation (3.2), (Banaszek, 1985). Thus:

\[
\Delta P = -\frac{k \rho V^2}{2}
\]

(3.3)

It is evident that a pressure-intake geometry which achieves a near-zero value for \( k \) will provide the best performance for a pressure tide gauge deployed in a flow field. The flow can be laminar or turbulent depending on the details of the pressure housing, supporting structure etc. In the present paper the response of a pressure transducer to laminar and turbulent flows are presented and discussed.

3.3 Description of experiments and results

A Digiquartz differential shallow water pressure transducer was used for the experiment. Among the currently available pressure transducers, those made from quartz crystals offer the best performance and are reported to have negligible hysteresis (Wearn and Larson, 1982., Busse, 1987). Details of the experimental setup have been given in Section 2.4. The experiments were performed firstly without a piling and subsequently with a piling in the vicinity of the transducer housing. The second setting was meant to simulate a practical situation where the transducer might be mounted on some mechanical structure.

3.3.1 Response of a pressure transducer to laminar flow

A pressure transducer may be deployed in a bottom-mounted fashion, on a simple structure, or on a piling. In the first two cases the flow field may experience
negligible disturbances, whereas the third case may introduce some disturbances in the flow field in the vicinity of the transducer housing. In this section the response of a pressure transducer to a steady laminar flow field is examined. Schematic diagrams of differing hydro-mechanical front-ends of the transducer are given in Fig. 3.1. Experimental results are shown in Fig. 3.(2,3,4). The configuration of the pressure intake mechanism for the first set of experiments was somewhat similar to many conventional settings where the pressure inlet protruded out into the flow field. In the present case the protrusion was from the centre of the circular end-plate of the pressure housing. The edge of the plate was rounded to reduce flow separation and shedding. The protruding stainless steel tube of length 2.5 cm was filled with silicone oil to prevent trapping of air inside the pressure inlet. During each set of experiments the response of the pressure transducer was first monitored in still water and then at differing flow speeds. It can be seen (Fig. 3.2) that the pressure transducer exhibited a large $\Delta P$ with increasing flow speeds, reaching a value of 19.18 millibars at a flow speed of 200 cm/sec. As expected from Bernoulli's theory $\Delta P$ exhibited a square law relationship with respect to the flow speed.

The second set of experiments, where the pressure inlet remained flush with the horizontal plane of the end plate, yielded a significant improvement in the response of the pressure transducer to a flow field compared to that of a protruding pressure inlet. The pressure reduction in this case at a flow speed of 50 cm/sec was less than a millibar, corresponding to an under-estimation in water level of
Figure 3.1: Differing hydro-mechanical front-ends of pressure transducer (No piling in the vicinity)

Figure 3.2: Response of a pressure transducer for hydro-mechanical front-ends of Figs. 3.1(a,b,c) to a steady laminar flow field
less than 1 cm.

The third set of experiments were performed with the addition of a parallel plate, supported by three equally spaced cylindrical stand-offs of 8 mm diameter and separated by a distance equal to the diameter of the pressure housing (Fig. 3.1c). As stand-offs have been found to alter the flow field in their vicinity (Joseph and Desa, 1994) the azimuthal response of the transducer with changing flow direction has also been investigated. The results (Fig. 3.3) indicate that a parallel-plate arrangement gave rise to an increased ΔP compared to a single-plate arrangement. Reduction of the separation between the two parallel plates to half the diameter of the pressure housing (Fig. 3.1d) gave rise to a larger spread of ΔP in the azimuthal response. Locating the pressure inlet at the centre of a larger circular plate, whose diameter was 3 times the diameter of the pressure transducer housing (Fig. 3.1e) yielded a significant improvement in the response of the pressure transducer, especially at large flow rates (Fig. 3.2). However, the trend in the spread of the azimuthal response for plate separations of D and 0.5D were similar to those for plate diameter of D (Fig. 3.4).
Figure 3.3: Spread in horizontal azimuthal response of a pressure transducer for small parallel plates of Figs. 3.1 (c,d) for a steady laminar flow field

Figure 3.4: Spread in horizontal azimuthal response of a pressure transducer for large parallel plates of Figs. 3.1 (f,g) for a steady laminar flow field
3.3.2 Role of a large circular thin plate

The advantage of locating the pressure inlet at the centre of a large thin plate is that the flow at the bottom portion of the plate (Fig. 3.1c), where the pressure inlet is located, will be free from the influences of the modified velocity field around the pressure transducer housing, and also the vortices shed from the edges of this housing as a result of flow separation. The velocity field around a cylinder is given by (Eskinazi, 1965):

$$V = \sqrt{V_r^2 + V_\theta^2}$$  \hspace{1cm} (3.4)

$V_r$ is the radial flow velocity component along the line joining any given point distant $r$ from the axis of the cylinder, where:

$$V_r = U_\infty \left[ \left( \frac{a_0}{r} \right)^2 - 1 \right] \cos(\theta)$$  \hspace{1cm} (3.5)

Here $U_\infty$ is the undisturbed mainstream flow approaching the cylinder, $a_0$ is the radius of the cylinder, $r$ is the distance between the axis of the cylinder and the given point in the flow field, and $\theta$ is the angle between $r$ and the vector $U_\infty$. In equation (3.4), $V_\theta$ is the flow component vector at the tail of the vector $V_r$ and perpendicular to it, given by:

$$V_\theta = U_\infty \left[ \left( \frac{a_0}{r} \right)^2 + 1 \right] \sin(\theta)$$  \hspace{1cm} (3.6)

The expressions for $V_r$ and $V_\theta$ are strictly valid only for cylinders of infinite length and when the flow is steady. Although such conditions might not be met, these
calculations enable first order estimates to be made of the flow distribution in the vicinity of the cylinder.

For a circular thin plate whose diameter is 3 times that of the pressure housing (Fig. 3.1c), Eq. (3.5) and Eq. (3.6) become:

\[ V_r = 0.89U_\infty \cos(\theta) \quad (3.7) \]
\[ V_\theta = 1.11U_\infty \sin(\theta) \quad (3.8) \]

With the use of such a thin plate the adverse influences of the pressure housing on pressure measurement can be reduced. The improvement that can be obtained by selection of differing values of \((a_0/r)\) is given in Fig. 3.5.

This shows that an increase of the diameter of the thin plate to 4 times that of the pressure housing can achieve a value of near unity for \((V/U_\infty)\). Further increase in the diameter of the plate does not yield a corresponding enhancement. On account of the plate being thin, the pressure inlet located at its centre will be free from the effects of separated flows and vortices unless the flow is at some angle-of-attack.
Figure 3.5: Dependence of \( \frac{V}{U_{\infty}} \) on \( \frac{a_0}{r} \)
3.3.3 Response of a pressure transducer to turbulent flow

A pressure transducer together with its housing is often attached to a vertical piling. Flow tank experiments by Shih and Baer (1991) on a stilling-well model attached to a piling model indicated that the water level inside the well is influenced by the pressure field around the piling. These observations indicate that the output of a pressure transducer mounted near a piling is influenced by the turbulence generated by the latter. The set of experiments reported here were performed with the pressure housing mounted in the neighbourhood of a cylindrical vertical piling model whose diameter was twice that of the pressure transducer housing. The top end of the piling extended 5 cm above the water surface and its bottom end extended below that of the pressure housing by a distance equal to half the diameter of the pressure transducer housing. Differing experimental settings are shown in Fig. 3.6. Pressure reduction as a function of flow speed for different configurations are shown in Figs. 3.7, 8, 9.

The first experiment in this series was performed in a setting shown in Fig. 3.6(a). The horizontal azimuthal angular response of the pressure transducer for differing flow arrival angles (Fig. 3.7) indicated that the effect of having a piling in the vicinity of the pressure transducer housing is to give rise to an increased $\Delta P$ compared to that in the absence of a piling. While this error was less than 2 millibars for flow speeds of less than 50 cm/sec for all angles of flow arrival, the corresponding error at 100 cm/sec was very significant. $\Delta P$ was minimum for
Figure 3.6: Differing experimental settings for the pressure transducer housing mounted near a cylindrical piling.
Figure 3.7: Performance of a pressure transducer for differing relative orientations of its housing and a cylindrical vertical piling for various mainstream flows.
$\theta = 180^\circ$ and maximum for $\theta = 90^\circ$ and $135^\circ$. The values of $\Delta P$ were intermediate for intermediate values of $\theta$. This shows that the response of a pressure transducer is highly sensitive to the directions of flow arrival, especially at large flow speeds, if the pressure inlet is not protected by some appropriate techniques.

A previous study (Joseph et al, 1995) indicated that placing a perforated sheet around the piling at a suitable distance in the flow path significantly enhanced the flow pattern distribution in the region surrounding the piling. In order to examine the influence of such a sheet on the performance (i.e., value of $\Delta P$) of a pressure transducer mounted on a piling, a few sets of experiments were performed by placing a stainless steel perforated sheet (holes of 7/16" diameter and 5/8" pitch) at differing distances from the transducer housing. A perforated sheet placed 8.4 cm away from the transducer housing degraded the performance of the pressure transducer as a result of the swirling motion generated by this sheet. The transducer's performance improved (Fig. 3.8) when the sheet was placed at a distance of 2D from the periphery of the transducer housing (Fig. 3.6c). Mounting the perforated sheet at a distance of 4D did not yield any additional improvement.

The practical difficulties involved in shielding the pressure housing by a perforated sheet and a large drag force acting on such a large sheet led to the investigation of an alternate feasible methodology such as the use of a large horizontal thin circular plate. Result of the experiments, with the pressure inlet located at the centre of a horizontal thin circular plate of diameter 3D and flush with the
plate surface, was similar to that obtained from placing a perforated sheet at a large distance in front of the pressure transducer housing. The transducer with a single-plate front-end such as this, was found to be sensitive to differing flow arrival angles; the azimuthal response had a spread of approximately 2 millibars. Use of a second identical plate separated from the first by a distance equal to D yielded a smaller spread in the horizontal azimuthal response in the flow range of 0 to 100 cm/sec, but a larger spread when the flow speed exceeded 100 cm/sec (Fig. 3.9).
Figure 3.8: Effect of a perforated curved sheet in the vicinity of the pressure transducer housing on the performance of the pressure transducer.
3.4 Discussion of results

In the present discussion boundary layer theory has been applied. In the absence of a piling in the vicinity of the pressure transducer the incoming flow towards the transducer was laminar in the present experiment. For motion of a uniform stream of Newtonian fluid over a motionless flat plate, the velocity $u$ within the laminar boundary layer of the plate is given as (Eskinazi, 1965):

$$\frac{u}{U_\infty} = 0.332\eta - 0.00229\eta^4 + 1.996 \times 10^{-5}\eta^7 - 1.567 \times 10^{-7}\eta^{10} + 1.129 \times 10^{-9}\eta^{13} \quad (3.9)$$

In the above relation $U_\infty$ is the mainstream flow. $\eta$ is given by the relation:

$$\eta = y\sqrt{\frac{U_\infty}{\nu x}} \quad (3.10)$$

where

- $y$: distance normal to the plate
- $x$: distance along the plate from its leading edge
- $\nu$: kinematic viscosity, which is the ratio of absolute viscosity and density of fluid. (For sea water $\nu$ is approximately equal to $1.3 \times 10^{-2}$ cm$^2$/sec and for pure water it is approximately equal to $1 \times 10^{-2}$ cm$^2$/sec).

Increase of $u/U_\infty$ with increasing transverse distance from the pressure inlet for circular flat plates of diameter $D$ and $3D$ are shown in Figs. 3.10 and 3.12 respectively. Flow velocities, near the pressure inlet, within the boundary layer of the circular plates of diameter $D$ and $3D$ are shown in Figs. 3.11 and 3.13 respectively. In the present experiment $D$ was equal to 12.8 cm. At a finite value of $\eta$ the fluid velocity $u$ within the boundary layer blends into the free-stream velocity $U_\infty$. The boundary layer thickness $\delta$, arbitrarily defined as the distance
from the plate where the boundary layer velocity $u$ differs from the free stream velocity $U_\infty$, by 1%, is given by the relation (Yuan, 1967):

$$\delta = 5.64 \sqrt{\frac{\nu x}{U_\infty}}$$

(3.11)

While flow near the leading edge of a flat plate may be in smooth layers (i.e., the flow is laminar), further along the plate the laminar boundary layer may break down and become unstable, leading to a turbulent boundary layer at a critical Reynolds number. For a flat plate this number is given by the relation (John and Haberman, 1971):

$$Re_{(crit)} = \left[ \frac{x U_\infty}{\nu} \right]$$

(3.12)

where $x$ is the distance from the leading edge of the plate. For purposes of calculation $Re_{(crit)}$ is usually taken as $5 \times 10^5$. Thus, if a uniform flow with a velocity $U_\infty$ passes over a flat plate aligned to the flow, the transition from laminar to turbulent boundary layer flow will occur at $x = 5 \times 10^5 \times \nu/U_\infty$. In the present experimental setup the maximum Reynolds number, corresponding to $x = 19.2$ cm and $U_\infty = 200$ cm/sec, was $3.84 \times 10^5$ which was less than the critical Reynolds number. Thus the flow over the plate in the present experiment never underwent a transition from laminar to turbulent regimes. The laminar boundary layer thickness for differing mainstream flow velocities are shown in Fig. 3.14. The variation of the laminar boundary layer thickness at the position of the pressure inlet for differing mainstream flows are shown in Fig. 3.15.
Figure 3.10: Transverse distance from the pressure inlet with increasing \( \frac{u}{U_\infty} \) for indicated mainstream flows in the case of plate diameter \( D \), as in Fig.3.1(b); \( D=12.8 \) cm

Figure 3.11: Flow velocity \( u \) within the laminar boundary layer for differing transverse distances from the pressure inlet for indicated mainstream flows in the case of plate diameter \( D \)
Figure 3.12: Transverse distance from the pressure inlet with increasing \((u/U_\infty)\) for indicated mainstream flows in the case of plate diameter 3D, as in Fig. 3.1(e)

Figure 3.13: Flow velocity \(u\) within the laminar boundary layer for differing transverse distances from the pressure inlet for indicated mainstream flows in the case of plate diameter 3D
To
The Head
Department of Physics,
Goa University
Taleigao Plateau, Goa.

Sub: Ph.D. viva-voce examination.

Sir,

This is to inform you that the viva voce examination of Shri Antony Joseph K., Ph.D. student in Physics of this University is fixed on Tuesday, 11th March, 1997 at 11.00 a.m. in the Department of Physics, Goa University, Taleigao Plateau, Goa. The other details are as under:

Title of the thesis : "Analysis of the Performance of a Pressure Transducer for Sea Level Measurements.

Name of the Guiding Teacher : Dr. J.A.E. Desa
Reader
Department of Physics
Goa University.

You are requested to take note of the Ordinance 19.9(xi). One copy of the thesis has been sent to our Library as per provision of our Ordinance 19.9(xii).

Yours faithfully,

( A.G. Khanolkar )
Controller of Examinations

Copy to:

The Dy. Library, Goa University, alongwith the copy of the thesis for information.
3.4.1 Role of a flat plate (laminar flow)

It was noted (Section 3.3.1) that a protruding pressure inlet exhibited the largest error in pressure measurement. Fig. 3.14 shows that this protrusion (2.5 cm) was considerably outside the boundary layer and was therefore exposed to the mainstream flow. Fig. 3.16 shows that the observed values of $\Delta P$ were consistently higher than the calculated values [$U_\infty$ in place of $V$ in Eq. (3.2)] in the $U_\infty$ range of 0 to 150 cm/sec. The higher values of the experimentally measured $\Delta P$ may have been caused by the fact that the protruding pressure inlet lay within the separated flow region where the velocity is higher than $U_\infty$. The observed reduction in $\Delta P$ when the pressure inlet remained flush with the end plate of the transducer’s housing, can be attributed to a retarded flow within the boundary layer. For a parallel plate, the observed large spread of azimuthal response (Fig. 3.3) may have been caused by the modified velocity field due to the stand-offs.

It has been noted that the transducer exhibited a much lower $\Delta P$ when the pressure inlet was located at the centre of a horizontal thin plate of diameter 3D, with the inlet grazing the surface of the plate (Fig. 3.1e). In addition to the considerations mentioned in Section 3.3.2, this improved performance may have resulted from the thicker laminar boundary layer associated with a large plate (Fig. 3.14).

The use of a second parallel plate of the same diameter caused a slight increase in $\Delta P$. This degradation is likely to have resulted from the disturbances from
stand-offs of parallel-plate assembly. A special effect noticed only in the case of parallel-plates of diameter $3D$ was small negative values of $\Delta P$ for most azimuthal angles when the mainstream flow was $25 \text{ cm/sec}$. The observed phenomena may, perhaps, be due to 'creeping motion' known as the Hele-Shaw flow (Schlichting, 1968). Creeping motions occur in the case of slow motions of fluid between two parallel flat surfaces separated by a small distance and when cylindrical stand-offs are inserted between them normal to these surfaces. The fact that negative $\Delta P$ was not observed when the parallel plate had a diameter $D$ may have been due to the absence of Hele-Shaw flow.
Figure 3.14: Growth of laminar boundary layer thickness over a flat plate, from its leading edge, for indicated mainstream flows $U_\infty$ (Location of the pressure inlet for plate diameters $D$ and $3D$ are indicated by the broken lines)

Figure 3.15: Laminar boundary layer thickness at the centre of the end-plates of diameter $D$ and $3D$, for indicated mainstream flows $U_\infty$
Figure 3.16: Variation of experimentally observed and calculated values of $\Delta P$ with mainstream flow velocities $U_\infty$, for protruding pressure inlet as in Fig. 3.1(a)
3.4.2 Influence of a vertical cylindrical piling

Fig. 3.7 shows that the presence of a piling near a pressure transducer has an adverse effect on its performance for most of the flow arrival angles ($\theta$). The $\Delta P$ values were comparatively less for flow arrival angles of $0^\circ$ and $180^\circ$, and maximum at $90^\circ$ and $135^\circ$. An analysis revealed that the experimental values of $\Delta P$ (i.e., $\Delta P_{\text{exp}}$) were similar to the calculated values of $\Delta P$ (i.e., $\Delta P_{\text{cal}}$) for $\theta < 90^\circ$ (Fig. 3.17). However, $\Delta P_{\text{exp}}$ values were at variance with $\Delta P_{\text{cal}}$ for $\theta$ between $90^\circ$ and $180^\circ$. In this analysis the values of $\Delta P$ were calculated based on the modified flow at the pressure inlet arising from the influence of the cylindrical piling, as given in Eq. (3.1). The difference between $\Delta P_{\text{exp}}$ and $\Delta P_{\text{cal}}$ as a function of flow arrival angle $\theta$ for various flow speeds is shown in Fig. 3.18. The values of $\Delta P_{\text{exp}}$ were consistently higher than $\Delta P_{\text{cal}}$ in the angular range $70^\circ$ to $150^\circ$.

The observed phenomena can be explained on the basis of the following known facts about flow separation near a circular cylinder. In this case the approaching laminar flow separates from the surface of the cylinder at $82^\circ$ from its forward stagnation point, and the fluid near the cylinder is transported out into the mainstream on either side of the cylinder (Kundu, 1990). In the present experiment, for flow speeds up to $117$ cm/sec the Reynolds number was less than the critical value of $3 \times 10^5$ beyond which the flow becomes turbulent in the vicinity of a cylinder. At $150$ cm/sec the Reynolds number is $3.84 \times 10^5$, and as this corresponds to
turbulent flow the steady flow assumption of Eq. (3.4) is not applicable. Between 70° and 150°, the additional flow transported out into mainstream on either side of the piling as a result of separation resulted in a larger \( \Delta P_{\text{exp}} \) compared to \( \Delta P_{\text{cal}} \). A lower value for \( \Delta P_{\text{exp}} \) at 180° compared to \( \Delta P_{\text{cal}} \) can be explained on the basis of a lower pressure field in the vicinity of the leeward stagnation point of the piling.
Figure 3.17: Experimental and theoretical values of $\Delta P$ for various flow speeds and directions when the pressure transducer was mounted near a cylindrical piling as in Fig. 3.6(a)

Figure 3.18: Dependence of difference between experimental and theoretical values of $\Delta P$ on flow directions for various flow speeds
3.4.3 Role of a thin perforated sheet

It has been observed that a perforated sheet placed very close to a pressure transducer gives rise to a large $\Delta P$ value in a flow field. However, locating it far away ($\approx 25$ cm.) from the transducer or piling significantly improves the transducer's performance in a flow field. These experimental observations can be explained as follows: A thin perforated sheet can be considered as a two-dimensional array of orifices present on a sheet. The flow through a perforated sheet, at $90^\circ$ incident angle, can therefore be considered as effluxes of free jets emanating from a two-dimensional array of orifices. In the present experiment the orifices were circular. The expressions for the axial velocity component $u$ and the radial velocity component $v$ of a turbulent circular jet has been given by (Schlichting, 1968), who showed that both $u$ and $v$ decrease as the transverse distance from the perforated sheet increases.

In practice a jet begins with a swirling motion, and the swirl moves in the downstream direction. However, the swirl decreases faster with the distance from the orifice than the jet velocity. During the present experiment, the glass side-windows of the working section of the flow channel permitted visual observations of the twists and turns associated with the swirl motion of water. These swirls damped out after travelling over a distance of approximately 15 cm along the axis of the orifices. Thus, the increase in $\Delta P$ when the perforated sheet was located very close to the pressure housing can be attributed to the swirling motion
associated with the jet in the vicinity of the perforated sheet. The much lower $\Delta P$ when the transducer was located far away from the perforated sheet can be explained on the basis of a reduced flow velocity of the jets.

### 3.4.4 Role of a single horizontal plate (turbulent flow)

When a pressure transducer is deployed near a piling the flow at the pressure inlet of the transducer will change from laminar to turbulent as the flow direction changes from $0^\circ$ to $180^\circ$. The flow direction at which the transition from laminar to turbulent flow occurs at the pressure inlet will depend on various factors such as the magnitude of the flow, diameter of the piling, the value of $\theta$ and the proximity of the transducer housing to the piling. For turbulent flows the boundary layer on the surface of the plate is predominantly turbulent. In this case there is a thin region of laminar flow very close to the plate known as laminar sub-layer whose thickness $\delta'$ is given by (Lal, 1986):

$$
\delta' = \frac{11.6 \nu}{\sqrt{\tau_0/\rho}}
$$

where :

- $\tau_0$ : shearing stress at the plate
- $\rho$ : density of fluid
- $\sqrt{\tau_0 / \rho}$ : shear velocity
- $\nu$ : kinematic viscosity of fluid

For a flat plate $\tau_0$ is given by (Rathy, 1976):

$$
\tau_0 = 0.343\mu\sqrt{\frac{V}{\nu x}}
$$
where \( V \) is the flow velocity at the position of the transducer and \( \mu \) is the coefficient of molecular viscosity (\( 10^{-2} \) dynes-sec/cm for water at 20 °C). Distribution of laminar sublayer thickness along a flat plate, estimated based on Eqns (3.13) and (3.14), is shown in Fig. 3.19. Laminar sub-layer thickness at the centre of plates of diameter D and 3D is shown in Fig. 3.20. It can be seen from Figs. 3.14 and 3.19 that for a plate diameter of 3D the laminar sub-layer thickness at the pressure inlet decreased in comparison to the laminar boundary layer thickness by factors in the range 4.5 to 8.5 depending on the flow speed. For a given \( U_\infty \) the turbulent flow speeds at the transducer will vary with differing orientations of the transducer with respect to the piling. This will cause the laminar sub-layer thickness to vary and result in a spread of \( \Delta P \) with changing azimuthal angles.
Figure 3.19: Growth of laminar sub-layer thickness over a flat plate for indicated mainstream turbulent flows $U_\infty$. (Location of the pressure inlet for plate diameters D and 3D are indicated)

Figure 3.20: Laminar sub-layer thickness at the centre of the end-plates of diameters D and 3D for various mainstream turbulent flows
3.4.5 Role of a pair of parallel horizontal thin plates (turbulent flows)

It has been noted in Section 3.3.3 that the azimuthal response of the transducer improved when a parallel-plate arrangement was used. The observed improvement can be understood qualitatively on the basis of stability theory for Poiseuille flows (Rathy, 1976). In any turbulent flow the disturbances contain some kinetic energy and if there is a transfer of energy from the basic flow into the disturbances then these grow in magnitude and the flow becomes unstable. If there is a reversal of energy transfer the flow will become stable. Parallel plates are known to stabilize the flow upto a certain Reynold's number, determined by various factors such as the ends, finite size and roughness of the plates. For turbulent flow bounded between two parallel surfaces the average velocity distribution, upto a certain Reynold's number, becomes far more uniform than that for laminar flow, with a much weaker velocity distribution near the solid boundaries (Rouse, 1970). In the present study the parallel plates stabilised the flow upto a Reynold's number of $1.92 \times 10^5$ corresponding to 100 cm/sec. Beyond this speed there appears to have been a reversal of energy transfer. The conclusions of the present studies are given in Chapter 6.