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RPT - THE ROVING PRESTON TUBE

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ABSTRACT

This paper describes an item of equipment developed by the authors for measuring local boundary shear stress in experimental studies and teaching laboratories. The purpose of the paper is to make freely available details of the equipment so that it can be applied, when appropriate, to further fundamental research.

The Roving Preston Tube (RPT) is a development of the method introduced by Preston [1954], improved by others including Patel [1965] and Hwang & Laursen [1963] and used in a number of research investigations from the 1960's through the 1980's.

The advantage of the RPT is that, unlike the Preston tube, static wall tappings are not required. Local boundary shear stress measurements with the RPT are based on the measurement of the pressure difference between a forward facing (Pitot or Preston) tube placed in contact with the surface and a "wake pressure" tube exposed to the wake pressure region behind the Pitot tube. It can be applied to measurements in both open channels and closed conduits.

NOTATION

d	pitot tube outside diameter	[m]
D	circular conduit diameter	[m]
p	transducer pressure	[Pa]
R	hydraulic radius	[m]
S_f	slope of the energy grade line	
x	x-axis coordinate (stream wise direction)	[m]
x^*	log-dimensionless differential pressure	
x^*_{RPT}	x^* value for the RPT	
y^*	log-dimensionless boundary shear stress	
y^*_{RPT}	y^* value for the RPT	
Δp_P	Preston tube differential pressure	[Pa]
Δp_{RPT}	RPT differential pressure	[Pa]
ν	kinematic viscosity	$[m^2/s]$
ρ	fluid density	$[kg/m^3]$
τ_0	local boundary shear stress	[Pa]
τ'_0	dimensionless local boundary shear stress	
BSS	boundary shear stress	
RPT	Roving Preston tube	

INTRODUCTION

The accurate measurement of boundary shear is of vital importance to much research undertaken in connection with open channel flow.

Preston [1954] developed a simple technique for measuring local shear on smooth surfaces in a turbulent boundary layer using a pitot tube placed in contact with the surface. This method is based on the assumption of an inner law (law-of-the-wall) relating the boundary shear stress to the velocity distribution near the wall. Using the pressure drop in a circular conduit to calibrate the instrument, Preston obtained equations relating shear to the difference between 'dynamic' (pitot tube) and 'static' pressure readings.

Investigations by other researchers cast doubt on the applicability and accuracy of Preston's method. In response, Patel [1965] undertook further experiments to produce a reliable and definitive calibration curve to replace that developed by Preston. Additional supportive research concerning rough surface shear measurement was also undertaken by Hwang and Laursen [1963].

Since then considerable research has been undertaken using Preston's technique in both smooth and rough open channel applications. Much of this research has generally been concerned with measurements confined to a single measuring station because the Preston tube necessitates installation of static pressure tappings about the wetted perimeter of the section at the measuring station. Ghosh & Roy [1970] partially overcame this restriction with the use of a 'static tube' to replace the external pressure tappings. Their technique required that the 'static tube' be positioned separately from the Preston tube. Unfortunately this approach tended to make the measurement process somewhat cumbersome, and occasionally led to the introduction of unquantifiable inaccuracies.

In recognition of the merits associated with Ghosh & Roy's approach investigations were undertaken to develop an adaptation of the Preston tube which provided both ease of application and reliability. This undertaking resulted in the development of a new probe which has been named the Roving Preston Tube, or RPT.

THEORY

The Preston Tube Technique

Preston [1954] developed a non-dimensional relationship between Preston tube differential pressure (ie. difference between 'dynamic' and 'static' pressures) and boundary shear stress of the form:

$$\left(\frac{\tau_o d^2}{4\rho\nu^2}\right) = f\left(\frac{\Delta p_P d^2}{4\rho\nu^2}\right); \qquad (1)$$

where f is a calibration function determined from measurements in fully developed pipe flow.

Patel [1965] undertook calibration experiments using three different pipes with nominal bores of approximately 12.5 mm, 50 mm and 200 mm, and fourteen Preston tubes with outside diameters ranging from 0.6 mm to 12.6 mm. His experiments showed close agreement between calibration in the three pipes, and also that data obtained from the various tubes all fell on a single curve. This implied a unique *f* function and an identical law-of-the-wall for all three pipes.

Patel's calibration results, although in reasonable agreement with Preston's, did not produce a linear relationship as concluded by Preston but rather three separate functions covering the range $0.0 < y^* < 5.3$:

- for $y^* < 1.5$,
  $$y^* = 0.5\, x^* + 0.037 \; ; \tag{2}$$
- for $1.5 < y^* < 3.5$,
  $$y^* = 0.8287 - 0.1381\, x^* + 0.1437\, x^{*2} - 0.0060\, x^{*3} \; ; \tag{3}$$
- for $3.5 < y^* < 5.3$,
  $$x^* = y^* + 2 \log (1.95\, y^* + 4.10) \; ; \tag{4}$$

where, x^* is the log of dimensionless differential pressure:

$$x^* = \log\left(\frac{\Delta p_P\, d^2}{4\rho\nu^2}\right) ; \tag{5}$$

and, y^* is the log of dimensionless shear stress:

$$y^* = \log\left(\frac{\tau_o\, d^2}{4\rho\nu^2}\right) ; \tag{6}$$

Patel's research also included theoretical verification of the above relationships using experimentally derived law-of-the-wall coefficients and Pitot tube displacement corrections. For the above ranges Patel found that equation (3) fitted experimental calibration data to within ±1.5% of t_o, and equation (4) fitted to within ±1%. No accuracy value was given for equation (2).

It is also noted that, according to Preston [1954], tube diameter should not exceed 0.2 times the boundary layer thickness (flow depth in fully developed turbulent flows).

Tube diameters of 2.0 mm and 1.6 mm were utilized for the current research.

The RPT Adaption

Physical details of the Roving Preston Tube (RPT) are described in the following section and Figure 1. It's basic function is identical with that of the standard Preston tube with the difference being that differential pressures are measured between the tube's 'dynamic' and 'wake' tappings.

In order to provide compatibility with Patel's relationships a log-dimensionless relationship was developed with which to convert RPT differential pressures into *equivalent* Preston tube differential pressures:

$$x^* = f_{RPT}(x^*_{RPT}) \; ; \tag{7}$$

where:

$$x^*_{RPT} = \log\left(\frac{\Delta p_{RPT}\, d^2}{4\rho\nu^2}\right) ; \tag{8}$$

and f_{RPT} is a function derived through calibration.

Once established, this functional relationship can then be applied in conjunction with Patel's equations to give boundary shear stress measurements directly from RPT differential pressure readings.

RPT CONSTRUCTION

A typical sketch of the basic RPT is presented in Figure 1. The probe comprises two pressure tubes (in this case manufactured from stainless steel): a *dynamic* pressure tube with a 20 mm upstream projection; and a *wake* pressure tube directed toward the boundary surface with a 1 mm surface clearance. The two tubes were epoxied together with the upper lengths fitted into a larger diameter instrument guide stem.

The RPT must be placed orthogonally to the boundary surface and separate probes were manufactured to satisfy this requirement[1].

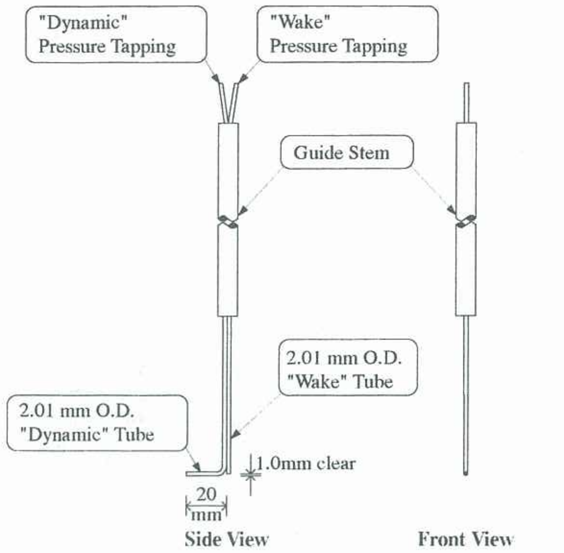

FIGURE 1. — The Roving Preston Tube

CALIBRATION APPARATUS

Calibration experiments were undertaken using two sets of experimental apparatus:

- a circular conduit - air flow; and
- a rectangular open channel - water flow.

Circular Conduit

The circular conduit comprised an 80 mm nominal bore PVC pipe approximately 11 m in length, open to the atmosphere at one end and connected to an electrically driven centrifugal suction pump at the other. Flow was controlled by means of an adjustable orifice plate mounted on the discharge side of the pump. A 'honeycomb' mesh was fitted within the inlet transition (bell-mouth) to the pipe to enhance the development of turbulent flow.

Particular attention was paid to ensuring accurate alignment of individual conduit segments as previous researchers had shown such connections to be potential sources of experimental error (Patel [1965]).

The measuring station was located approximately 10.4 m downstream from the inlet. A probe guide assembly was fitted to the pipe at this location. The assembly included a graduated scale which permitted accurate radial probe positioning within the conduit (velocity profiles were also measured using the RPT as a pitot tube). Measurements were made using a 2.0 mm diameter RPT probe.

A total of fourteen individual pressure tappings were installed over the length of the conduit. Pressures were measured using a single electrical pressure transducer which was connected to the various tappings via a 48-way valve. Transducer output voltages were displayed on a digital voltmeter which gave a full scale pressure reading (1 volt) of 1000 Pa, to a 1 Pa resolution. All pressures were measured relative to atmospheric.

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[1] Three probes were required for a rectangular channel: one for each of the vertical walls and one for the base.

Rectangular Open Channel

The rectangular open channel was 20 m long and had a uniform section 250 mm wide and 270 mm deep. Both walls and bed were made from glass sheet. The channel was supported on an elevated steel truss and set to a uniform slope of 0.1%.

Regulated water flows were supplied from a constant head tank feeding an inlet transition to the channel. Flow rates were volumetrically measured in a calibrated basin installed under the channel outlet.

Tailwater levels in the channel were controlled with an adjustable outlet weir. Longitudinal flow depths were measured using rail mounted pointer gauges positioned over the centreline of the channel. Although these gauges were fitted with vernier scales (0.1 mm sub-division) their practical accuracy was to the order of ±0.25 mm.

The measuring station was located at approximately 6.3 m upstream from the channel outlet. Three 'static' bed tappings were installed across the bed of the channel at the station: one centrally located and the other two symmetrically offset by 95 mm.

Calibration measurements were made using a 1.6 mm diameter set of RPT probes - two for the vertical walls (left & right) and one for the base. RPTs were fitted into a guide trolley which was mounted on instrument rails aligned orthogonally across the channel. Scales were fixed to the trolley which permitted accurate RPT positioning to any location on the wetted perimeter.

RPT ('dynamic' and 'wake') and 'static' bed tapping pressures were digitally recorded using an electrical pressure transducer coupled to computer controlled data logging apparatus.

METHODOLOGY

A total of ten calibration runs were undertaken using the circular conduit apparatus (air) and eleven calibration runs using the rectangular open channel (water). These runs produced boundary shear stresses ranging from 0.2 Pa to 1.8 Pa.

Principal experimental measurements comprised RPT and Preston tube differential pressures (at common probe locations) and the slope of the energy grade line.

Differential pressure measurements were only made at one location in the circular conduit as boundary shear stresses were taken be be constant about the perimeter. However the boundary shear stress distribution in the rectangular open channel was non-uniform and differential pressure measurements were therefore taken about the entire wetted perimeter. Measurement points were spaced at approximately 10 mm intervals.

Viscosity and density values were established from measurements of water temperature, air temperature, and barometric pressure.

Measurements of the energy grade line slope were used to compute average boundary shear stress. For flow in the circular conduit, boundary shear stress was calculated from the longitudinal pressure gradient as follows:

$$\overline{\tau}_e = -\frac{D}{4}\frac{\mathrm{d}P}{\mathrm{d}x}; \qquad (9)$$

For uniform flow in the rectangular calibration channel, average boundary shear stress was calculated from the slope of the energy gradeline as follows:

$$\overline{\tau}_e = \rho g R S_f; \qquad (10)$$

Verification of measurements was made through comparison of this shear stress to that determined by integrating point measurements taken about the wetted perimeter of the section. Patel's calibration relationships were used to compute point shear stress values by applying the RPT as a standard Preston tube.

All experimental measurements were undertaken under uniform fully developed turbulent flow conditions. For the circular conduit apparatus this condition was confirmed by the presence of a linear longitudinal static pressure gradient. Uniform flow in the open rectangular channel was achieved through careful adjustment of the tailwater weir level to the channel in conjunction with accurate measurement of the longitudinal water surface profile.

Two complete sets of measurements were made for each run and the average adopted for analysis.

ANALYSIS

Preston Tube Verification

Results from an analysis of error between Preston tube based and energy grade line based average boundary shear stress values, for both the circular conduit and open channel are presented in Table I.

TABLE I. — Summary of Preston Tube Errors

Apparatus	Average		Standard Deviation	
	(Pa)	(%)	(Pa)	(%)
Circular Conduit	-0.018	-1.7	0.019	1.1
Open Channel	-0.001	-0.2	0.011	3.4

These error terms are comparable with those obtained by other researchers (for example, Knight et al [1984]: an average error of +1.5%, and standard deviation of 4.4%). It is also interesting to compare these values with Patel's [1965] stated an accuracy limit of ±1.5% for his calibration relationships.

RPT Calibration

Calibration data for the RPT adaption comprised pairs of Preston tube and RPT differential pressure measurements taken at a common probe position about the test section boundary. These measurements were non-dimensionalized in accordance with equations (5) & (8) to produce x^* and x^*_{RPT} values. This data is presented in Figure 2 and covers an x^* range from approximately 3.5 to 6.0. This range is comparable with that covered by Patel [1965].

Review of calibration data clearly shows that a coherent relationship can be defined in terms of a two linear functions having a gradient discontinuity at approximately x^*_{RPT} equal to 5.

The calibration data for $x^*_{RPT} > 5$ essentially corresponds to the circular conduit experiments. Application of linear regression techniques resulted in the following function:

$$x^*_P = 0.1512 + 0.9391\ x^*_{RPT}\ ; \qquad (11)$$

This function fitted experimental data (x^* data) with a standard deviation of 0.1%, and is valid within the range $5.0 \leq x^*_{RPT} \leq 6.2$.

For $x^*_{RPT} \leq 5$, linear regression techniques produced the following relationship:

$$x^*_P = -0.5417 + 1.080\ x^*_{RPT}\ . \qquad (12)$$

This function fitted experimental data with a standard deviation of 0.8%, and is valid for the range $3.8 \leq x^*_{RPT} \leq 5.0$.

Application of equations (12) and (13) to Patel's calibration equations (2) to (6) gives the complete RPT calibration and is presented in Figure 3. It supports a combined range of applicability defined by $3.8 \leq x^*_{RPT} \leq 6.2$. Patel's original function is also plotted in this figure for reference.

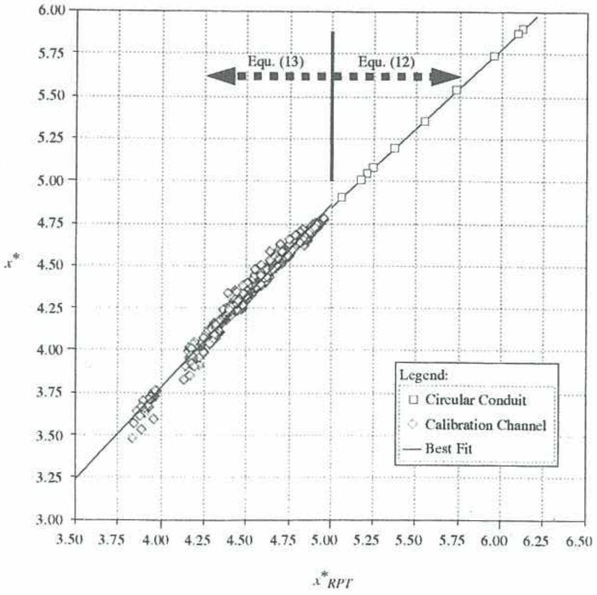

FIGURE 2. — RPT x^* Calibration

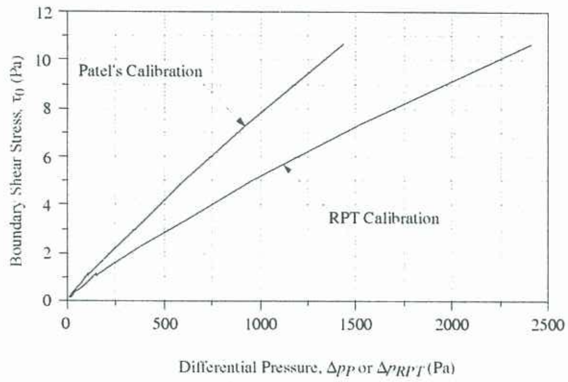

FIGURE 3. — RPT Calibration

Back-substitution of RPT calibration functions into calibration data produced average errors in predicted experimental t_o values of +1.5% (standard deviation of 3.3%) for $x^*_{RPT} \leq 5.0$, and -1.9% (standard deviation of 1.1%) for $x^*_{RPT} > 5.0$. Comparison of these error characteristics with those obtained from Preston tube verification investigations (Table I), shows comparable performance, with the Preston tube supporting a marginally lower average error value (-0.2% of τ_o for $x^*_{RPT} \leq 5.0$). This slight difference is not however considered to be of significance when consideration is given to associated standard deviation values (around 3%). The RPT calibration was therefore accepted as being satisfactory for the purpose of measuring total boundary shear force.

APPLICATION

The RPT has been applied to the measurement of boundary shear stress in a variety of open channels. A selection of resulting distributions are presented in Figures 4 and 5 and correspond to a rectangular compound and trapezoidal compound channels respectively. It should be noted that normalized boundary shear stress values are plotted in these figures with average waterway shear stress ($rgRS_f$) used as a normalizing function. All channel surfaces were hydraulically smooth.

Comprehensive details of the experimental program and explanations of the features depicted in Figures 4 & 5 may be obtained from Macintosh [1990].

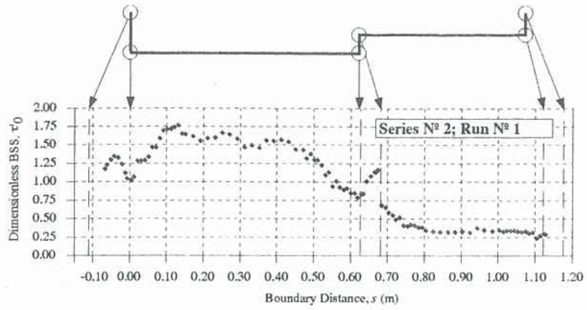

Figure 4. - Rectangular Compound Channel BSS

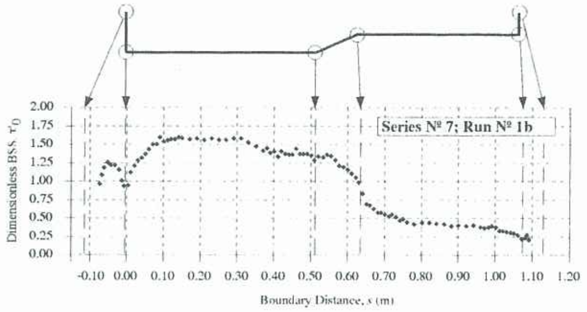

Figure 5. - Trapezoidal Compound Channel BSS

CONCLUSIONS

Development and calibration of the RPT has shown that it may be reliably applied to the measurement of boundary shear stresses in hydraulically smooth channels. The calibration produced a unique relationship between measured RPT and equivalent Preston tube differential pressures. It also confirmed the applicability of Patel's [1965] calibration relationships for measurement of boundary shear stress using the Preston tube.

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