Eighth Australasian Fluid Mechanics
Conference, University of Newcastle,
N.S.W., 28 November/2 December 1983.

WALL EFFECT ON A HOT WIRE IN A TURBULENT BOUNDARY LAYER

L.V. KRISHNAMOORTHY, D.H. WOOD, A.J. CHAMBERS
AND R.A. ANTONIA

DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF NEWCASTLE,NSW. 2308 AUSTRALIA

SUMMARY This study investigates the influence of diameter, overheat ratio, and prong inclination of a hot wire on mean velocity measurements close to a conducting wall in a turbulent boundary layer. A decrease in each of these parameters reduces the departure of the measured mean velocity from the expected linear sublayer value. The results indicate that a procedure for correcting the mean velocity should at least reflect the influence of all these parameters. Available correction procedures preclude these influences and consequently cannot be regarded as universal.

INTRODUCTION

As a hot wire is brought close to a solid conducting boundary in a turbulent boundary layer, the indicated mean velocity increases above the mean velocity given by the viscous sublayer equation $\overline{U}^+ = y^+$ for y^+ less than 5. An estimate of the difference $\Delta\overline{U}$ between the indicated and the true mean velocity was obtained by Wills (1962) for laminar flow. He suggested that half the laminar correction should be applied to turbulent flows to obtain a sufficiently accurate mean velocity profile close to the wall. Zemskaya et al (1979) showed that Wills' correction failed when applied to different wire diameter, d, for the range 3.8 μm ≤ d ≤ 41.6 μm and suggested an empirical correction which accounted for the effect of d. Hebbar (1980) and Bhatia et al (1982) did not consider the effects of d and so produced a correction in the form of $\Delta\overline{U}^+$ (= $\Delta\overline{U}/U_\tau$, where U_τ is the friction velocity) which depended on y^+ alone. No previous study has seriously considered the effect of overhead ratio a. To minimise wall proximity effects Gupta and Kaplan (1972) used smaller values of d (1.25 μm) and overheat ratio a (0.33) than used in most studies. They also used a wall material (plexiglass) of low thermal conductivity k_w. Polyakov et al (1978), Van Thinh (1969) and Bhatia et al (1982) showed that the correction decreased as k_w decreased whereas Singh and Shaw (1972) suggested that wall material had no effect. Van Thinh (1969) found that the effect of wire length to diameter ratio (ℓ/d) was negligible for $\ell/d \geq 240$. Polyakov et al (1978) and Van Thinh (1969) showed that prong interference is minimised when the inclination β between the wire prongs and the mean streamlines is less than or equal to 5°.

The departure ($\Delta\overline{U}^+$) of the indicated mean velocity distribution from $\overline{U}^+ = y^+$ depends, in general, on the following parameters:
(i) the distance of the wire to the wall (y);
(ii) the wire diameter (d);
(iii) the wire overheat ratio ($a = R_{hot}/R_{cold} - 1 = \alpha T$, α is the temperature coefficient of resistance and T is the temperature of the wire above ambient);
(iv) the mean flow velocity ($\overline{U}$);
(v) thermal conductivity of the wall material k_w and that of the fluid k_f;
(vi) the length of the wire (ℓ);
(vii) the probe geometry;
(viii) the state of the flow (laminar or turbulent).

The aim of this study is to investigate the dependence of $\Delta\overline{U}^+$ on the following parameters:
(i) Wire Diameter : the range considered here, 0.63 μm ≤ d ≤ 5 μm, extends that of Zemskaya et al (1979). The upper limit of our range was chosen to allow comparison with their results and 5 μm diameter wires are commonly used for turbulence measurements. The lower limit of 0.63 μm diameter was chosen as these wires, when operated by constant current circuits at extremely low overheats, are used to measure temperature in turbulent flows. These "cold" wires are used to determine accurately the mean temperature close to a slightly heated wall (e.g. Browne and Antonia, 1982).
(ii) Overheat Ratio : a detailed study of this effect has not previously been made.
(iii) Inclination (β) of the Wire Prongs to the Wall : this is known to influence the mean velocity for y^+ much larger than 5 (Polyakov et al, 1978). The main objective here is to establish the value β_{min} of β which minimises $\Delta\overline{U}^+$.

The effect of d was studied by keeping a and β constant (a = 0.8, β = 5°). The effect of a was evaluated for β = 5° and d = 5 μm. For d = 5 μm and a = 0.8, three values of β (5°, 30°, 90°) were used to establish β_{min}. Bhatia et al's (1982) procedure for correcting instantaneous velocity signals and Chauve's (1980) method of correcting the mean velocity are also applied to the present data.

EXPERIMENTAL ARRANGEMENT

The longitudinal velocity was measured in a turbulent boundary layer which developed with a small favourable pressure gradient on a smooth aluminium floor of a small wind tunnel described by Browne and Antonia (1982). The measurements were carried out at a free stream speed of 9 ms^{-1}, U_τ = 0.38 ms^{-1} and the momentum thickness Reynolds number 2000. The skin friction coefficient (c_f) was obtained with a Preston tube (two diameters 0.45 mm and 4.6 mm were used) using the simplified calibration of Head and Ram (1971). The Preston tube value was within 4% of the Clauser chart value when log-law constants K = 0.41 and A = 5.2 were used. The velocity measurements were made using a hot wire (Pt-10% Rh, α = 0.0016/°C) operated with a DISA 55M10 constant temperature anemometer. The probes were calibrated in the free stream in the working section against a pitot-static tube. The dynamic head was read using a Furness micromanometer with a least count of 0.01 mm of H_2O. The hot wire calibration, carried out before and after each experiment, covered the near-wall velocity range of interest. The initial distance to the wall was determined using a cathetometer (least count 0.01 mm) and halving the distance between the wire and its reflection in the polished aluminium surface. Typically the reproducibility was approximately ±4% for y = 0.5 mm.

RESULTS

The difference $\Delta\overline{U}^+$ decreases as d decreases (Figure 1). The results for d = 5 μm and a = 0.8 is in agreement with the results of Zemskaya et al (1979) and Hebbar (1980). The value of y^+ (≃ 4) above which the deviation is negligible, does not seem to depend on the diameter. A decrease in d is accompanied with a bodily shift of

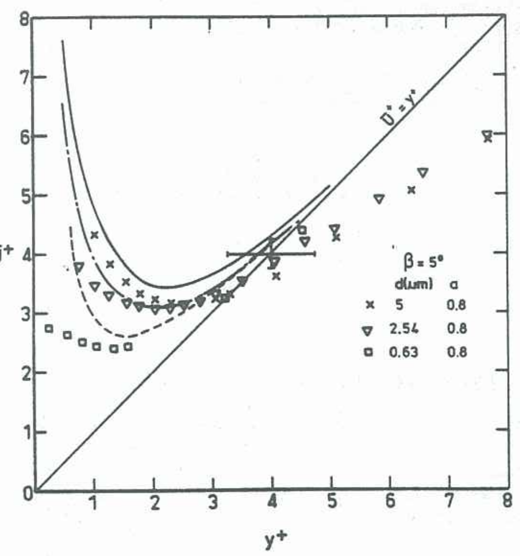

Figure 1 Effect on $\overline{U}^+$ of the diameter of the wire. ——, Zemskaya et al (1979) d = 4.4 μm, a = 0.8; — - —, Hebbar (1980) d = 3.8 μm, a not given; ---, correction equation of Zemskaya et al (1979) for d = 0.63 μm. —┼—, error bar - see text.

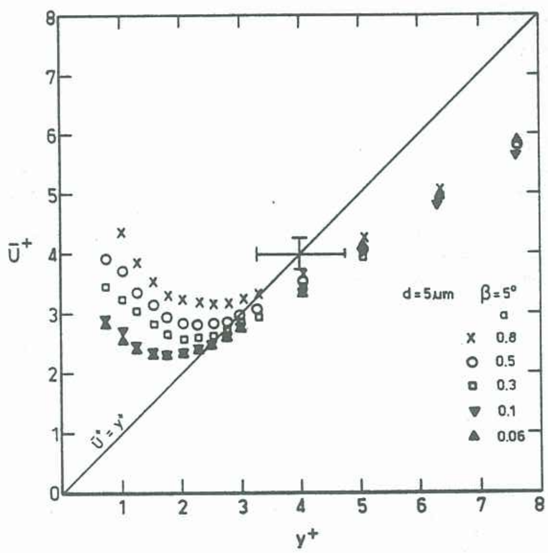

Figure 2 Effect on $\overline{U}^+$ of the overheat ratio. —┼—, error bar - see text.

the velocity distributions towards smaller values of y^+. There is also a downward shift in the minimum value of $\overline{U}^+$, a trend that is noticeable in the results of Zemskaya et al (1979) and when comparing the results of Hebbar (1980) for d = 3.8 μm. Note that the major source of error occurs in the measurement of y. Estimates of the errors shown in Figures 1-3 in $\overline{U}^+$ and y^+ at $y^+ = 4$ are 6% and 15% respectively. However, the experiment was carried out on different days and by different people and for $y^+ > 5$, where the effect of wall on hot wire is expected to be small, the good collapse of all data (Figures 1 and 2) suggests that actual errors are much smaller than these estimates. Since the error in y^+ is larger than that in $\overline{U}^+$, the minimum value of $\overline{U}^+$ is probably the most reliable indication of the diameter effect.

The range of overheat ratios (0.06 to 0.8) considered is equivalent to a wire temperature range of 35°C to 500°C above ambient. The effect of overheat ratio on $\overline{U}^+$ (see Figure 2) is similar to that of d. The lower the wire

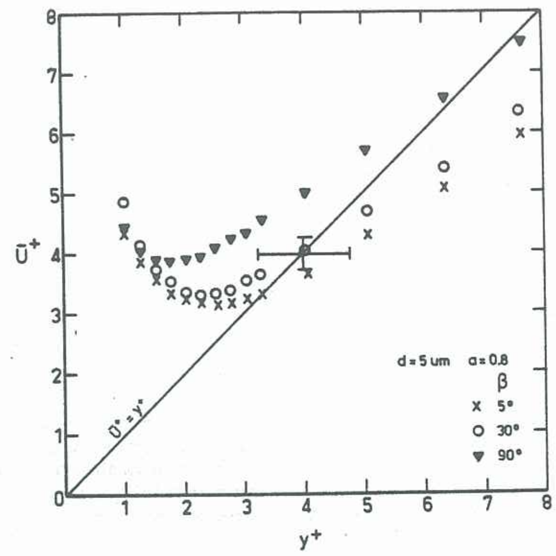

Figure 3 Effect on $\overline{U}^+$ of the prong inclination. —┼—, error bar - see text.

temperature, the smaller the heat loss to the wall and the smaller the correction. There is very little difference between $\overline{U}^+$ distributions for a = 0.06 and 0.1. This can probably be attributed to a small change in the fluid properties, dynamic viscosity, density and thermal conductivity at these low overheat ratios. The results suggest that the variation of fluid properties with temperature should be included in any theoretical account. Bhatia et al (1982) did not allow for a variation in fluid properties in their numerical study of the heat loss from a wire near a conducting wall.

Polyakov et al (1978) found that the indicated mean velocity was insensitive to β when β ≤ 5° but increased monotonically for β > 5°. The present results (Figure 3) support these conclusions. For $y^+ \le 2$, the results are insensitive to β. The present results, not shown here, indicate no dependence on β for $y^+ \ge 20$, in agreement with Polyakov et al's result.

CORRECTION PROCEDURES

The correction procedure suggested by Bhatia et al (1982) is an iterative one based on a correction curve ($\Delta\overline{U}^+$ vs y^+) derived by them from a numerical solution of the additional heat losses from a line source close to a conducting wall in a two-dimensional laminar flow. Starting with an assumed instantaneous value of U (the U obtained from the calibration curve) it is possible to calculate U_τ [$= (\nu U/y)^{\frac{1}{2}}$] and y^+. The magnitude of ΔU, obtained from the correction curve (Figure 5 of Bhatia et al), is then subtracted from the original estimate of U to obtain a new estimate of U. This procedure is repeated until the change in ΔU is less than a predetermined level, usually 1%. The correction procedure was applied to results obtained with two values of d (5 and 1.27 μm, β = 5°, a = 0.8 and 0.5 respectively). Figure 4 indicates that the method is not successful.

A correction procedure developed by Chauve (1980) is based on the formula

$$E^2(R',U,y) = \left(1 + \frac{\Delta w}{w}\right) A(R,\infty) + \left(1 - \frac{\Delta w}{w}\right) B(R,\infty)\, U^n$$

where $A(R,\infty)$ and $B(R,\infty)$ and n are determined by the calibration of the probe in the free stream (large y). The ratio $\Delta w/w \equiv [E^2(R,0,y)-E^2(R,0,\infty)]/E^2(R,0,\infty)$ is determined with no flow as is the value of R', the adjusted hot resistance of the wire at each value of y, so that the anemometer bridge voltage E(R',0,y) is equal to E(R,0,∞), the free stream value.

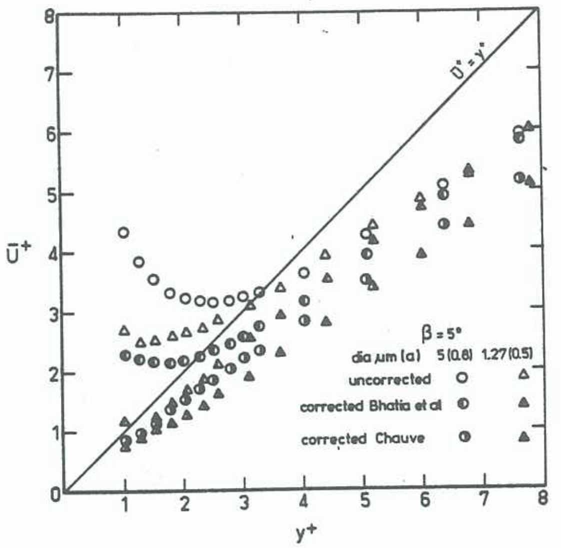

Figure 4 Application of available corrections for $\overline{U}^+$.

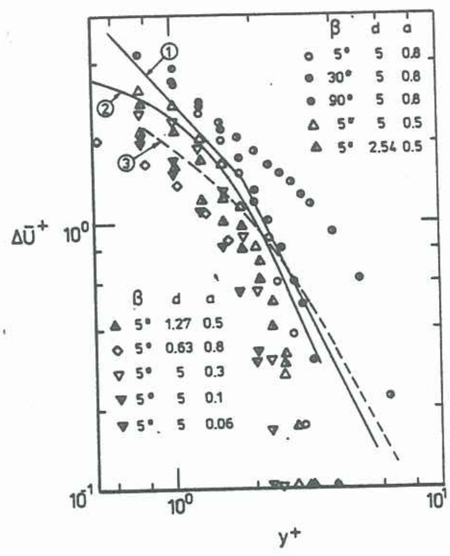

Figure 5 Non-dimensional correction $\Delta\overline{U}^+$ for all the parameters d, a and β. 1. Oka and Kostic (1972); 2. Hebbar (1980); 3. Bhatia et al (1982).

This procedure, which was developed for d = 5 µm was applied to the results for d = 5 and 1.27 µm with β = 5° and a = 0.8 and 0.5 respectively. Figure 4 indicates that the correction yields small values of U^+. Chauve's prong inclination β was 50°. It is expected that $\overline{U}^+$ vs y^+ for β = 50° would fall between β = 30° and β = 90° (see Figure 3) and it is possible that for β = 50°, Chauve's correction may give a closer approximation to $U^+ = y^+$. However for $y^+ < 2$, where the effect of β is small (Figure 3), the correction is perhaps appropriate. Moreover, the wall effect on the hot wire in no flow is observed to $y^+ = 30$. This necessitates a correction to well beyond $y^+ = 5$. Furthermore, it is unlikely that a method based on free convection will apply to cases, such as the present, where free convection effects are negligible. Even at the smallest value of y^+, the Reynolds number based on wire diameter is 10 times greater than the cube root of the Grashof number (Collis and Williams, 1959).

The effect of parameters d, a and β on $\Delta\overline{U}^+$ are summarised in Figure 5. The correction curves given by Bhatia et al, Hebbar and Oka and Kostic are included for comparison. The scatter in Figure 5 appears to preclude the possibility of producing a universal correction relation to account for the varied influence of the parameters considered in this study.

CONCLUSION

The results of Figure 1 show that the error in $\overline{U}^+$ at small y^+ occurs for a larger range of diameters than previously measured and that the error in $\overline{U}^+$ diminishes as d decreases. The effect of overheat ratio is qualitatively similar to that of d in that the error in $\overline{U}^+$ decreases as a is decreased and is important only in the region $y^+ \leq 4$. The results for prong inclination are consistent with Polyakov et al's findings that the effect of β is minimum when β ≤ 5°. The correction procedures of Bhatia et al and Chauve did not correctly predict $\overline{U}^+$ for the present results.

The influence of parameters d, a and β on $\Delta\overline{U}^+$ appears to preclude the possibility of a universal correction. For a given probe geometry, the use of a smaller diameter wire operated at low overheat ratio will require a smaller correction. However, this must be balanced against the decrease in the wire's velocity sensitivity as the diameter and overheat ratios are decreased.

REFERENCES

BHATIA, J. C., DURST, F. N. and JOVANOVIC, J. (1982) Correction of Hot-Wire Anemometer Measurements. J. Fluid Mech., 122, 411-431.

BROWNE, L. W. B. and ANTONIA, R. A. (1982) Measurements in a Thermal Laminar Boundary Layer with a Constant Pressure Gradient, Letters in Heat Mass Transfer, 9, 179-185.

CHAUVE, M. P. (1980) Détermination des Contraintes de Frottement à la Paroi par Anémométrie Fil Chaud, Euromech 132, Lyon, 39-49.

COLLIS, D. C. and WILLIAMS, M. J. (1959) Two-Dimensional Convection from Heated Wires at Low Reynolds Numbers, J. Fluid Mech., 6, 357-384.

GUPTA, A. K. and KAPLAN, R. E. (1972) Statistical Characteristics of Reynolds Stress in Turbulent Boundary Layer, Phys. Fluids, 15, 981-985.

HEAD, M. R. and RAM, V. (1971) Simplified Presentation of Preston Tube Calibration, Aeronautical Quart., August, 295-300.

HEBBAR, K. S. (1980) Wall Proximity Corrections for Hot-Wire Readings in Turbulent Flows, DISA Information, No. 25, 15-16.

OKA, S. and KOSTIC, Z. (1972) Influence of Wall Proximity on Hot-Wire Velocity Measurements, DISA Information, No. 13, 29-33.

POLYAKOV, A. F. and SHINDIN, S. A. (1978) Hot-Wire Anemometer Measurement of Mean Velocity Very Close to a Wall, Letters in Heat Mass Transfer, 5, 53-58.

SINGH, U. K. and SHAW, R. (1972) Hot-Wire Anemometer Measurements in Turbulent Flow Close to a Wall, Proc. DISA Conference, 35-38.

VAN THINH, N. (1969) On Some Measurements Made by Means of a Hot-Wire in a Turbulent Flow Near a Wall, DISA Information, No. 7, 13-18.

WILLS, J. A. B. (1962) The Correction of Hot-Wire Readings for Proximity to a Solid Boundary, J. Fluid Mech., 12, 388-396.

ZEMSKAYA, A. S., LEVITSKIY, V. N., REPIK, Ye. U. and SOSEDKO, Yu. P. (1979) Effect of the Proximity of the Wall on Hot-Wire Readings in Laminar and Turbulent Boundary Layers, Fluid Mechanics, Soviet Research, 8, 133-141.