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Measurement of Local Wall Friction Force Exerted by Skewed Turbulent Boundary Layers by Means of an Improved Preston Tube*

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In order to measure the local wall friction force exerted by a skewed turbulent boundary layer on a smooth surface, an improved Preston tube has been developed. A semi-circular shroud is applied to a conventional Preston tube to make it insensitive to direction of flow, just like a Kiel total-pressure probe. The improved Preston tube is used to measure the wall friction force on the flat end wall of a curved channel with 180 degree turning angle, and the results are compared with those deduced from the Clauser chart method.

1. Introduction

Wall friction force is the crucial factor to determine the feature of flow and the pressure loss in a flow passage. In many cases the boundary layer flow is three-dimensional, and in some cases the magnitude and direction of velocity vary with time. Therefore, flow phenomena are so complex that accurate measurement of wall friction force is difficult to carry out.

In a two-dimensional boundary layer flow, techniques, which are schematically shown in Fig.1, are commonly used to measure the turbulent wall friction force.⁽¹⁾⁽²⁾ In Fig.1(a) the friction force acting on the test surface or the floating element is directly measured.⁽³⁾ In Fig.1(b) the wall friction force is estimated from the pressure drop and the momentum difference between two stations. In Fig.1(c) the analogy between heat and momentum diffusions in the near-wall region is used. In the following three other methods, the law of the wall is used in different ways to measure the wall friction force. They are the Clauser chart method in Fig.1(d), the Stanton tube or the sublayer stagnation pressure-probe method in Fig.1(e),⁽⁴⁾ and the Preston tube method in Fig.1(f).⁽⁵⁾

A Preston tube is mounted on a wall and the wall friction force is estimated from the dynamic pressure recorded by the

tube. This method is simple and very easy to use. However, the application is limited to two-dimensional boundary layers on smooth surfaces. After Preston proposed this device, extensive studies have been carried out to apply this technique to measure the wall friction force, for example, in turbulent boundary layers with large pressure gradients, and in blown and sucked turbulent boundary layers.⁽²⁾⁽⁶⁾⁻⁽¹⁰⁾ The calibration curves are established for these conditions, and good accuracy is expected. Preston tubes are so sensitive to flow direction as shown by Prahlad⁽¹¹⁾ that they should be aligned to the flow direction. However, in the case of a skewed turbulent boundary layer, it is difficult to orient the tube properly, as the direction of velocity changes across the layer.

If a Preston tube is made insensitive to the flow direction, not only the orientation problem of the tube is solved for two-dimensional flows, but also the measurement of the wall friction force exerted by skewed turbulent boundary layers is

Fig.1 Methods to measure the wall friction in two-dimensional boundary layer

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possible, providing that the law of the wall is valid.

In the present paper an improved Preston tube is developed, which does not change the reading even when the direction of flow varies considerably, and applicability of the improved Preston tube to skewed turbulent boundary layers is discussed.

2. Preston tubes

Experiments were performed using six Preston tubes. The configurations and dimensions are shown in Fig.2 and Table 1. Fig.2(a) is a conventional type Preston tube. Fig.2(b) and Fig.3 show the improved type Preston tube. As a Kiel probe is insensitive to the direction of flow, a Preston tube is covered with a semi-circular shroud.

No.1 and No.2 Preston tubes as shown in Table 1 have different pipe lengths e

Table 1 Dimensions of Preston tubes

No.	type	a	b	c	d	d_1	e
1	Conventional	—	—	—	1.0	0.7	4.5
2	Conventional	—	—	—	1.0	0.7	2.0
3	Conventional	—	—	—	1.0	0.7	2.0
4	Improved	3.5	3.7	1.24	1.0	0.7	2.0
5	Conventional	—	—	—	0.7	0.5	1.9
6	Improved	3.1	3.4	0.94	0.7	0.5	1.9

Fig.2 Configurations of Preston tubes

Fig.3 The improved Preston tube on a plug

but they have an identical pipe-diameter of $d=1.0$ mm. In the case of No.2, the opening of the pipe is located at the center of the plug. No.3 tube is made identical to No.2 to study the reproducibility. Later a shroud is attached to No.3 tube to make No.4. The effect of the shroud can be estimated from comparison between the characteristics of No.3 and No.4 tubes. No.5 and No.6 tubes are similar to No.3 and No.4 tubes respectively, but the pipe diameter is 0.7 mm instead of 1.0 mm. The inner and outer radius ratios of all tubes are about 0.7.

As shown in Fig.3, every Preston tube is mounted on a plug of 5 mm diameter. Each Preston tube on a plug is inserted in a measuring station. As it was quite difficult to keep the surface of the plug flush with the test wall, the influence of the discrepancy of the levels on the pressure reading was examined beforehand using the No.1 and No.2 Preston tubes. Fig.4 shows the results. The abscissa is the discrepancy of the levels Δy mm and the ordinate shows the error of pressure reading or $(P_t - P_{t0})/P_{t0}$. P_t is the reading recorded at various Δy . P_{t0} shows the true pressure reading of the Preston tube at $\Delta y=0$, and $P_{t0}=P_{t0}-P_{s0}$. Open circles indicate the results obtained with No.2 tube which show that the error is less than 1 percent when the discrepancy of the level of the plug is ± 0.1 mm, but No.1 tube is more susceptible to the level of plug. A

Fig.4 The effect of discrepancy between the plug surface and the test wall on the reading of Preston tube

Fig.5 The effect of discrepancy between the test wall and the surface of plug with a pressure hole on the pressure reading

plug having a pressure tap of 0.8 mm diameter is used to measure the static pressure at the wall, and a similar study was made for the pressure measuring plug. The data are shown in Fig.5. From Fig.4 and Fig.5 the technique using plugs is proved acceptable to perform measurement with reasonable accuracy.

3. Experiments

Experiments were made between Reynolds number $Re=2.4 \times 10^4$ and 1.38×10^5 , which is calculated from the hydraulic diameter of a calibration channel and the mean velocity.

3.1. Yaw characteristics

At first an experiment was carried out to prove that the shroud applied to the Preston tube provided a constant reading over a broad range of flow directions. Fig.6 shows the test results. Triangular marks and circular marks in the figure respectively indicate the results of a conventional type Preston tube and those of the improved type. Fig.6(a) shows the results of No.3 and No.4 tubes, and Fig.6(b) shows those of No.5 and No.6 tubes. The abscissa indicates the yaw angle α or the angle between the flow direction and the direction of the Preston tube. As for the ordinate the error of pressure reading, which is defined as $\Delta P/P_{d0}$, is adopted, where ΔP is the difference between the pressure reading at $\alpha=0$ and the pressure measured at a yaw angle α . P_{d0} is the apparent dynamic pressure calculated from the pressure reading of the Preston tube at $\alpha=0$ and the wall pressure. Both figures indicate that the shroud is quite effective

Fig.6 Yaw characteristics of the Conventional type and the improved type Preston tubes

to make the Preston tube insensitive to flow direction. If an error of 1% of the apparent dynamic pressure is admitted, the constant pressure reading is obtained up to ± 20 deg of yaw angle in the case of the improved type, but up to ± 7 deg in the case of the conventional type. As it is recognized that No.4 and No.6 tubes have almost identical characteristics, geometries of the shrouds have little effect in these cases.

The pipe opening of No.1 Preston tube was sharpened as shown in Fig.7 and the yaw characteristic was tested. The reading did not change in a range of ± 10 deg of yaw angle, which is a little better than No.1 tube, but narrower than the improved type Preston tubes of No.4 and No.6.

3.2. The calibrations of Preston tubes

3.2.1. Calibration channel

In order to obtain the relation between the pressure reading and the wall friction force, a special channel as shown in Fig.8 was used.⁽¹²⁾ In the test cross-section, which is 12.5 mm deep and 150 mm wide, the flow is fully developed in the depth direction, though a zone of identical velocity distribution exists at the middle of the width. In other words there is a region of an almost two-dimensional fully-developed flow in the test section. Taking into account the small change of momentum due to the development of the boundary layer on the side walls, the turbulent wall friction force is accurately decided from the pressure drop between the upstream and downstream stations.

Fig.7 Influence of the geometry of the tube opening on the yaw characteristics

Fig.8 The calibration channel

Fig.9 Logarithmic plot of velocity distribution in the test section

As for the preliminary experiments, the measurement of the velocity distribution across the test section was conducted traversing a flattened pitot tube which had a thickness of 0.2 mm with a 0.1 mm opening. Using the wall shear stress decided from the pressure drop, a logarithmic representation of velocity distribution was made. Fig.9 shows the results. Open circles and closed circles respectively indicate the data of $Re = 8.0 \times 10^4$ and those of $Re = 3.5 \times 10^4$. Measured values coincide quite well with the solid line, which represents Reichardt's equation

$$u/u_\tau = 5.75 \log \frac{u_\tau y}{\nu} + 5.5 \quad (1)$$

, where the friction velocity u_τ is defined as $u_\tau = \tau_w/\rho$, and u is the local velocity at y which is the distance from the wall. Friction coefficient C_f is defined using the maximum velocity U so that $C_f = \tau_w / \frac{\rho}{2} U^2$. The formula of friction coefficient C_f is derived from Eq.(1), putting $u=U$ and $y=h/2$ at the center of the test section.

$$1/\sqrt{C_f} = 4.07 \log \frac{U h}{2\nu} \sqrt{C_f} + 3.28 \quad (2)$$

In the experiments described in the next section, the friction coefficient is calculated from the reading of Preston tube and the maximum velocity in the test section, and it is compared with the wall friction coefficient using Eq.(2).

3.2.2. Results and discussion

The Preston tube method is based on the law of the wall or Eq.(1). If d or the external pipe diameter of Preston tube, the pressure reading and the wall shear force are concerned, the law of the wall is represented by the following equation from a dimensional analysis;

$$P^+ = F(\tau^+) \quad (3)$$

, where $P^+ = (P_t - P_s)d^2/4\rho\nu^2$, $\tau^+ = \tau_w d^2/4\rho\nu^2$, P_t is the reading of the Preston tube, and P_s is the static pressure. Preston proved validity of Eq.(3) and established the experimental formula for the relationship. Ideally the internal to external diameter ratio of the pipe d_i/d should be involved

Fig.10 Calibrations of Preston tubes

in Eq.(3), but d_i/d does not influence P^+ according to the literature.(1)

Individual Preston tube was tested at various velocities and the results are presented in Fig.10. These data cover the range of the tube Reynolds numbers $u_\tau(d/2)/\nu$ from 18 to 145.

If the pressure reading of the Preston tube is the area mean value of the stagnation pressure acting on the opening of the tube, the relation between the reading of the Preston tube and the wall shear is theoretically derived from the velocity distribution.(8) If Eq.(1) is used to represent the velocity distribution in the boundary layer and the diameter ratio of Preston tube is put as $d_i/d=0.7$, the following equation is obtained.

$$P^+ = 4.134\tau^+ (\log^2 \tau^+ + 3.723 \log \tau^+ + 3.620) \quad (4)$$

Eq.(4) is approximated by the following equation with sufficient accuracy.

$$\log \tau^+ = -1.306 + 0.863 \log P^+ \quad (5)$$

A solid line in Fig.10 indicates this equation. A chain line and a dotted line respectively show the experimental formula proposed by Preston(5) and N.P.L.(6) It is recognized that there are little differences among these lines. It might be due to the differences on the coefficients of the equation of logarithmic velocity distribution which was used to describe the velocity profile of the turbulent boundary layer.

According to Fig.10, the effect of the shroud on the Preston tube characteristics is not apparent, as almost all of data align on a straight line. In order to precisely determine the influences of the shroud, an experimental formula is derived, and the coefficients of the formula for the individual tube are determined using the least square method. The coefficients are listed in Table 2 together with the formula. The confidence region is calculated from the 95 percent confidence interval. According to Table 2, the characteristic

Table 2 Coefficients of the characteristic equation of Preston tubes

$\log \tau^+ = A + B \log P^+$				
No.	A	Confidence region	B	Confidence region
1	-1.419	-1.586~-1.252	0.882	0.910~0.854
2	-1.456	-1.626~-1.286	0.888	0.917~0.859
3	-1.522	-1.611~-1.433	0.895	0.911~0.879
4	-1.548	-1.623~-1.473	0.898	0.910~0.885
5	-1.497	-1.592~-1.402	0.891	0.908~0.874
6	-1.578	-1.847~-1.309	0.905	0.954~0.856

curve of the conventional type is applicable to the improved type Preston tube ignoring the effect of the shroud.

3.3. Measurements of wall friction force on the end wall of a curved channel

3.3.1. Procedures

Using a curved channel with 180 degree turning angle, experiments were conducted to study the applicability of the improved Preston tube for the measurement of wall friction force exerted by skewed turbulent boundary layers. Fig.11 schematically shows the test channel. The cross-section is 80 mm wide and 160 mm deep, and five measuring stations A, B, C, D and E are located on the flat end wall as shown in the figure. Boundary layer is kept thin at the inlet section so that the main flow or the potential core exists all the way to the outlet section of the curved channel. The measurement of turbulent wall friction force using the improved Preston tubes was carried out at these five stations, and the data were compared with the results deduced from the boundary layer profile data.

3.3.2. Skewed boundary layer

Using a pitot tube and a two-hole type yawmeter with 0.7 mm pipe-diameter by turns, measurements of velocity distribution and skewed angle distribution were carried out at these stations.*

Fig.12(a) shows the distribution of velocities measured at the station C. c/u_τ is adopted as the ordinate, where c is the velocity at y or the distance from the wall, and u_τ is the friction velocity calculated from the distribution of velocity using Clauser's method. Fair agreement of the data with a solid line or the logarithmic law is observed.

The distribution of skewed angles in the turbulent boundary layer at the same station C is shown in Fig.12(b). Using the data in Fig.12(a) and Fig.12(b), the distribution of the main flow-component velocities is calculated and presented in Fig.12(c), where $u_\tau \phi$ is the friction velocity deduced from the distribution of the main flow component velocities using the Clauser chart method. It is seen that the logarithmic law is applicable to the main flow component, too.

Fig.11 The measuring stations on the curved channel

a) Distribution of velocities

b) Distribution of the skewed angles

c) Distribution of the main flow-component velocities

Fig.12 Boundary layer measured at station C on the end wall of the curved channel

* As the pressure gradient perpendicular to the flat wall was negligible, a plug with a pressure hole shown in Fig.5 was used to measure the static pressure, which was used to calculate the velocity.

Table 3 Wall friction coefficient C_f estimated by various methods

	No. 4	No. 6	CLAUSER	JOHNSTON	β_w°
A	0.003 74	0.003 74	0.003 72	0.003 78	26.0
B	0.004 32	0.004 31	0.004 29	0.004 41	20.0
C	0.004 37	0.004 42	0.004 30	0.004 40	22.5
D	0.004 24	0.004 21	0.004 24	0.004 34	20.5
E	0.004 36	0.004 38	0.004 25	0.004 36	22.5

In the cases of other four stations, similar results were obtained.

3.3.3. Turbulent wall friction

When the improved Preston tube on a plug was inserted at these five stations and it was rotated around the axis of the plug, the maximum value of the pressure reading was kept over a broad range of yaw angles, including the direction of the main flow.

Table 3 shows the wall friction coefficient C_f measured at the five stations. It is seen that the values of the No.4 Preston tube and those of the No.6 agree within 1%. In the columns of CLAUSER and of JOHNSTON, C_f was calculated respectively using the procedures proposed by them.⁽¹³⁾ The former procedure uses a chart method which directly indicates C_f by plotting the experimental data of velocity distribution on the chart with many logarithmic law lines of different friction coefficients. In the latter the only main flow component is used to decide the main flow component of wall friction coefficient $C_{f\phi}$ using Clauser's method, and then C_f is deduced from $C_{f\phi}$ and the skewed angle at the wall β_w . Coefficients estimated from various methods at every station coincide within 3%. β_w listed in Table 3 is decided by the extrapolation of the skewed angle distribution to the wall as shown in Fig.12(b).

4. Conclusions

From the present experimental investigation, the following conclusions are derived.

- 1) By adding a shroud to a conventional Preston tube, the allowance of alignment of

the tube in the direction of flow increases up to 20 deg.

- 2) The relation between the Preston tube reading and the wall friction force is hardly influenced by the shroud of the improved Preston tube.

- 3) The wall friction force exerted by a skewed turbulent boundary layer is measured satisfactorily with the improved Preston tube which is fixed on the wall. The orientation of the tube may be in the direction of the main flow if the direction of skewing is unpredictable, but if the direction of skewing is predictable, it may be oriented approximately 20 deg toward the direction of skewing.

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