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CORRECTION OF SUBLAYER TURBULENCE MEASUREMENTS FOR WALL PROXIMITY EFFECTS IN HOT-WIRE ANEMOMETRY

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ABSTRACT

The error due to wall proximity has been removed from hot-wire amemometer measurements in the viscous sublayer of a turbulent boundary layer by two methods. The first method, developed from the work of Oka and Kostic (1972) and of Bhatia, Durst and Jovanovic (1982), relies on the assumption that the error in instantaneous velocity measurement can be expressed as $\Delta\check{u}^+ = f(\check{y}^+)$. Use of this method has produced viscous sublayer turbulence statistics which agree well with other experimental data believed to be free of wall proximity errors. The second method, derived from dimensional analysis of heat flow from the hot-wire, makes two additional simplifying assumptions which allow modelling of changes in wall proximity effect caused by variation of operating parameters such as overheat ratio. While physically enlightening, corrections of experimental data by this method are less satisfactory, and so cast doubt on the validity of the assumptions.

NOTATION

d	hot-wire diameter	u	actual air speed
y	distance from wall	u_m	measured air speed
ν	kinematic viscosity	$\Delta u = u_m - u$	

Superscript $^+$ is used for quantities nondimensionalised with friction velocity and kinematic viscosity. Superscript ˇ indicates a quantity which may vary as a function of time. Time averaged quantities are written in upper case.

INTRODUCTION

The error in air speed measurement produced by placing a hot-wire probe close to a wall is known as wall proximity effect. It has an aerodynamic and a thermal component. The aerodynamic component, due to perturbation of the velocity field around the heated wire sensing element, is a function of probe geometry, probe orientation and shear rate in the fluid, and can be reduced to a negligible level by correct design of the hot-wire probe. The thermal component is due to heat transfer from the fluid to the wall and is usually significant only if the sensor is placed within the viscous sublayer. This component can be suppressed only by selecting a working fluid with a very high Prandtl number.

By assuming $U^+ = y^+$ in the viscous sublayer, Oka and Kostic (1972) found that for channel-flow Reynolds numbers ranging from 11700 to 61000, the error in measuring the sublayer mean velocity ΔU could be represented by a single function of the form $\Delta U^+ = f(y^+)$. They then used this function successfully to correct the mean velocity profiles measured in the vicinity of a two-dimensional roughness element. Bhatia et. al. (1982) used the same form of velocity error, but calculated it from a finite difference solution of the energy equation. They assumed the instantaneous sublayer velocity profile to be linear and performed an iteration which simultaneously corrected each sample in the experimental data stream and obtained the instantaneous friction velocity. Acharya and Escudier (1984) have since shown that $\Delta U^+ = f(y^+)$ can be written as a parametric equation which, after constructing a graph of $\Delta U/U_m$ versus yU_m/ν_∞, allows the measurement error to be found without iteration or measurement of the friction velocity.

ANALYSIS

The dimensional analysis of the thermal component of wall proximity effect begins by writing the coefficient of convective heat transfer (h) from the hot-wire to the wall as an unknown function of the probe geometry, flow field characteristics and physical properties of the wall, hot-wire and fluid. For any particular experiment in which the wall conductivity, probe geometry and ambient fluid properties do not change, this function can be reduced eventually to a Nusselt number ($Nu_y = hy/k$) that is a function of only the hot-wire Reynolds number $\check{R}e_d$ and its distance from the wall $\check{y}^+$. The total heat flow from the hot-wire is observed as a measured air speed $\check{u}_m$ and, with typically negligible heat loss by radiation, consists of convection to the fluid and convection to the wall. In nondimensional form, the total heat flow is

$$Nu_d(\frac{\check{u}_m d}{\nu}) = Nu_{\rm fl}(\check{R}e_d, \check{y}^+) + \frac{d}{y}Nu_y(\check{R}e_d, \check{y}^+) \qquad (1)$$

where Nu_d is the hot-wire calibration and $Nu_{\rm fl}$ is the Nusselt number of heat transfer to the fluid. The data of Krishnamoorthy et. al. (1985) indicates that if the heat transfer to the fluid is assumed to be unchanged by wall proximity effect (i.e. $Nu_{\rm fl} = Nu_d(\check{R}e_d)$), the values of $Nu_y(\check{y}^+)$ for varying overheat and wire diameter lie close to a single curve. This curve can be re-expressed in terms of a measured air speed and compared with experimental data, for example, as shown in Figure 1. The close agreement between the two seems to imply that Equation 1 can be simplified to

$$Nu_d(\frac{\check{u}_m d}{\nu}) = Nu_d(\check{R}e_d) + \frac{d}{y}Nu_y(\check{y}^+). \qquad (2)$$

This relation, which also assumes that Nu_y is independent of $\check{R}e_d$, is sufficient to define a method for correcting the thermal component of wall proximity effect.

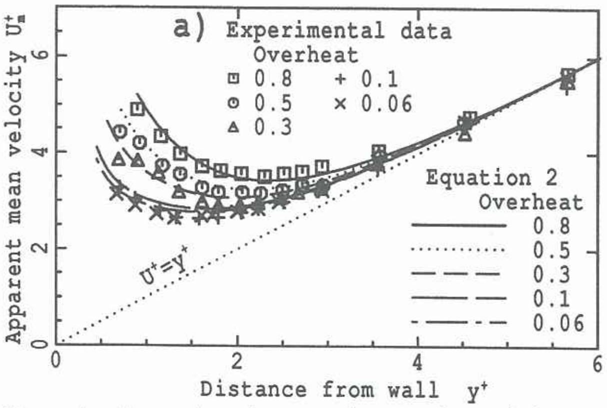

Figure 1: Comparison between the experimental data of Krishnamoorthy et. al. (1985) and Equation 2.

VELOCITY ERROR CORRECTION METHOD

In both correction methods described in this paper, an error function is formulated from the experimental data and is then applied to each individual sample in the data stream. The first method is a "velocity error" method developed from the work of Oka and Kostic (1972) and Bhatia et. al. (1982). The first step is to calculate a nondimensional velocity error

$$\Delta U^+ = U_m^+ - U^+ = f(y^+) \tag{3}$$

from a mean air speed measurement U_m^+ and an assumed a sublayer mean velocity $U^+ = y^+$. A curve of the form

$$f(y^+) = \frac{1}{y^+} e^{-P(y^{+2})}. \tag{4}$$

where $P(y^+)$ is a quadratic polynomial selected by a least squares process, is then fitted to the velocity error data. If the velocity error ΔU^+ is determined from measurements in a laminar boundary layer, the velocity data can be corrected by the iteration procedure of Bhatia et. al. (1982) or by the parametric formula of Acharya and Escudier (1984). The results presented here were calculated by obtaining an initial estimate from the Acharya and Escudier method and then refining it with the Bhatia et al. iteration. Because the velocity error is derived from mean air speed measurements in a turbulent boundary layer, but is used to correct each individual data sample, a small error is introduced into the calculation of each corrected value. The effect of this error on corrected mean velocity can be almost completely eliminated by introducing the factors k_h and k_v (with initial values $k_h = k_v = 1$) so that

$$\Delta U^+ = k_v f(\frac{y^+}{k_h}). \tag{5}$$

After $f(y^+)$ is determined, k_h and k_v are adjusted until the mean error in the data stream $(\overline{\tilde{u}_m^+ - \tilde{u}^+})$ is in optimal agreement with ΔU^+. Typical final values are $k_h = 0.95$ and $k_v = 1.05$.

HEAT FLOW CORRECTION METHOD

The second technique, which follows from the dimensional analysis presented earlier, may be called the "heat flow" method. If a particular hot-wire probe is operated at fixed overheat in a constant air temperature, and if end conduction loss is ignored, Equation 2 can be written in terms of the anemometer output voltage e_m and an empirical correction function $f(\tilde{y}^+)$: viz.

$$\tilde{v}_m^2 = \tilde{v}^2 + \frac{1}{y} f(\tilde{y}^+). \tag{6}$$

The form chosen for $f(y^+)$ is

$$f(y^+) = k_v e^{-P(y^+)/k_h}. \tag{7}$$

where the polynomial $P(y^+)$ is determined (with $k_h = k_v = 1$) by applying the least-squares technique to the appropriately transformed time-averaged experimental data. Finally, k_h and k_v are adjusted to compensate for the effects of applying a mean correction to the instantaneous signal. The corrected anemometer voltage $\tilde{v}$ and corrected air speed data are obtained from Equation 6 by iteration.

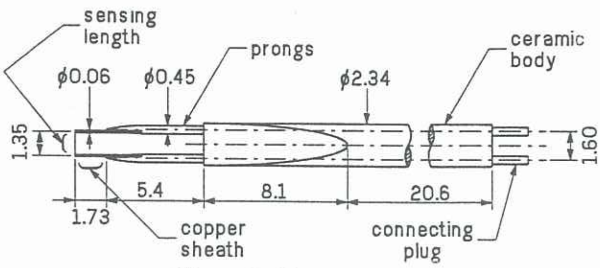

Figure 2: Hot-wire probe

EXPERIMENTAL TECHNIQUE

The experimental results were obtained by measuring velocity profiles in the boundary layer developed on the upper wall of the test section of an induced-flow open-circuit wind tunnel. The boundary layer was tripped to a turbulent state by a single row of 4.76 mm diameter balls placed 10 mm downstream of the leading edge. The profiles were measured at distance of 2.53 m downstream from the leading edge with a free stream speed of 1.67 m/s. Each data point shown in Figures 3 to 7 is calculated from 5000 data samples recorded at a rate of 167 Hz.

The details of the probe used for the measurements are shown in Figure 2. The active part of the sensor was a tungsten wire with a diameter of 5 μm and a length of 1.35 mm. The ends of the tungsten wire were copper plated to a diameter of about 60 μm, were bent back at right angles to form a flat bottomed U and were inclined at an angle of between 5 and 10 degrees to the flow. This probe design allowed the wire to be placed very close to the wall and ensured that the aerodynamic component of wall proximity effect was negligible. The hot-wire probe was operated at constant temperature with a nominal overheat ratio of 0.5.

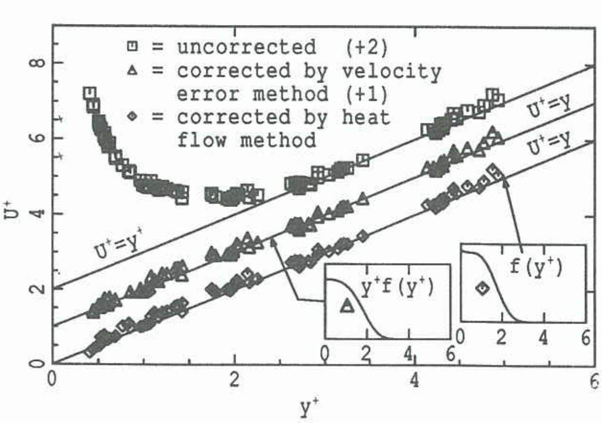

Figure 3: Mean corrected and uncorrected streamwise velocity profiles in the viscous sublayer. Values in parentheses in the legend are the vertical displacements of the data

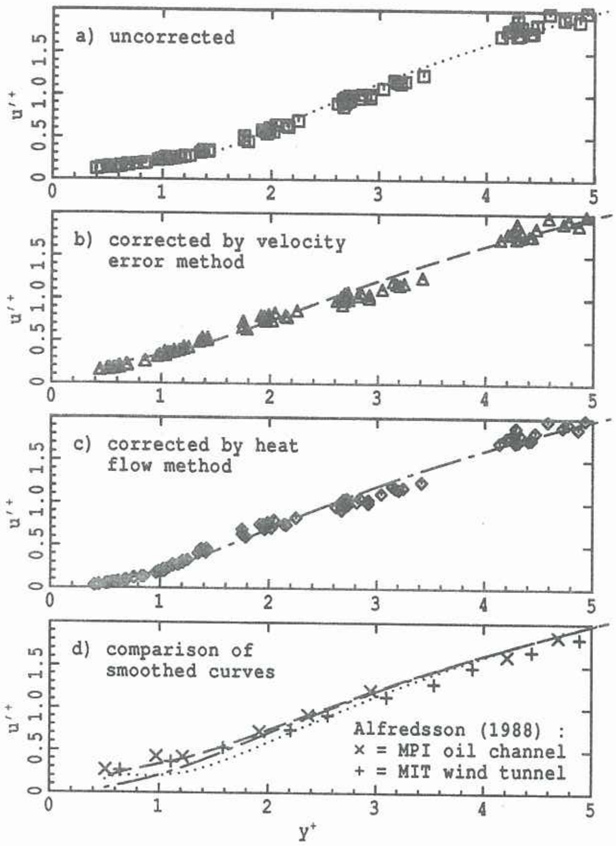

Figure 4: R.m.s. fluctuating streamwise velocity in the viscous sublayer.

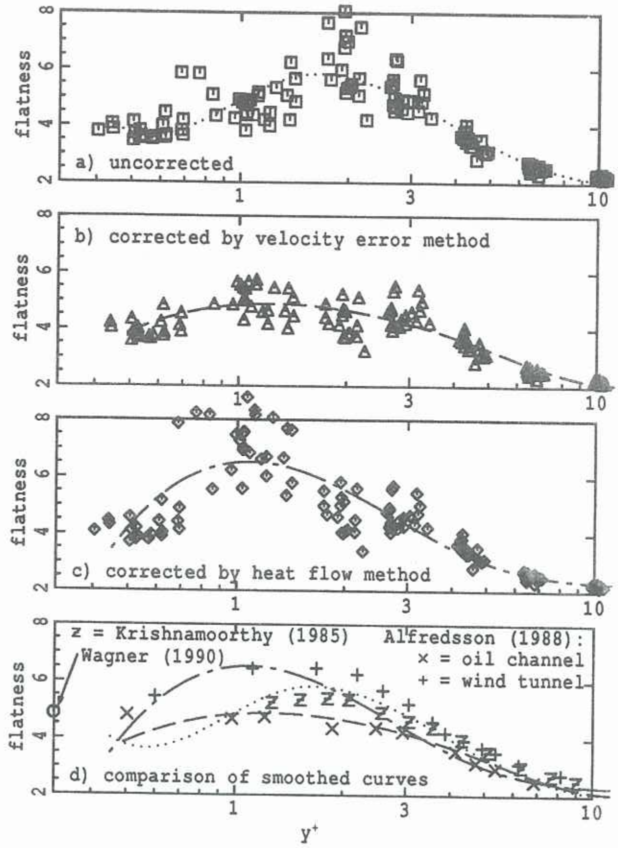

Figure 6: Flatness of streamwise velocity in the viscous sublayer.

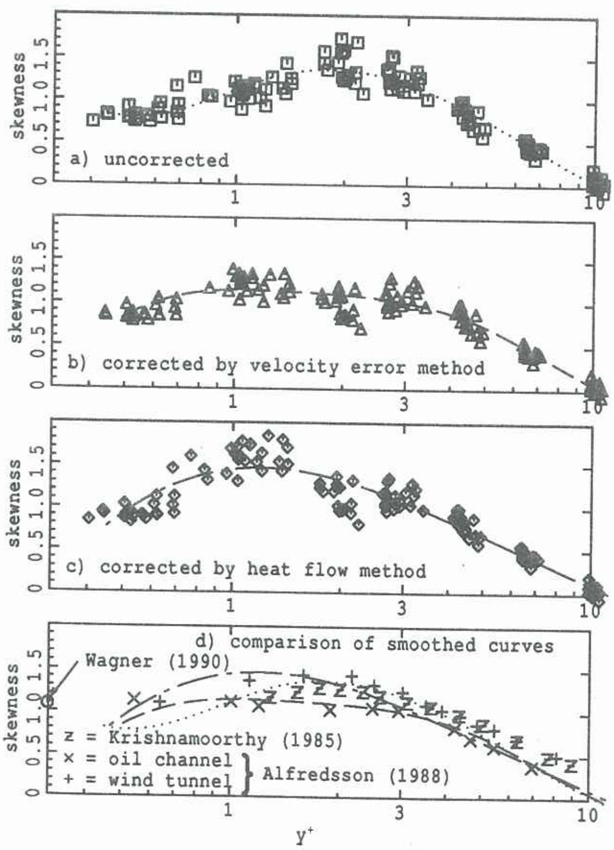

Figure 5: Skewness of streamwise velocity in the viscous sublayer.

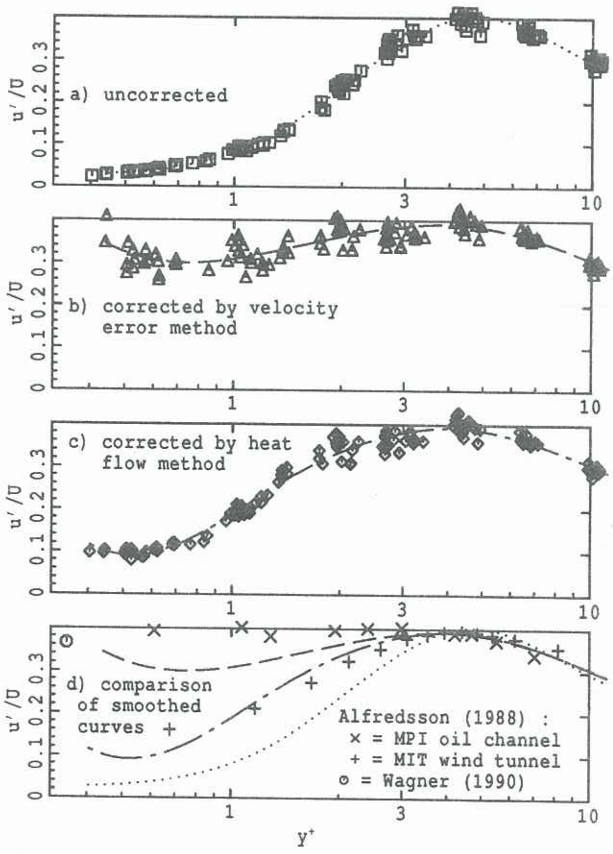

Figure 7: Relative turbulence intensity of streamwise velocity in the viscous sublayer.

RESULTS AND DISCUSSION

The mean values of the uncorrected and corrected streamwise velocity data are shown in Figure 3. For both correction methods, the corrected values agree quite well with the ideal mean velocity profile $U^+ = y^+$ throughout the viscous sublayer. The extent of this agreement depends on the scatter in the uncorrected data and the accuracy of the estimated error functions $f(y^+)$. The insets in Figure 3 indicate the shape of $f(y^+)$ for each method.

Figure 4 shows the effect of correcting the measurement of r.m.s. fluctuating streamwise velocity. A smooth curve has been fitted to the data of each uncorrected and corrected profile (Figures 4(a), (b) and (c)). Both correction processes increase the r.m.s. values between $y^+ = 1$ and $y^+ = 3$. This can be seen clearly by drawing all of the smooth curves on the same set of axes (Figure 4(d)). Ideally, measured r.m.s. velocity fluctuation in the viscous sublayer should be proportional to distance from the wall. The uncorrected data exhibits pronounced curvature in the region $0 < y^+ < 3$ and so clearly does not satisfy this criterion. Both correction methods significantly improve the linearity of the r.m.s. profile data, but in neither case does a straight line of best fit cross the horizontal axis at $y^+ = 0$. For the "velocity error" method, this small discrepancy is small and may be attributed to experimental error. The line of best fit for the "heat flow" method crosses the axis at a significantly greater distance from the origin. This suggests that the assumptions required to produce Equation 2 from Equation 1 may not be justified. Data from the MPI oil channel and the MIT wind tunnel experiments of Alfredsson et. al. (1988) are included in Figure 4(d). The measurements from the MIT wind tunnel boundary layer are modified by the wall proximity effect and the r.m.s. profile has the same sort of positive curvature in the region $1 < y^+ < 3$ as the uncorrected result shown in Figure 4(a). When the wall proximity effect is absent, as is the case in the MPI oil channel experiments, the r.m.s. sublayer profile is linear.

The skewness distribution of the uncorrected and corrected streamwise velocity signals is shown in Figure 5. The corresponding distributions of flatness and relative turbulence intensity (u'/U) are shown in Figures 6 and 7 respectively. Clearly, each correction method produces different changes in the distributions of skewness, flatness and relative turbulence intensity. Figure 6 shows that the effects of the correction process on the flatness of the velocity signal are similar to the effects on skewness. In Figures 5(d) and 6(d), the smooth curves fitted to the skewness and flatness of the uncorrected signal agree closely with the values obtained by Krishnamoorthy et. al. (1985). Application of the "velocity error" correction produces skewness and flatness distributions which agree closely with the MPI oil channel measurements of Alfredsson et. al. (1988) for $y^+ > 1$ and with Wagner's (1990) values for skewness and flatness (1.08 and 4.8 respectively) of wall shear stress. The skewness and flatness from the "heat flow" correction seem to agree fairly well with Alfredsson's MIT wind tunnel data, but this is believed to be coincidental.

The values obtained for relative turbulence intensity (Figure 7) again show that the closest agreement with Alfredsson's MPI oil channel data is obtained by using the "velocity error" method. This agreement is significant and the correction is substantial. Wagner's (1990) value of between 0.36 and 0.37 for the turbulent wall shear stress intensity confirm these data. The large range of values produced by the "heat flow" correction method over $0 < y^+ < 4$, again suggests that this method is based on faulty assumption .

The results presented in Figures 4 to 7 indicate that the "velocity error" method of correcting instantaneous velocity for wall proximity effect is successful for distances from the wall of $y^+ > 1$. This success is qualified only by the small reduction in relative turbulence intensity as the probe is moved towards the wall from $y^+ = 4$. The failure of the correction technique to produce correct values of skewness and flatness for $y^+ < 1$ is probably due to amplification of experimental error by the correction process (which is essentially one of subtraction) and by the extreme sensitivity of skewness and flatness to the corrected velocity data.

In contrast, the "heat flow" method does not produce turbulence statistics which agree closely with experimental data known to be free of wall proximity errors. This failure of the "heat flow" method implies that Equation 1 cannot be simplified without introducing deficiencies into the model. It is expected that if the hot-wire calibration function ($Nu_d(\hat{Re}_d)$) were to be subtracted from Equation 1, the overall dependence of the resulting function on hot-wire Reynolds number would be quite weak. However, because the wall cools the thermal wake of the hot-wire, heat flow to the wall "displaces" heat transfer to the fluid so that the dependence of the individual functions ($Nu_{fl}(\hat{Re}_d, \hat{y}^+) - Nu_d(\hat{Re}_d)$) and $Nu_y(\hat{y}^+, \hat{Re}_d)$ on Reynolds number $\hat{Re}_d$ would be much stronger.

CONCLUDING REMARKS

Thermal wall proximity effect influences not only the mean velocity measurement, but also the measurement of the fluctuating velocity component and the higher statistical moments (skewness, flatness etc.). The effects on skewness and flatness are quite significant even in the region where the effect on the mean velocity measurement is small.

Both correction methods presented in this paper are consistent with Equation 1 which is the result of dimensional analysis. An attempt to simplify this further and develop it into the "heat flow" correction method failed because it did not take account of the interaction between heat flow to the wall and heat flow to the fluid. Unfortunately, the more successful "velocity error" method seems not to facilitate understanding of this interaction.

REFERENCES

Acharya M. & Escudier M.P. (1984) : A direct formulation of correlations for wall-proximity corrections of hot-wire measurements, Experiments in Fluids, 2, 135–136.

Alfredsson P.H., Johansson A.V., Haritonidis J.H. & Eckelmann H. (1988) : The fluctuating wall-shear stress and the velocity field in the viscous sublayer, Physics of Fluids, 31(5), 1026–1033.

Bhatia J.C., Durst F., Jovanovic J. (1982) : Corrections of Hot-Wire Anemometer Measurements Near Walls, Journal of Fluid Mechanics, 122, 411–431.

Krishnamoorthy L.V., D.H. Wood, A.J. Chambers & R.A. Antonia (1985) : Effect of Wire Diameter and Overheat Ratio Near a Conducting Wall. Experiments in Fluids, Vol. 3, 121–127 .

Oka S. & Kostic Z. (1972) : Influence of wall proximity on hot-wire velocity measurements. DISA Information, 13, 29–33.

Wagner P.M. (1990) : The use of near-wall hot-wire probes for time-resolved skin-friction measurements. Advances in Turbulence 3, Springer-Verlag