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A time-resolved hot-wire shear stress probe for turbulent flow: use of laminar flow calibration

Y. T. Chew, B. C. Khoo, G. L. Li

Abstract A specially-designed rotating rig for producing near Couette flow was used in the calibration of a marginally elevated hot-wire shear stress probe. The probe was then used for measurements in both the turbulent boundary layer and pipe flows. Results showed that the mean wall shear stress can be accurately predicted and the near wall statistical quantities of intensity, skewness and flatness of shear stress fluctuations concurred well with previous works, thereby supporting the notion of a time-resolved shear stress probe for turbulent flows.

List of Symbols

A	Calibration constant in Eq. (4)
B	Calibration constant in Eq. (4)
F	Flatness of the shear stress (or velocity) fluctuations
n	Calibration constant in Eq. (4)
r	radial coordinate
Re_s	Reynolds number ($\equiv \omega\delta^2/\nu$)
S	Skewness of the shear stress (or velocity) fluctuations
u	streamwise velocity
$\bar{u}$	mean streamwise velocity
u_τ	mean shear velocity, $(\bar{\tau}/\rho)^{0.5}$
y^+	height in wall units, $u_\tau y/\nu$
z	vertical coordinate

Greek symbols

δ	Gap between the top rotating disk and the bottom stationary disk
ε	dimensionless coordinate, z/δ
ν	kinematic viscosity
ρ	density
τ	wall shear stress
$\bar{\tau}$	mean wall shear stress
μ	dynamic viscosity
ω	angular velocity of the top rotating disk

Subscript

rms	root-mean-square
m	independently measured quantities

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1 Introduction

The use of hot-film as a shear stress probe is still very prevalent among researchers. Its main advantage lies in the ease of operation coupled with a reasonable degree of responsiveness when compared to the use of flat plate force balance with its associated intricacies of mechanical linkages. However, as the hot-film shear stress probe is normally flush-mounted on the wall, it suffers from complex response characteristics due to the effect of heat transfer to the substrate. The probe by itself may be made very small with a low thermal inertia but its contact with the wall (and associated large thermal inertia of the substrate) has made it much less sensitive to rapid shear stress fluctuations (see also Ajagu et al. 1982; Alfredsson et al. 1988, for more details of the limitations of wall mounted probe). This raises the question whether such a probe can be used for time-resolved shear stress measurements as encountered in turbulent flows. To a certain extent, the hot-film probe may still fulfill its role of measuring the *mean* shear stress after calibrating in a (known) similar turbulent flow. Ajagu et al. (1982) have advocated that "the determination of even mean skin friction in turbulent flows requires a turbulent calibration". Implicit in the assertion is that near-wall turbulent flows somehow shared common heat transfer characteristics such that the resultant mean shear stress as measured by the hot-film probe is not too strongly influenced by the details of the heat loss to the wall substrate, thereby implying the possibility of calibrating in a known turbulent flow for subsequent measurements in other turbulent flows. An ideal situation would be an insitu turbulent calibration for further examination of the *same* flow field. However, insitu calibration places unnecessary restriction on the usefulness of a hot-film probe and quite often, one is interested in the mean shear stress of another altered flow like the placement of LEBU device(s) or riblets in internal/external flows, polymeric flow over axisymmetric body or flow over a step surface. Even then, the fluctuating wall shear stress characteristics may not be followed as mean calibration in turbulent flow must necessarily imply the loss of such time-resolving ability of the probe.

To overcome the difficulties associated with the flush-mounted hot-film probe, Ajagu et al. suggested mounting a hot-wire at a suitably small distance from the wall to limit the thermal inertia effect of the wall on the performance of the probe. They further proposed the use of a flush-mounted hot-film placed nearby to serve as a heat guard with sufficiently high overheat so that the probe is completely invariant of the wall condition. Ajagu et al. went on to construct such a probe and showed that after calibrating it in a fully developed two-dimensional laminar duct flow, it can be used for predicting the mean shear stress in a turbulent flow. This is a necessary test for time-resolved shear stress measurements which they showed was not possible for flush-mounted hot-film probe or elevated hot-wire without heat guard. The fluctuating shear stress as detected by the probe also showed features consistent with that found in Willmarth and Lu (1972) and Corino and Brodkey (1969), hence providing further support that it can measure time-resolved shear stress. In a similar fashion, Aoyagi et al. (1985) used a set up of two sensors, one of which was a wall-embedded sensor acting as a "guard" while the other functioned as an ordinary shear stress probe, and obtained improved correspondence between static and dynamic response. That an avalanche of works using such a probe configuration for both direct shear stress measurements and accurate prediction of burst activities near the wall with VITA technique or others does not seem to materialize can be partly attributed to the complexities of making such a probe and which is not available commercially. Furthermore, the flush-mounted hot-film must be placed downstream of the elevated hot-wire in order to rule out any possible direct interference with the function of the latter. It is not known nor tested the region of wall influence by the hot-film and certainly, one must exercise caution in using such a probe in a flow where the direction of mean shear stress is not known a priori.

A few researchers have avoided the issue of the additional flush-mounted film as heat guard by discarding it altogether, Wagner (1991) proposed that the hot-wire be mounted further away from the wall, possibly larger than the "few wire diameters" as described by Alfredsson et al. (1988), but still within the viscous sublayer. Intuitively, it is viable that such a hot-wire probe will be less susceptible to the influence of wall temperature and yet lies in the viscous sublayer where the instantaneous velocity profile is still linear albeit a fluctuating one as in a turbulent flow. It is imperative to note that the elevated hot-wire is cooled by the convective velocity and the shear stress is directly related to the gradient of the linear velocity profile extending from the wall. Unfortunately, both Wagner and Alfredsson et al. only performed an insitu calibration in either the turbulent boundary layer or channel flows for further analysis of the *same* flow field. No attempt is made to check on the validity of the calibration constants in laminar flow or other turbulent flows. However, since their hot-wires are elevated, it is reckoned that a better response characteristic is possible and is thus aptly reflected in the magnitude of $\tau_{rms}/\bar{\tau}$ (i.e. the ratio of the fluctuating rms shear stress to the local mean shear stress) attaining between 0.35 to 0.39, fairly comparable to other independent measurements using pulse hot-wire, flash analysis, LDA, mass transfer technique and direct numerical simulation (see Alfredsson et al. 1988, for more details of each test).

In our work, we seek to utilize the marginally elevated hot-wire as a shear stress probe with the proviso of testing it in both laminar and turbulent flows. Calibration of the probe is carried out in a previously suggested rotating rig capable of generating near Couette flow (Brown and Davey, 1971). Subsequent tests are done in both fully developed turbulent pipe flow and turbulent boundary layer flow. Comparisons are made between the mean shear stress predicted by the calibration as obtained in the laminar flow with the independently measured quantities by means of pressure drop, Preston tube and Clauser plots for the pipe flow and Clauser plots and Preston tube for the boundary layer flow. The concurrence of the mean quantities and the general agreement of the higher-order moments of shear stress fluctuations with previous studies strongly suggest that the probe is capable of time-resolved measurements. A secondary objective of this work is also attained revealing the possibility of calibrating the shear stress probe in a laminar flow rig as opposed to the usual practice of carrying out in turbulent flow. Our specially-made laminar flow rotating rig is very compact and allows not only the calibration over a very wide range of shear stress but enable the shear stress values to be deduced without further instrumentation. Overall, since the probe is calibrated in laminar flow for use in turbulent flow, it provides an alternative to calibration in a known turbulent flow where reservation arises about its applicability to an unknown flow field undergoing major changes.

2 Apparatus and experimental procedure

2.1 Elevated hot-wire shear stress probe

The shear stress probe consists of a DISA 55P11 hot-wire probe secured within a plug by means of two sets of set-screws as shown in Fig. 1. The plug is eventually mounted flush with the wall where shear stress measurements are taken. Originally, the plug is made entirely of perspex (to minimize conduction heat loss to the surrounding substrate) but it is subsequently made of stainless steel to increase rigidity and accord a better fit to the wall. In both cases, the results were quite invariant and is probably due to the small size of the plug measuring 2.2 mm at the top where the hot-wire prongs reside. The prongs are first coated with a very thin layer of wax before fitting into the plug. High temperature epoxy of very low conductivity is then used to fill the top of the plug such that the prongs are not in direct contact with it. After the epoxy is cured, the hot-wire prongs are removed for the surface to be polished flat. Finally, with the cleaned prongs at the desired position, a Dantec 5 μm diameter (d) platinum-coated tungsten wire is soldered across the tips. The height of the wire is determined with a precision microscope and checks are made to ensure that the wire is straight and parallel to the wall. In our tests, the wire height was set at 85 μm throughout. With the wire length (l) of 1.0 mm, the ratio l/d works out to be 200 to ensure negligible heat loss through the prongs (Ligrani and Bradshaw, 1987).

The probe was connected to a DISA 55M01 CTA unit and operated at an overheat of 0.3, similar to that used in Alfredsson et al. (1988) but slightly lower than Wagner (1991)'s overheat of 0.35. The frequency response of the plug assembly/DISA 55M01 circuit was checked using the usual square-wave technique with an estimated frequency of better than 15 kHz. This static frequency response is close to that obtained for a (wall-remote) DISA 55P11 hot-wire/DISA 55M01 circuit used in instantaneous velocity measurement, which provides indication of a potentially fast response shear stress probe. Prior to every run with the newly soldered wire, we took the added precaution of heating the wire at the same overheat in a stagnant flow environment for a few hours to ensure that there is no change in the base voltage. A visual check to ensure there is no sagging of the wire was also

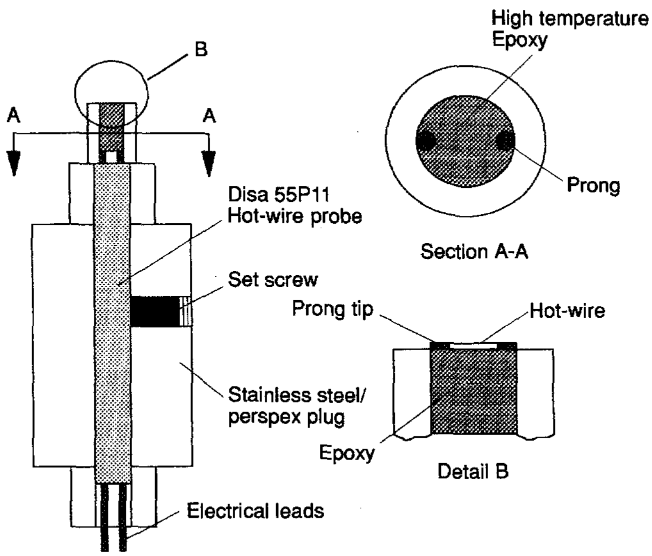

Fig. 1. Schematic of the hot-wire shear stress probe

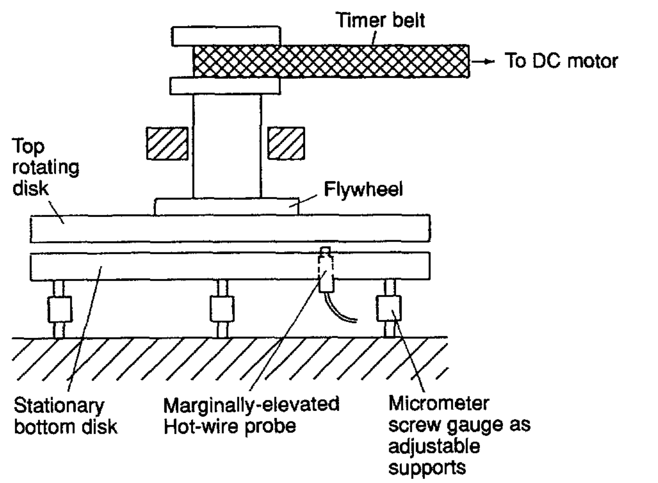

Fig. 2. Schematic layout of the apparatus for the generation of near-Couette flow field between the disks

made. This procedure helps to rule out the possibility of improper soldering of the wire or any loose connections, and indirectly checks on the constancy of the wire resistance. A new wire is installed if there is any breach of these conditions.

In our experiments, the acquisition through a micro-computer was set nominally at 5.0 kHz. Tests were carried out in the turbulent boundary layer and pipe flow with different acquisition rate of 2.0 kHz and 10.0 kHz with the power spectral density showing almost identical distributions, thereby implying the sufficiency of using 5.0 kHz for data collection. There is no localized sharp peak in the power spectral density plot with negligible level of energy residing at the very high frequency range.

2.2
Laminar flow calibration rig

The shear stress probe was calibrated in a laminar flow rig. The rig is very similar in design to that suggested by Brown and Davey (1971). Brown and Davey's intention is the development of a simple calibrating device for wall shear stress probe. We realized the implication of a successful laminar flow calibration for subsequent turbulent flow measurements. The rig consists of a top rotating perspex disk of radius 160 mm and a bottom stationary disk of similar size and material (see Fig. 2). The bottom disk rests on three adjustable supports to aid in the levelling and maintenance of the gap size. Each perspex disk was machine-finished to a nominal thickness of 20 mm with a smooth surface of less than 1 μm variation. The top plate has a flywheel placed axially and was made to rotate via a timer belt linked to a D.C. motor. The rotational speed of the disk ranged from 200 to 2000 rpm in our tests and can maintain to ± 1 rpm of the preset value. The gap (δ) between the disks varied from 0.3 mm to 0.45 mm. The gap size was checked using the travelling microscope. During operations, some video recordings of the gap at various circumferential positions with close-up lens were made and subsequently played back at slow motion to ensure that the dynamic gap size does not change by more than a few percent.

The flow field between a rotating disk at angular velcoity ω and a stationary surface can be taken from Stewartson (1953) for small Reynolds number ($Re_s \equiv \omega\delta^2/\nu$) as

$$v = \omega r[\varepsilon - (Re_s^2/6300)(8\varepsilon + 35\varepsilon^4 - 63\varepsilon^5 + 20\varepsilon^7) + O(Re_s^4)] \quad (1)$$

$$u = -\omega r(Re_s/60)(4\varepsilon - 9\varepsilon^2 + 5\varepsilon^4) + O(Re_s^3) \quad (2)$$

whereupon

$$\tau = \mu(\omega r/\delta)[1.0 + (1/1050)(Re_s^2) + O(Re^4)] \quad (3)$$

Here u and v are the tangential and radial velocity components, $\varepsilon(\equiv z/\delta)$ is the non-dimensional vertical coordinate and r is the radial distance from the axis of rotation. Brown and Davey proposed keeping Re_s small at below 5; in our calibration, Re_s was less than 3 and τ becomes nearly the tangential shear stress and the flow approximates a Couette flow.

In our calibration, the probe was mounted on the stationary plate at various radial positions with different gap size and rotational speed to accord a very wide range of shear stress possible. This compares very favourably to the traditional use of boundary layer or channel flows where maintenance of laminar flow regime at high flow with its associated large wall shear stress requires special effort. Calibration was carried out on all occasion prior to measurement of turbulent shear stress in either the pipe or boundary layer flows. Furthermore, after each series of test, a check on the calibration constants was made to rule out any possibility of drift. The time taken for the calibration process ranged from 5 to 30 minutes; the longer duration encompassed the changing of the gap size and/or radial position of the probe.

As also noted in Alfredsson et al. (1988), the contribution of the spanwise component of the wall shear stress to the basically one-dimensional wall shear stress probe for measurement in the streamwise direction, due to tangential cooling of the hot-wire element, is not expected to be significant since the tangential cooling coefficient k_T is of $O(0.2)$ (see also Champagne et al. 1967; Chew and Ha, 1988). This is especially true for our calibration and the subsequent measurement of wall shear stress in the turbulent flows where the convective streamwise velocity component predominates.

2.3
Pipe flow system and subsonic wind tunnel facilities

The apparatus for generating the fully developed pipe flow consists of a perspex pipe over 12 meters in length with an internal diameter of 92 mm. Placed at the exit of the pipe system is the axial fan driven by a three-phase motor linked to a controller which can maintain a preset fan speed to within ±1 rpm. For our tests, the fan speed ranged from 1500 rpm to over 3000 rpm, corresponding to Reynolds number Re_D (based on mean flow velocity and pipe diameter) between 2.8×10^4 and 1.3×10^5. To reduce any vibration from the fan transmitting upstream, a section of flexible tube and flow straightener are used to separate it from the rest of the system. At the entrance to the pipe system, a conical inlet made according to British Standard Specifications (BS 848), is installed for measuring the volumetric flow rate from the pressure drop across it.

In all the runs, the probe was placed in the fully developed pipe flow regime at 7.5 m from the inlet. Wall shear stress measurements were determined from 3 independent means: pressure drop, Preston tube and the use of Clauser plots. Pressure taps are made at intervals of 0.4 m along the length of the pipe system. At each location, four pressure taps distributed equally round the pipe circumference were connected to a Setra-made pressure transducer and data were acquired using the ("Keithley–MetraByte" made) DAS-20 acquisition system linked to a micro-computer. (The DAS-20 acquisition system has a 16 digital I/O cannels with DMA for both A/D and D/A channels and is capable of acquiring data up to 100 kHz). In our runs, the pressure data were acquired at a nominal rate of 5 kHz. The constant pressure drop observed for the section where the probe was mounted and beyond gave further evidence that the flow was fully developed. Mean velocity measurements across the pipe section using hot-wire anemometer (and counterchecked by pitot tube measurement to be within 3%) were undertaken to construct the Clauser plot thereby yielding the skin-friction coefficient. There were close agreement of results between the various means of measurements to within ±5%.

The open circuit subsonic wind tunnel for generating a boundary layer flow has a 4 m long square (0.33 m × 0.33 m) working test section. As in the case of the pipe flow system, the axial fan at the exit is isolated from the rest with flexible coupling to ensure no extraneous vibration is transmitted upstream. At the test section, a flat perspex plate of over 4.0 m long was mounted with a trip wire at 0.1 m from the rounded leading edge. The shear stress probe was positioned at the center at 2.8 m from the leading edge. Velocity measurements were made at the same location using either the pitot tube or hot-wire anemometer. Clauser plots were constructed for evaluation of the skin friction coefficient under different free stream velocity ranging from 6.0 to 21.0 m/s, equivalent to the Reynolds number, Re_δ (based on boundary layer thickness) of between 2×10^4 and 4.6×10^4. The evaluated skin friction concurred well with that obtained using Preston tube to within ±3% in all cases.

3
Results and discussions

3.1
Laminar flow calibration

Following Brown and Davey (1971)'s use of the relationship between heat transfer from a heated element on a surface adjacent to a viscous boundary layer as derived in Spence and Brown (1968), we have

$$E^2 = A + B\tau^n \tag{4}$$

Here E is the anemometer voltage representing the heat transfer from the active hot-wire element, τ is the associated shear stress, and A, B and n are treated as constants. This is essentially the same form used by Alfredsson et al. (1988) and Ajagu et al. (1982) for the calibration of their respective hot-wire skin friction gauge in known flow for other subsequent measurements. In Ajagu et al., they took into account the variation of the air temperature between tests by introducing the temperature difference term, $T_s - T_\infty$ (between the heated element and the surrounding air), into the RHS of Eq. (4). Since the air temperature does not vary by more than ±0.2 °C in our experiments, we used Eq. (4) directly for the calibration of our probe and subsequent measurements of wall shear stress in turbulent flows.

In the calibration, E^2 is plotted against τ^n where n is selected such that a linear regression coefficient is obtained with a value closest to one. In all cases, the fluctuating voltage E' is much less than 1% of the mean voltage thereby implying an essentially laminar flow prevails. This also provides the assurance that the gap between the disks is effectively constant. Each data point consisted of 10 × 2048 readings, acquired at 5 kHz, for averaging and many repeats were carried out to ensure consistency of results. Shown in Fig. 3 is a typical case with a regression coefficient of 0.99. The quantities A and B are obtained from the figure as the slope and intercept of the graph. In most cases, n lies between 0.40 and 0.46, which is significantly higher than the value of 0.33 as usually reported in wall-mounted hot-film probe. Spence and Brown (1968) showed that for a flush-mounted wall shear stress probe, a necessary condition for $n = 0.33$ is $u_\tau L/\nu > 6.6\sigma^{0.5}$($L$ being the streamwise length of the probe and σ is the Prandtl number of the fluid). This condition is not satisfied in our experiments where $0.27 > u_\tau L/\nu > 0.06$. In Ajagu et al. and Alfredsson et al., the exponent n was set arbitrarily to 0.33 in their calibration and the values of A and B followed. Likewise, proceeding in a similar manner, the use of $n = 0.33$ for our data also produces a reasonable linear graph although with a linear regression coefficient smaller than that obtained previously but still having a respectable value of greater than 0.95 (not shown).

It should be noted that the exponent $n = 0.33$ is strictly for the configuration of a flush-mounted hot-film gauge. In our application, the 5 μm wire is mounted at 85 μm away from the wall and *not* "a few diameters" as in Alfredsson et al. In Wagner (1991), the hot-wire was intentionally mounted at a distance further away from the wall with h (height) varying from 60 μm to 110 μm and an exponent in the region of 0.42 ensued. For the usual hot-wire anemometer (in velocity measurements) very far from the wall, Collins and Williams (1959) have suggested a value of $n = 0.45$ (close to King's law of $n = 0.5$ which is valid for high

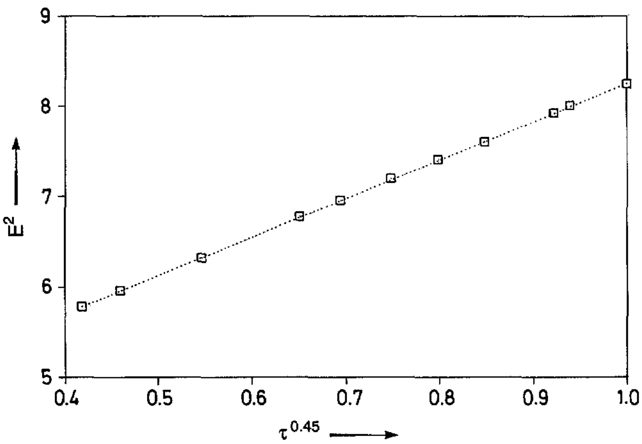

Fig. 3. Laminar flow calibration: E^2 versus $\tau^{0.45}$

Reynolds number flow). Hence it is not inconceivable for our marginally elevated wire to possess an exponent between 0.33 as in flush-mounted configuration where n is probably affected by the wall presence and 0.45 as in wall remote situation.

3.2
Measurements of wall and near-wall shear stresses in turbulent flows

3.2.1
Turbulent boundary layer flow

Figure 4 shows the comparison between the measured mean wall shear stress ($\bar{\tau}_m$) in turbulent boundary layer flow against the results obtained/predicted using the wall shear stress probe. The latter was obtained assuming the validity of the calibration constants as expressed in equation (4) for the instantaneous fluctuating shear stress quantity. Each mean shear stress ($\bar{\tau}$) was computed from large samples of at least 40 × 2048 readings acquired at 5 kHz. There is a rather good agreement of results for a wide range of flow conditions with $\bar{\tau}$ varying from 0.15 to 0.9 N/m^2. Repeats were carried out on other occasions (with newly obtained calibration constants) and showed concurrence of the evaluated shear stress with the independently measured quantities, thereby providing support that the probe is capable of time-resolved shear stress fluctuations.

Further evidence of the time-resolving capability of the probe can be seen in the following figures of the rms level, the skewness and flatness of "near-wall" shear stress fluctuations. Figure 5 shows the plot of $\tau_{rms}/\bar{\tau}$ (where τ_{rms} is the rms value of τ) against y^+ ($\equiv yu_\tau/\nu$, i.e. the height of the hot-wire measured in wall units). $\tau_{rms}/\bar{\tau}$ assumes a range between 0.32 and 0.39 which indicates broad agreement with the quantities of 0.36 to 0.37 by Wagner (1991). Alfredsson et al. (1988) also obtained equivalent quantities of 0.39, 0.36 and 0.35 for their marginally elevated hot-wire/film shear stress probe in air, oil and water flows, respectively. Shown in the same figure is the intensity of the streamwise velocity fluctuations as measured by Alfredsson et al. for the viscous sublayer region in an oil channel flow using hot-wire anemometer. The data is obtained for Reynolds number, based on half channel width, of 3800. Their results can

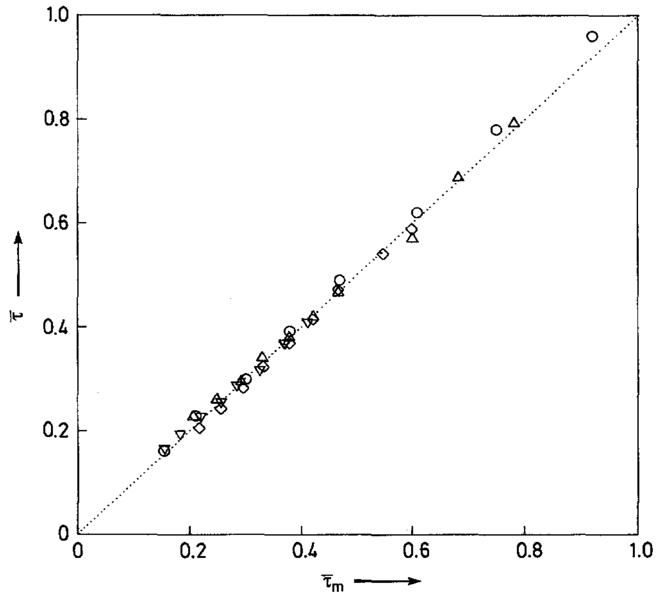

Fig. 4. The mean turbulent wall shear stress in boundary layer flow between predicted ($\bar{\tau}$) and measured ($\bar{\tau}_m$) quantities. Different symbols indicate repeats carried out on different occasions

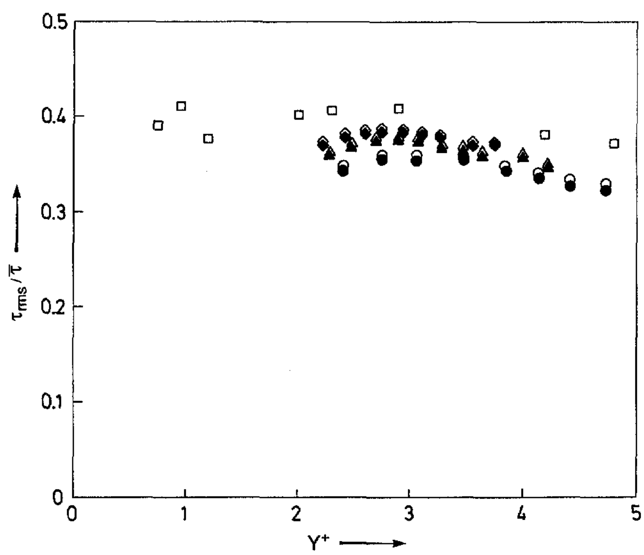

Fig. 5. Intensity of shear stress fluctuations in boundary layer flow: ○, △, ◇, with the full symbols representing "turbulent calibration". Intensity of velocity fluctuations: □ (Alfredsson et al., 1988)

be used for comparison since in the viscous sublayer ($y^+ \leqslant 5$, conservatively), the velocity profile is linear and the shear stress is directly related to the magnitude of velocity. (Alternatively, it can be viewed that the calibration used in equation (4) be expressed in terms of velocity and the resulting signals obtained in the boundary layer flow interpreted as velocity fluctuations.) The fluctuating velocity intensity of Alfredsson et al. indicates a distribution of about 0.4 and decreasing in magnitude as y^+

becomes larger. (The decrease is even larger for $y^+ > 5$ (not shown)). Our findings are also consistent with the normalized shear stress intensity obtained using different instrumentation: a value of 0.32 by Mitchell and Hanratty (1966) using electrochemical method based on mass transfer for pipe flow, a value of 0.4 by Castro and Dianat (1985) using pulse hot-wire, a value of 0.38 by Popovich (1969) using flash photolysis and a value of 0.40 by Karlsson and Johansson (1988) using LDA, all the latter are either for boundary layer or channel flows. Even the direct numerical simulation work by Kim et al. (1987) for a channel flow yielded a quantity of 0.36, which is comparable to our results.

In the next Fig. 6 showing the skewness (S) of τ versus y^+, the results range from 1.25 at small y^+ and decreases to about 0.73 for y^+ approaching 5. The shear stress skewness found in Alfredsson et al. attained the values of 1.0, 1.1 and 0.9 for the respective experiments carried out in boundary layer flow with air, and channel flows with oil and water. In terms of the hot-wire/film above the substrate, these worked out to be $y^+ = 0.3$, 0.2 and 2.0 for the case of air, oil and water flows. (The probe elevation in air is calculated based on 5 wire diameters as the original text only mentioned a qualitative figure of a few wire diameters.) One may notice a slight decrease in the skewness with distance from the wall. Also plotted in the same figure is the skewness of the velocity fluctuations by Alfredsson et al. The skewness showed a small but discernible decrease from 1.15 to 1.0 at $y^+ \simeq 3.0$, and a sharper decrease with further increase in height, thereby marking a fairly similar trend to our results. Our results are also in general agreement with the range of skewness between 0.98 and 1.18 as reported by Wagner (1991) and $S = 1.35$ as given by Ajagu et al. for $y^+ \simeq 0.4$. Unfortunately, no mention is made by Wagner about the variation of skewness with y^+ (based on the probe's height expressed in wall units) which would facilitate comparison with our results.

The flatness (F) of the shear stress fluctuations is shown in Fig. 7. Our results indicate a decrease of F from about 5.2 at

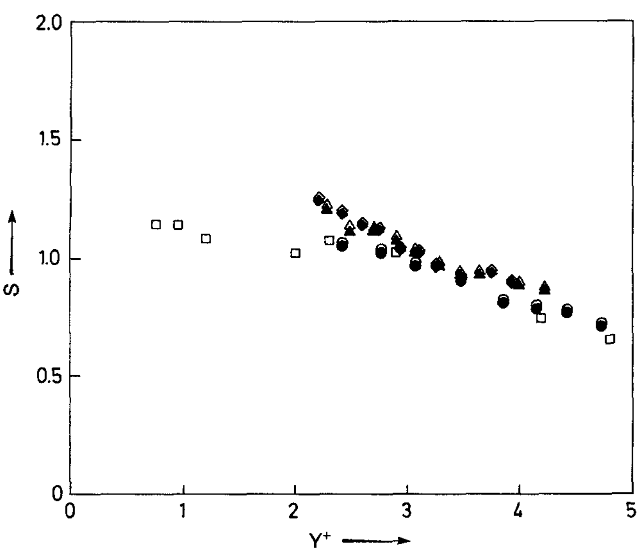

Fig. 6. Skewness of shear stress fluctuations in boundary layer flow: ○, △, ◇, with the full symbols representing "turbulent calibration". Skewness of velocity fluctuations: □ (Alfredsson et al., 1988)

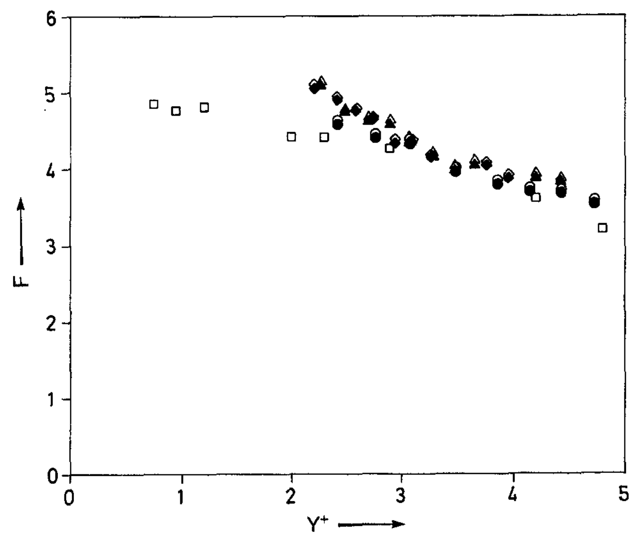

Fig. 7. Flatness of shear stress fluctuations in boundary layer flow: ○, △, ◇, with the full symbols representing "turbulent calibration". Flatness of velocity fluctuations: □ (Alfredsson et al., 1988)

$y^+ \simeq 2.2$ to around 3.6 at $y^+ \simeq 4.7$. The elevated shear stress probe of Alfredsson et al. registered a value of $F = 4.8$, 4.8, and 4.0 for boundary layer flow in air, and channel flows with oil and water, respectively. In their velocity measurements within the viscous sublayer in oil channel flow, the flatness also showed a decline in value from about 4.9 at $y^+ \simeq 0.75$ to 3.3 at $y^+ \simeq 4.8$ (see Fig. 7). This behavior bears a similar trend to ours. Wagner reported a smaller range of flatness between 4.6 and 5.1 when compared to our measurements, but no mention is made of the associated y^+.

Ajagu et al. (1982) has advocated the necessity of a heat guard placed downstream of the elevated hot-wire shear stress probe for time-resolved measurements. They went on to show that without the heat guard, the probe having been calibrated in a laminar channel flow *cannot* be used for prediction of the mean shear stress in a turbulent channel flow. This seems to be in apparent contradiction to our findings. However, it is important to note that their calibration of the probe with heat guard is carried out with y^+ ranging from 0.1 to 0.9 wall units, and the corresponding range of y^+ between 0.1 to 0.45 for the probe without heat guard. All their subsequent measurements in turbulent channel flow has the probe at equivalent *maximum* height of 1.5 wall units from the wall. It is not inconceivable that the mounting of the active hot-wire element very close to the wall has resulted in greater influence by the wall and its accompanying heat transfer such that a heat guard becomes a necessity in presenting a constant wall temperature condition. Chew and Shi (1993) showed in their numerical computation of two-dimensional air flow past a 5 μm diameter hot-wire near a non-conducting wall that wall proximity effects become increasingly significant for $y^+ < 2$. Hence it is not surprising that our probe's height varying in wall units between 2.0 and 5.0 near a perspex wall does not require the use of a heat guard which reduces the complexity of experiment.

Another point worth reiterating (as pointed out previously by Alfredsson et al.) is that the medium of the fluid flow will also determine the extent of the heat loss to the wall. In the oil channel flow, Alfredsson et al. is able to maintain the linearity of $\bar{u}/u_\tau$ versus y^+ ($\bar{u}$ being the mean streamwise velocity) in the viscous sublayer region of $y^+ \leqslant 5.0$ while departure from the linear behavior is clearly observed for those measurements made in wind tunnel for $y^+ \leqslant 3.0$. Similar observations are also clearly discernible for the higher order moments of $u_{rms}/\bar{u}$, skewness and flatness of velocity fluctuations where the divergence of trend for the measurements made in air occurred for $y^+ \leqslant 3.0$. Since the hot-wire/film anemometer is most likely to be calibrated in free-stream and no mention is made of any wall corrections for those data in the viscous sublayer region, the anemometer is deemed capable of measuring instantaneous velocity. The linearity of $\bar{u}/u_\tau$ very close to the wall (up to $y^+ \simeq 0.4$) in oil flow seems to imply that the anemometer is not too unduly influenced by its proximity to the wall, which is contrary to the case of air flow. This is consistent with our suggestion based on Ajagu et al.'s findings conducted in air that heat guard becomes a necessity to maintain a constant wall condition for their elevated hot-wire element mounted at $y^+ \sim (0.1)$ to function as a time-resolved shear stress probe. Other evidence of the importance of the convecting fluid medium in influencing heat transfer from the active hot element are provided by Alfredsson et al.'s use of flush-mounted DISA 55R45 hot-film probe for measurement of shear stress fluctuations in *water* channel flow. They obtained statistics of wall shear fluctuations with $\tau_{rms}/\bar{\tau} = 0.40$, $S = 1.0$, and $F = 4.2$, which are comparable to those taken by the elevated hot-wire probe. (The corresponding velocity measurements and its higher order moments near the wall in the water channel indicates similar trend as that obtained in oil channel flow but unfortunately no data is available for very small y^+ for better comparison.) The equivalent DISA 55A93 hot-film probe (predecessor to DISA 55R45), however, when used in the oil channel flow gave rise to statistical quantities significantly lower than that provided by the elevated hot-wire probe. The effect of using DISA 55R45 for air flow in the wind tunnel yielded even lower quantities of statistics. From prior knowledge that heat transfer per unit length of probe to the water medium is about 10 times better than in oil flow, and close to two orders of magnitude better than air, this suggest the decreasing influence of the wall effects for flows in water, oil and air, respectively. Our results advocating the use of elevated hot-wire at height of $y^+ \sim O(1)$ and greater but within the linear region of instantaneous velocity profile in air without the need of a heat guard (in the light of the results by Ajagu et al. stipulating the necessity of heat guard for their flow at $y^+ \sim O(0.1)$) may be extended to smaller y^+ in other flows of appropriate fluid medium.

3.2.2
Fully developed turbulent pipe flow

To provide further support that our elevated probe is capable of measuring time-resolved shear stress fluctuations, it is tested in the turbulent pipe flow. Figure 8 shows the mean shear stress ($\bar{\tau}$) as evaluated from the instantaneous shear stress obtained using the laminar calibration equation to the probe's output against the independently measured mean shear stress ($\bar{\tau}_m$) with Preston tube, Clauser plot and pressure drop methods. There is close agreement of results for $\bar{\tau}$ ranging from 0.15 N/m^2 to a quantity close to 0.8 N/m^2. Repeats carried out also show excellent agreement.

The next three figures show the statistics of the shear stress fluctuations, namely the rms value ($\tau_{rms}/\bar{\tau}$), skewness (S) and flatness (F). $\tau_{rms}/\bar{\tau}$ is plotted against y^+ in Fig. 9, showing a fairly constant value of 0.35 and decreasing slightly at much larger y^+. This behavior is very similar to the distribution of shear stress intensity observed in boundary layer flow (Fig. 5). This is not

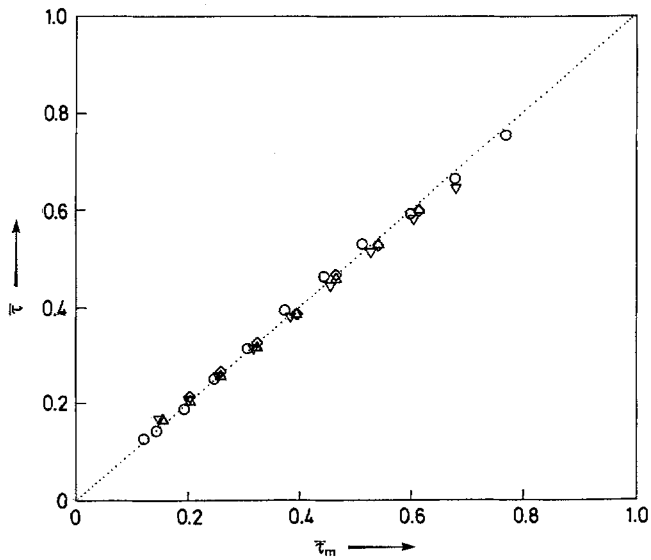

Fig. 8. The mean turbulent wall shear stress in fully developed pipe flow between predicted ($\bar{\tau}$) and measured ($\bar{\tau}_m$) quantities. Different symbols indicate repeats carried out on different occasions

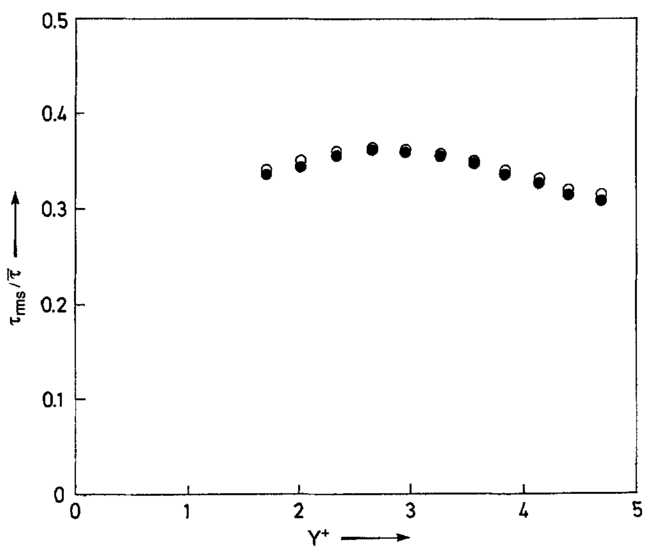

Fig. 9. Intensity of shear stress fluctuations in pipe fully developed pipe flow with the full symbol representing 'turbulent calibration"

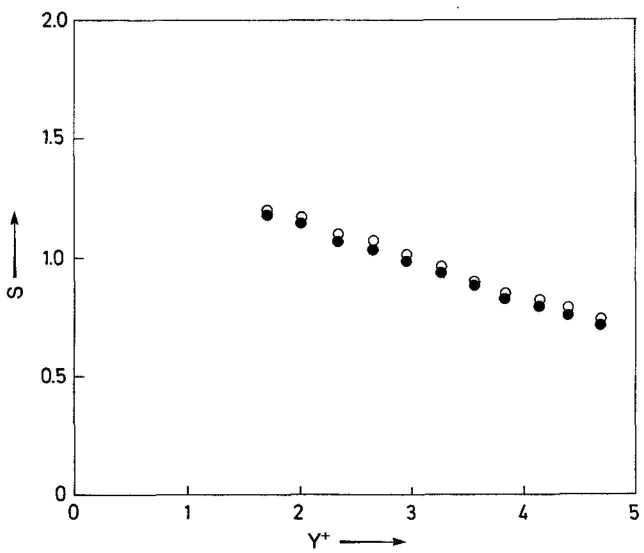

Fig. 10. Skewness of shear stress fluctuations in pipe fully developed pipe flow with the full symbol representing "turbulent calibration"

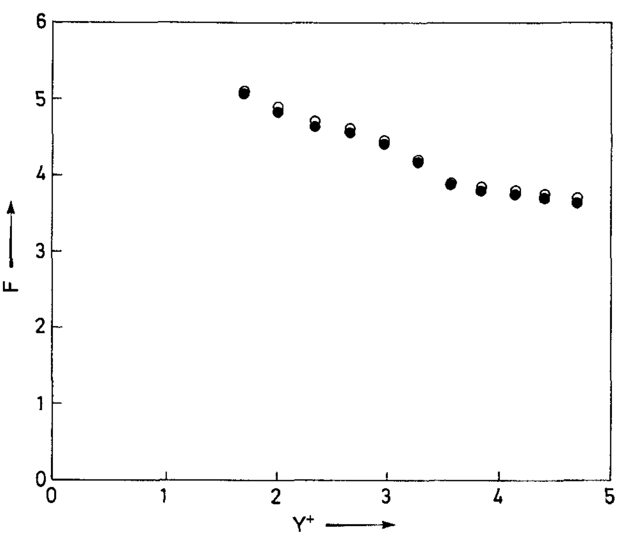

Fig. 11. Flatness of shear stress fluctuations in pipe fully developed pipe flow with the full symbol representing "turbulent calibration"

very surprising in view that there are many similarities in the velocity distributions for both pipe and boundary layer flows especially in the very near wall region (see Hinze, 1975). The skewness (S) in pipe flow is shown in the following Fig. 10 depicting a general trend of decreasing monotonically from a value of $S \simeq 1.2$ at $y^+ \simeq 2.0$ to around $S = 0.75$ at y^+ close to 4.7. This bears close resemblance to its counterpart in boundary layer flow and the skewness for velocity fluctuations as obtained by Alfredsson et al. in oil channel flow (see Fig. 6). Finally, the quantity F for pipe flow is shown in Fig. 11. The graph describes a general behavior of decreasing magnitude as y^+ increases, which is similar to the distributions obtained for flatness for both shear stress and velocity fluctuations (see Fig. 7).

Our findings that the shear stress probe having been calibrated in laminar flow for subsequent successful prediction of the mean shear stress in two types of turbulent flows with the concurrence of near wall statistical quantities with other investigations strongly support the notion of a probe capable of measuring time-resolved fluctuations. Such a probe circumvents the objection raised by sceptics about the validity of using probe calibrated in a known turbulent flow for subsequent measurement in other turbulent flows which may have undergone drastic changes in the near wall turbulence structure.

3.3
Turbulent flow calibration and measurements

In a strict sense, the insitu (turbulent) calibration of their shear stress probe by Alfredsson et al. and Wagner is only intended for further examination of their respective turbulent flows. Since our probe with the calibration constants obtained from laminar flow is deemed capable of time-resolved measurements, it would be interesting to examine and compare the *same* voltage signals from our turbulent flow measurements after subjecting it to "turbulent calibration". (In turbulent calibration, the independently measured mean shear stress is calibrated against the voltage mean values for evaluation of constants A, B and n, and subsequently applied to the same fluctuating voltage signals signifying shear stress fluctuations.) Besides reproducing the mean shear stress value from the fluctuating quantities in a self-consistency test, it would be appropriate to compute the higher-order moments of fluctuations for comparison to the corresponding values obtained using laminar flow calibration.

For boundary layer flow, the rms intensity, skewness and flatness evaluated according to turbulent calibration are plotted in Figs. 5, 6 and 7, respectively, in full symbols. They showed comparable quantities, albeit only marginally smaller than the counterpart obtained with laminar calibration. Similar plots for equivalent turbulent pipe flow are shown in Figs. 9, 10 and 11. In each of these figures, turbulent calibration has resulted in only very slightly smaller values when compared to the laminar calibration. These results imply that *insitu* turbulent calibration of the probe can still yield the true near-wall statistics in the same flow. This conclusion is consistent with the findings by Alfredsson et al. for the oil channel flow where there are close agreement of the said quantities between that obtained using hot-wire anemometer as in velocity measurement and the elevated hot-wire shear stress probe using turbulent calibration. The same magnitude is observed for the measurements made by the elevated probe for both the air and water flows. This tends to support Ajagu et al.'s remark that "turbulent calibration . . . accounts for the satisfactory measurement of mean shear stress" and others. In their turbulent channel flow, they observed comparable level of shear stress intensity between the elevated probe with heat guard and laminar calibration and the elevated probe without heat guard but with turbulent calibration. Their attempt using laminar calibration for the latter was not successful. It should be noted, however, that turbulent calibration is not a panacea as shown in the previous Sect. 3.2.1 that flush-mounted probe used by Alfredsson et al. in the air and oil flows did not produce the true near-wall statistics. Ajagu et al. also mentioned that the intensity given by their flush-mounted film was reduced by as much as 50% when compared to the elevated probe, despite the use of the same turbulent calibration procedure. In essence, the use of turbulent calibration must necessarily imply the loss of time-resolving capability of the probe from which the probe is used subsequently to provide time-varying shear stress fluctuations. The above results for the elevated probe may suggest that the reservations about turbulent calibration is to a certain extent mitigated if analysis of the time-series data is confined to the *same* flow used in the calibration. The main contending issue not addressed here is whether a probe with turbulent calibration can be used to predict other type of turbulent flows, which is shown possible for the case of our probe with laminar flow calibration.

4
Concluding remarks

In this work, we have demonstrated the feasibility of a marginally elevated hot-wire shear stress probe having been calibrated in a laminar flow be used for measurement in other turbulent flows. Experiments were carried out for both turbulent boundary layer and pipe flows where the predicted mean shear stress agrees very well with the independently measured quantities. These results and the evaluation of the higher-order moments of the shear stress fluctuations which show broad agreement with previous investigations support the contention of a probe capable of accurate time-resolved shear stress measurements. An important implication is the availability of such a probe without the need to calibrate in a known turbulent flow and reservation arises about its applicability to other unknown flow fields.

Another important outcome of this work is the use of a very compact rotating rig for the generation of a near Couette flow for calibration purpose. Simplicity of construction is an additional valuable feature of the rig and the wall shear stress can be deduced directly from the linear velocity profile without further instrumentation. This is very much preferred to the use of laminar boundary layer or channel flows not only in terms of the large space requirement of the latter but also the need of associated equipment for generation of flow and measurement of the wall shear stress for calibration.

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