J. Fluid Mech. (1982), vol. 122, pp. 411–431
Printed in Great Britain

Corrections of hot-wire anemometer measurements near walls

By J. C. BHATIA, F. DURST AND J. JOVANOVIC
Sonderforschungsbereich 80, Ausbreitungs- und Transportvorgänge in Strömungen, Universität Karlsruhe, Kaiserstraße 12, D-7500 Karlsruhe, F.R.G.

(Received 10 November 1980 and in revised form 3 March 1982)

Applications of hot-wire anemometers to velocity measurements near walls can result in erroneous velocity data owing to additional heat losses to the wall. It is difficult to account for these errors if calibration data are used that were obtained in calibration test rigs without walls. This has been recognized in many studies in which hot-wires were applied to measurements in wall boundary-layer flows and different suggestions for corrections have been given. The present paper summarizes these suggested corrections and points out existing differences. It is also shown that some hot-wire measurements have been performed without any corrections being applied and reasons for this are given. Whereas most of the existing suggestions for wall corrections of hot-wire data are based on experiments, the present approach uses results of a numerical study.

Assuming the problem to be two-dimensional and that the wire can be replaced by a line source of heat, a numerical study is carried out for the temperature distribution downstream of the wire, and computations are performed for the heat loss from the wire in presence of the wall. Computations are performed for two different boundary conditions representing ideally conducting and non-conducting materials. These different boundary conditions yield large differences in the computed heat losses from the wire, and these explain the existing differences in the experimentally obtained corrections. The numerical study also shows that the large heat losses for conducting walls are due to the distorted temperature distribution in the temperature wake of the wire.

Some of the results of the numerical studies were experimentally verified by the authors and a procedure has been developed to correct instantaneous hot-wire readings for additional heat losses to a wall. For non-conducting walls, the heat losses are much smaller and are negligible for most practical measurements.

1. Introduction

The heat loss from a hot wire can be employed to measure the local velocity in a flow field if the convective heat loss is known as a function of an effective cooling velocity. This functional relationship is usually obtained by calibrating the hot-wire anemometer output in a known, and in most cases uniform, velocity field. If the properties of the calibration flow field and the properties of the flow field to be studied differ greatly, questions arise with respect to the reliability of the interpretation of the hot-wire anemometer signal from a point in a flow in terms of the local instantaneous velocity. Similar problems arise if the flow boundaries in the calibration rig and those in the flow field to be studied differ in such a way that different heat losses occur, in spite of the same velocity at the wire sensor. If not accounted for, the differences due to boundaries will be interpreted as differences in local flow velocity, and hence erroneous measurements will result.

The above-mentioned cause of erroneous interpretations of hot-wire signals is well known from velocity measurements close to solid walls that consist of heat-conducting materials, e.g. metals. As the hot wire approaches the wall, the hot-wire anemometer output increases beyond the value corresponding to the local velocity at the wall distance where the wire is located. Very close to the wall, the output can take on values larger than those away from the wall, where the velocity is higher. This indicates clearly that the wall vicinity has to be taken into account to deduce the local velocity correctly from hot-wire signals.

Although the aforesaid problem of hot-wire anemometer-signal interpretation for near-wall measurements has been known for many years, no detailed study exists that deepens the insight into the physical causes of the heat-loss increase due to the presence of a wall. This is stressed in § 2, where a literature survey is provided in order to summarize the existing experimental and theoretical knowledge on this problem. Various suggestions for the causes of the increase in heat loss are discussed, and it is shown that most of them contradict the experimentally obtained dependence of the output of the hot-wire anemometer on flow and wall properties. This has encouraged the authors to carry out an approximate theoretical study described in this paper. Results of this study and some experimental and theoretical justifications of the approach are provided in § 3.

Section 4 provides an experimental set-up to study near-wall flow phenomena using the newly derived knowledge on wall corrections for hot-wire anemometer measurements. Results are presented that confirm the finding described in § 3 and give support to the suggested correction procedure described in § 5. The authors' findings are summarized in this section and are extended to be applicable to all near-wall measurements in turbulent wall boundary-layer flows. Conclusions and final remarks are provided in § 6.

2. Literature survey on wall corrections for hot-wire measurements

Most investigations of the required corrections for hot-wire measurements near walls have been carried out experimentally, and first attempts to suggest corrections originate from the early experiments of Van der Hegge-Zijnen and Dryden (work mentioned by Zarič 1972), who employed constant-current anemometers in their study. They concluded from their measurements that the wall influence can be interpreted as a velocity difference, which can be obtained from the heat loss to the wall at zero velocity. Their finding gave rise to suggestions that the heat loss is due to heat conduction from the wire to the wall and/or due to heat radiation. The results of Van der Hegge-Zijnen and Dryden could not be confirmed by later studies. It is for this reason that Reichhardt (1940) suggested the calibration of hot-wire anemometers in laminar channel flows in which the velocity is known as a function of distance. Reichhardt (1940) suggested the use of that calibration curve for measurements in turbulent wall boundary layers for which the friction velocity U_τ agrees with the friction velocity in the laminar calibration flow.

The above-mentioned work was followed up by various studies in which constant-temperature anemometers were used to obtain information on the wall influence on hot-wire measurements. Table 1 summarizes the most important studies known to the authors in this field and also summarizes the flow conditions under which the investigations were carried out. Information is also provided on the normalized distance y^+_{min}, which the various investigators approached during their measurements. Information on the probe type, the electronic signal-processing equipment and the wall material are also included in table 1.

The investigation that obtained most attention is that of Wills (1962), who suggested that Reichhardt's proposal of calibration in a well-defined laminar channel flow should not only be applicable to constant-current hot-wire anemometry but also to constant-temperature anemometry. Since the time constant for the constant-temperature operated hot-wire anemometer is small in comparison with the timescale of turbulence, it was claimed that it is possible to apply results of the static calibration in laminar flows to the instantaneous velocities recorded in turbulent wall boundary layers, and in this way to take into account the wall vicinity for the instantaneous velocity records. It was further suggested that the calibration data based on experiments in laminar channel flows may be used for measurements in turbulent boundary-layer flows for the same friction velocity U_τ. Very detailed calibrations over a wide range of friction velocities are required when this idea is applied to instantaneous velocity records. Additional information was not supplied by Wills (1962) about the possible effects of wall material on the calibration corrections.

Wills (1962) made use of his correction for experimental data of local mean velocity obtained in a turbulent channel flow. Comparing the corrected results with the expected velocity profile in the sublayer, e.g. $U^+ = Y^+$, too-low values were obtained. The suggested calibration in the laminar channel flow yielded too large a correction when applied to mean values in turbulent boundary-layer flows. In order to overcome this unexpected overcorrection, Wills suggested that half of the laminar correction should be applied to obtain a reasonable agreement with the presumed sublayer profile. No physical reason could be offered for this proposal.

Many investigators followed up Wills' work, among them Zarič (1972), who applied fast data-acquisition systems to hot-wire anemometer measurements near walls. His investigations suggest that Wills' correction is applicable if taken into account for every instantaneous velocity. This finding suggests that the overcorrection obtained by Wills (1962) is due to the presence of turbulence in the flow which was not accounted for in the calibration. Zarič's (1972) work suggests that the fast response of the hot-wire anemometer permits Wills' (1962) correction to be applied to instantaneous velocities yielding correct information for the final mean velocity profile.†

Another, more practical, approach to obtaining wall corrections for hot-wire mean velocity measurements was suggested by Oka & Kostic (1972). They carried out velocity measurements in a fully developed channel flow with smooth top and bottom walls. Postulating the existence of the mean-velocity profiles $U^+ = Y^+$, they recorded the deviations from this velocity profile when measured with hot-wires calibrated without the presence of the wall. Measurements were carried out for different Reynolds numbers and it was found that the measured uncorrected velocity profiles are universal

† It is worth noting that the correctness of a wall-correction procedure was always judged by comparing the final results with an *expected* linear normalized velocity profile in the wall sublayer.

Authors	Geometry	Re	y^+_{min}	Probe type	Measuring technique	Wall material
Piercy, Richardson & Winny (1956)	Rotating arm	—	—	Unplated	Analog	Brass
Wills (1962)	Channel	—	3	Plated	Analog	Duraluminium
Comte-Bellot (1965)	Channel	60×10^4	4	Unplated	Analog	Plexiglas Duraluminium
Clark (1968)	Channel	1×10^3–93×10^3	2	Unplated	Analog	Plywood
Van Thinh (1969)	Channel	39×10^3	2	Plated	Digital	Glass
Singh & Shaw (1972)	Plate	—	—	Unplated	Analog	Duraluminium, brass steel, perspex
Zarič (1972)	Channel	12×10^3	1·6	Plated	Digital	Steel
Gupta & Kaplan (1972)	Plate	18×10^3–56×10^3	2	Unplated	Digital	Plexiglass
Oka & Kostic (1972)	Channel	11×10^3–64×10^3	0·6	Unplated	Analog	Steel
Alcaraz & Mathieu (1975)	Plate	—	—	Plated	Analog	Plexiglas Duraluminium
Polyakov & Shindin (1978)	Channel	—	3	Unplated	Analog	Steel, copper, textolite
Hebbar (1980)	Plate	—	0·5	Plated	—	—

TABLE 1. Summary of publications on wall corrections for hot-wire anemometer measurements

in terms of normalized coordinates (U^+, Y^+). Their results show that the measured uncorrected velocity profiles start to deviate from the expected linear velocity profile at approximately $Y^+ \lesssim 5$–6. This finding was confirmed by Polyakov & Shindin (1978), and more recently by Hebbar (1980). Whereas neither Oka & Kostic nor Hebbar mention the possible influence of the wall material, the study by Polyakov & Shindin (1978) does show a strong dependence of the velocity deviations on the wall material. This is in agreement with studies by Clark (1968) and Van Thinh (1969), who used special wall materials to carry out measurements for the turbulent wall boundary layers without applying any corrections to their readings. Van Thinh used glass walls in his channel test section to obtain acceptable results without corrections being applied down to a minimum distance from the wall of $Y^+ = 2$. This is in agreement with measurements carried out by Clark, who used plywood as material for the walls of his channel test section.

In contrast to the aforesaid findings, Alcaraz & Mathieu (1975) and Singh & Shaw (1971) expressed opinions that the nature of the wall is not of great importance to the applicable wall corrections. It is difficult to deduce from the publications of these authors why they obtained results that differed from those of Clark, Van Thinh and Polyakov & Shindin.

To overcome the influence of the wall vicinity on hot-wire anemometer measurements, Gupta & Kaplan (1972) suggested the use of various overheating ratios to determine the wire temperature at the point of measurement. Since they used perspex as wall material, the low thermal conductivity and the low overheating ratio employed in the final measurements completely reduced the wall influence on their hot-wire data.

A unique study was carried out by Piercy, Richardson & Winny (1956), who investigated theoretically and experimentally the influence of wall proximity on the heat loss from hot-wires. They found that the amount of heat loss increased with an increase of fluid velocity, with the distance of the wire from the wall being kept constant. This finding is in agreement with experimental results of Oka & Kostic (1972) and also with those of other authors who carried out measurements for wall materials of high conductivity. Piercy *et al.* also recorded observations of the cooling of a hot-wire whirled through air round a large circular brass cylinder. Their experimental results showed a good agreement with the theoretical predictions but, as will be seen in § 3, the predictions of the required wall correction considerably underpredict experimental corrections obtained by Oka & Kostic (1972), Hebbar (1980) and others, and therefore their results cannot be used to correct hot-wire data in turbulent wall boundary-layer measurements.

Although the theoretical study by Piercy *et al.* (1956) does not yield correct quantitative information on the required wall corrections to hot-wire anemometry readings, it showed that the problem can be treated theoretically, and the present paper is an attempt to do so. The present approach takes into account the results of the previous authors, which suggest that the velocity distortion near the wall is not a cause of increase heat losses from the wire if wire positions of $Y^+ \gtrsim 2$ are considered. For smaller values, prong interferences with the flow have been observed experimentally; which means that the two-dimensional approach carried out here cannot be used.

3. Theoretical investigations

3.1. *General considerations*

As stated above, one of the earlier attempts to study theoretically the problem of wall corrections for hot-wire measurements was carried out by Piercy *et al.* (1956). They assumed the analytical problem to be two-dimensional and the fluid inviscid, incompressible and of uniform properties.† The boundary condition at the wall was that of a constant temperature, which implies a wall material of high conductivity. Using the stream function and the velocity potential as independent variables, Piercy *et al.* (1956) succeeded in obtaining an approximate solution of the energy equation. Using this approximate solution, the present authors carried out computations for several different velocities of the fluid and for various distances of the wire from the wall. These results are shown in figure 1, and provide informations on the deviations from the linear velocity profile (see figure 1*a*) and on the correction velocity (see figure 1*b*). The data are plotted in a normalized form, where the friction velocity and the viscosity are used for normalization. As may be observed from this figure, the velocity correction normalized with the friction velocity increases with increasing velocity of the fluid. This is in contradiction to some of the recent experimental work, (e.g. Zaric 1972; Oka & Kostic 1972; Hebbar 1980). All these authors suggest a universal correction curve when plotted in the normalized quantities employed in figure 1. Furthermore, the correction for the wall influence sets in at too close a distance to the wall, around $Y^+ \lesssim 2{\cdot}5$, while the experiments show that the deviations from the postulated linear mean-velocity profile begin as far as $Y^+ \lesssim 5$–6.

Figure 2 provides information on the applicability of the various suggestions for wall corrections to hot-wire anemometer measurements. It is clearly seen that the theoretically based correction proposed by Piercy *et al.* (1956) is too small when applied to actual data, yielding velocity information in excess of the $U^+ = Y^+$ profile.

† The velocity was constant in the entire flow field.

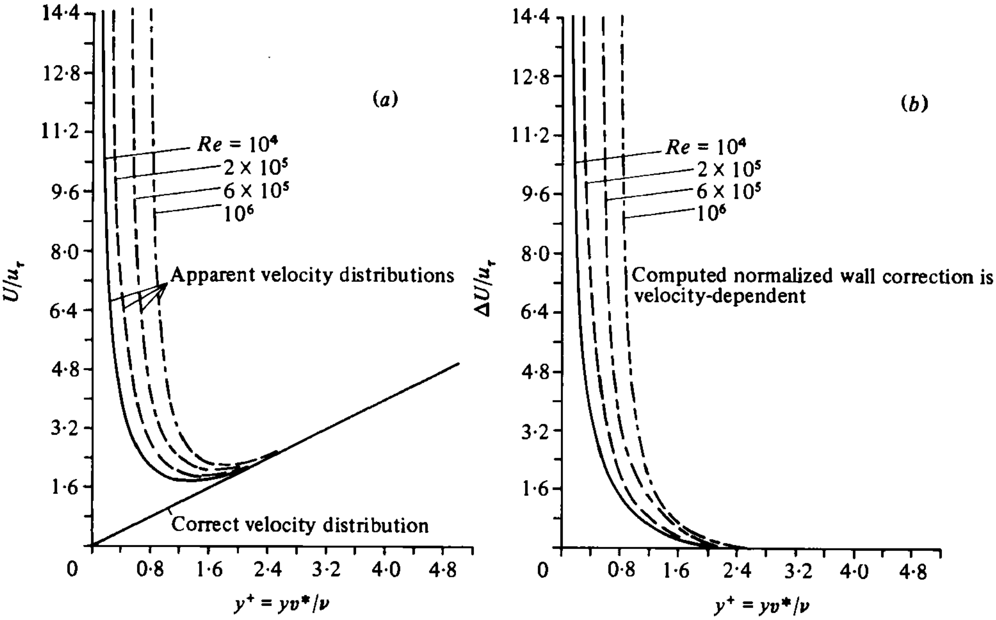


FIGURE 1. Computations of wall influence on hot-wire readings based on the theory of Piercy *et al.* (1956) ($u_\tau = v^*$).

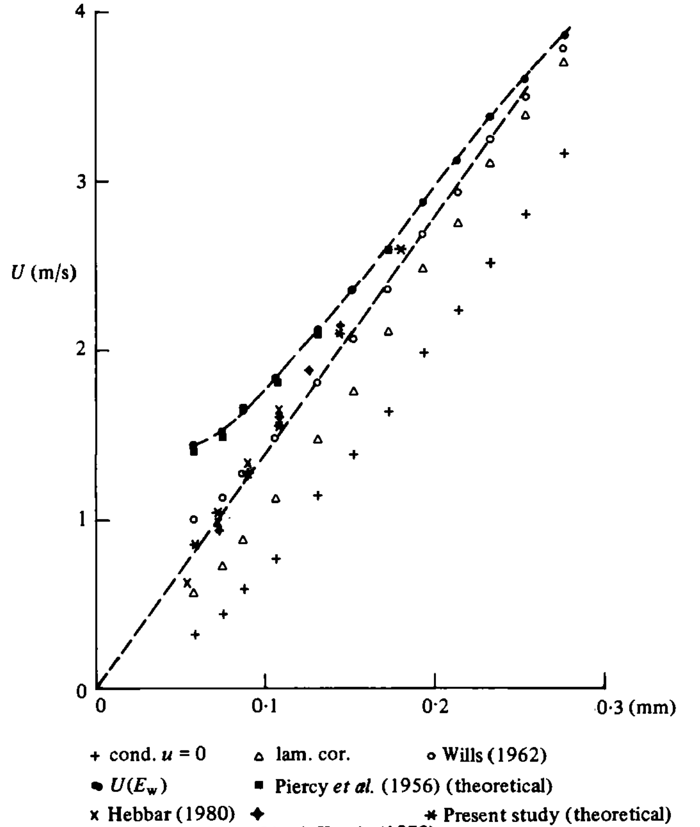


FIGURE 2. Various corrections for wall proximity applied to hot-wire anemometer data of Zarič (1972).

The literature survey in § 2 indicated that the precise reason for the additional heat loss when a hot wire approaches a solid boundary is still unknown. A possible explanation is that the heat is transferred to the wall by the thermal wake that hits the wall behind the wire. The altered temperature gradient thus established between the wall and the wire is then responsible for the additional heat loss from the latter. If this is the case, then the maximum variation in the temperature gradient should occur around the point where the wake meets the wall, and consequently the major contribution towards the amount of heat transferred to the wall comes from the variation of the temperature distribution in this region. Further, if the wall is non-conducting, the temperature wake will take on a different form, e.g. it will be reflected back to the fluid, and because of the reduced heat loss, the presence of the wall should have no appreciable effect on the heat loss of the wire. It was anticipated that a comparison of the heat loss in two cases – conducting and non-conducting walls – should provide a means of reliable correction. The final results obtained with this approach prove the correctness of this hypothesis, and it turns out that, in spite of several simplifying assumptions, the correction predicted by the present method is the best so far. Although obtained theoretically, it is in excellent agreement with experimentally proposed corrections for $Y^+ \gtrsim 2$. Closer to the wall, smaller corrections are predicted than required experimentally, and reasons for this are given below.

3.2. *Governing equations*

The analytical problem is assumed to be two-dimensional. The fluid, incompressible and of uniform properties, flows in the x-direction with a velocity that increases linearly with increasing distance from the wall:

$$U = \frac{U_0}{a} Y, \tag{1}$$

where Y is the distance measured perpendicular to the wall, and U_0 the velocity at the wire position a. Further, it is assumed that the wire, located on the Y-axis at a distance a from the wall, is very thin and has no influence on the flow field, i.e. its velocity wake is negligible. Hence the actual wire can be replaced by a line source of heat of uniform strength. In other words, the fluid velocity is assumed to be independent of x and is given by (1) everywhere in the computation domain. This leaves the parameter T, the temperature of the fluid, as the only unknown in the problem. To compute it for various wire temperatures and wall material properties the energy equation can be used:

$$\rho c U \frac{\partial T}{\partial x} = \kappa \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial Y^2} \right) + \mu \left(\frac{\partial U}{\partial Y} \right)^2, \tag{2}$$

where ρ, μ, κ and c denote respectively the density, viscosity, thermal conductivity and specific heat capacity of the flowing fluid.

To obtain information on the temperature field of the above-mentioned line-source–flow-field combination, a solution is sought that satisfies the following boundary conditions (see figure 3):

$$T = T_0(Y) \quad (x = x_0), \tag{3a}$$

$$\partial T / \partial X = 0 \quad (x \to \infty), \tag{3b}$$

$$T = T_\infty \quad (Y = 0) \quad \text{for a conducting wall, or} \tag{3c}$$

$$\partial T/\partial Y = 0 \quad (Y = 0) \quad \text{for a non-conducting wall,} \tag{3c'}$$

$$T = T_\infty \quad (Y \to \infty), \tag{3d}$$

where T_∞ is the temperature of the oncoming fluid, and $T_0(Y)$ is the temperature distribution in the fluid at a cross-section $x = x_0$, which still needs to be defined. It will be seen later that to overcome a singularity in the initial temperature distribution at the location of the wire centre, a non-zero value of x_0 is essentially required for the present treatment of the problem.

Denoting the kinematic viscosity by ν and the friction velocity by U_τ, and introducing a reference length $L = \nu/U_\tau$ together with a reference temperature T_∞, the following normalized quantities can be defined:

$$X^* = X/L, \quad Y^* = Y/L, \quad \theta = (T - T_\infty)/T_\infty. \tag{4}$$

Introducing these quantities into (2) and using (1) yields†

$$U^* \frac{\partial \theta}{\partial x^*} = Y^* \frac{\partial \theta}{\partial x^*} = \alpha \left(\frac{\partial^2 \theta}{\partial x^{*2}} + \frac{\partial^2 \theta}{\partial Y^{*2}} \right) + \beta, \tag{5}$$

where $\alpha = \kappa/\mu c$, $\beta = U_\tau^2/cT_\infty$, and U_0 and U_τ are related by $U_0 = aU_\tau^2/\nu$.

The boundary conditions for the normalized quantities, corresponding to those given in (3), are

$$\theta = \theta_0(Y) \quad (x^* = x_0^*), \tag{6a}$$

$$\partial\theta/\partial x^* = 0 \quad (x^* \to \infty), \tag{6b}$$

$$\theta = 0 \quad (Y^* = 0) \quad \text{for a conducting wall, or} \tag{6c}$$

$$\partial\theta/\partial Y^* = 0 \quad (Y^* = 0) \quad \text{for a non-conducting wall,} \tag{6c'}$$

$$\theta = 0 \quad (Y^* \to \infty). \tag{6d}$$

The 'initial temperature' distribution at a plane at $x^* = x_0^*$ is taken from Lauwerier (1954), who obtained an explicit solution of the diffusion equation

$$U \frac{\partial c}{\partial X} = D \frac{\partial^2 c}{\partial Y^2}, \tag{7}$$

for a source of uniform strength in presence of a plane conducting wall placed in a linear velocity field. The difference between (2) and (7) is due essentially to the presence of the term $\partial^2 T/\partial x^2$ in the former, which changes the nature of the equation from parabolic to elliptic. According to the postulated causes of the additional heat loss (see § 3.1) this term is essential to the theoretical treatment of the problem. However, it is assumed that Lauwerier's solution provides a suitable approximation for the initial temperature distribution function $T_0(Y^*)$ in a plane $X^* = X_0^*$. This solution is discontinuous and has a singularity if $x^* = 0$ is taken as plane. To overcome this difficulty, a small positive value of x_0^* ($= 10^{-7}$ m) was taken and the computations began at this point. The initial temperature profile is given by

$$\theta_0(\eta) = \frac{T_w - T_\infty}{T_\infty} \frac{F(\xi, \eta)}{F(\xi, 1)}, \tag{8}$$

† The Y-term on the left-hand side of (5) is due to the linear velocity profile given in (1).

where

$$F(\xi,\eta) = \frac{\eta^{\frac{1}{2}}}{3\xi} I_{\frac{1}{3}}(2\eta^{\frac{3}{2}}/9\xi)\exp\{-(1+\eta^3)/9\xi\}, \tag{9a}$$

$$\xi = (\kappa\nu^2/\rho c a^3 U_\tau^3)\, x_0, \tag{9b}$$

$$\eta = (\nu/aU_\tau)\, Y. \tag{9c}$$

$I_{\frac{1}{3}}$ is the Bessel function of order $\frac{1}{3}$ and T_w is the temperature at the point $X = 0$, $Y = a$, assumed equal to the wire temperature. A further assumption that is introduced into the present approximate solution to the heat loss from a wire close to the wall is that (8) and (9*a*–*c*) remain valid in the case when the wall is non-conducting. This implies that the wire is kept at constant temperature irrespective of the actual heat loss due to the presence of the wall.

The incorporation of the solution of Lauwerier (1954) as the initial condition for the present computations requires some physical justification. It implies that the shape of the temperature profile in the vicinity of the heat source is mainly given by the wake equation for near-wall flows provided by Lauwerier (1954) as a solution of the boundary-layer form of the energy equation. The downstream boundary conditions do not influence this shape, but have an influence on the temperature gradient only; i.e. on the distance between constant-temperature lines. This yields the change in the resulting heat transfer predicted below.

3.3. *Computation procedure and results*

The derivatives in (5) were replaced by second-order central-difference approximations, and the finite-difference equations solved on a non-uniform rectangular numerical mesh using the SOR technique. The grid lines were arranged to concentrate around the source and around the point of maximum heat transfer downstream of the source (this non-uniformly spaced grid was found by an approximate solution using a uniform grid). Under-relaxation was found to be useful in most of the computations for various flow velocities and wire positions. The region of integration extended up to $XU_\tau/\nu = 60$–80 and $YU_\tau/\nu = 7$–10, depending upon a, the distance of the heat source from the wall. The heat loss by the wire was obtained by carrying out a balance in the region of integration. For this purpose, a four-point formula for the temperature gradient and a three-point quadrature formula, derived for the non-uniform mesh, were employed.

Test runs showed that the heat loss to the conducting wall behaved as already known from experiments, i.e. the computations indicated that with increasing wire wall distance a the point of maximum heat transfer on the wall moved further downstream. Quantitative results of the computations are exhibited in figures 3–5. The temperature profiles to a typical case ($U_\tau = 0{\cdot}5$, $au_\tau/\nu = 0{\cdot}6964$) are shown in figure 3 for four different values of X. The source (wire) is located at point S. Figures 4 and 5 exhibit computed Nusselt numbers $Nu = H/2\pi\kappa(T_w - T_\infty)$ for $U_\tau = 0{\cdot}125$–$1{\cdot}0$, where H is the amount of heat loss by the wire. The full lines in figure 4 correspond to the case $T_{\mathrm{wall}} = T_\infty$ and the broken ones to the case $(\partial T/\partial Y)_{\mathrm{wall}} = 0$.

Figure 5 shows the computed correction curve for hot-wire readings close to the walls. The curve shows that the numerical computations predict correction below $Y^+ \gtrsim 6$ for the U_τ values employed by the authors in their computations, the resulted corrections came out to be independent of U_τ and Y^+ when plotted as

$$(\Delta U/U_\tau) = f(Y^+).$$

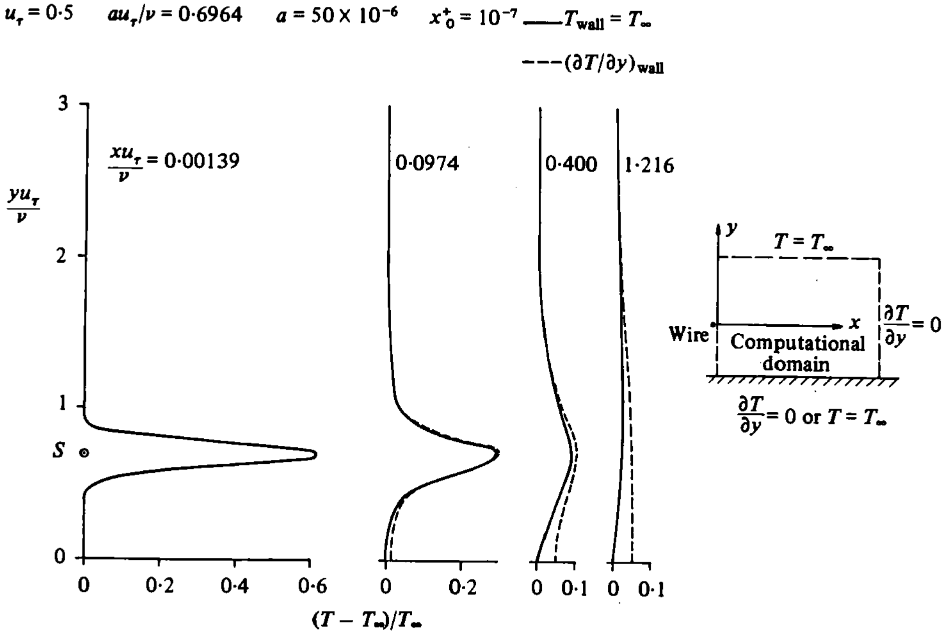


FIGURE 3. Computed temperature wakes for various x-locations.

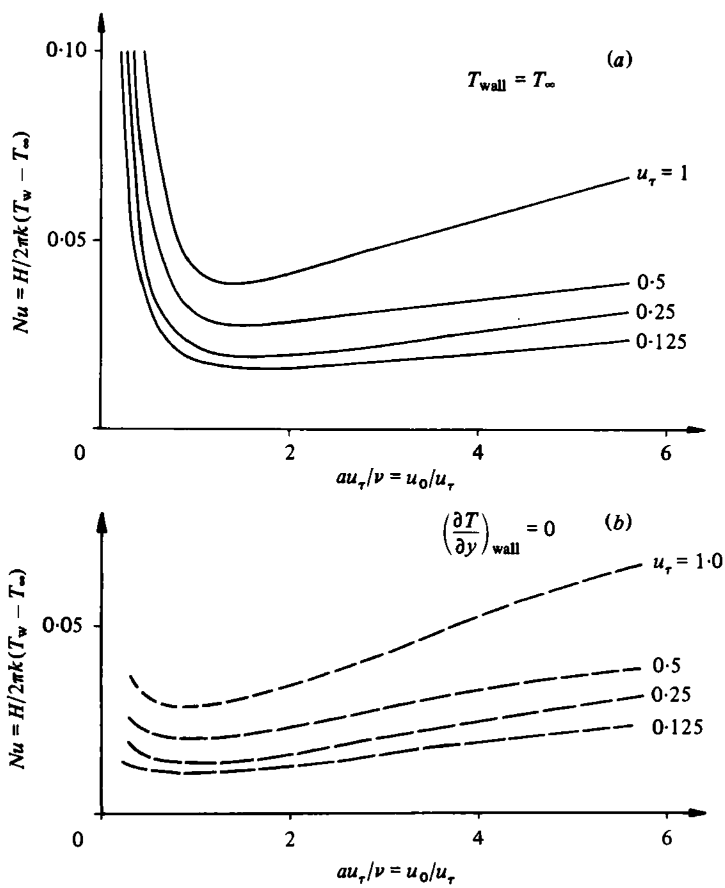


FIGURE 4. Computed Nusselt numbers for conducting and non-conducting wall materials.

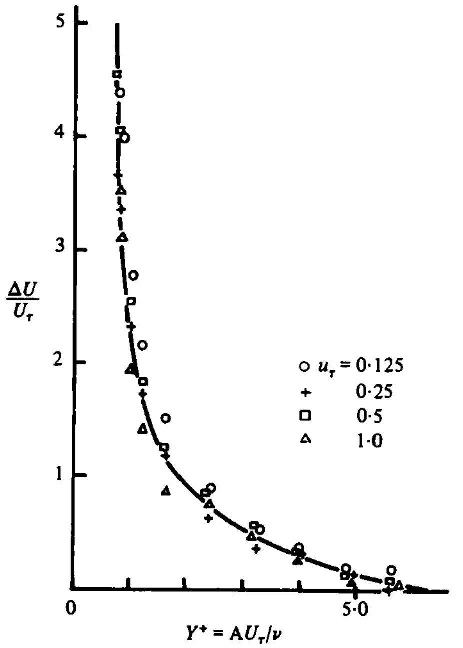


FIGURE 5. Computed correction curve for hot-wire readings close to walls.

This finding is in agreement with experiments, which also show that the correction curves scale with the wall variables. For wire positions close to the wall, $Y^+ \lesssim 2$, the present corrections are smaller than those obtained experimentally. This suggests that in this region, the distortion of the velocity profile, employed for example in the predictions of Piercy *et al.* (1956), due to the presence of the wire near the wall might become important.

4. Computation of corrections in a turbulent flow

Although the numerical predictions of the additional heat losses due to the presence of a wall have been carried out for a laminar flow, considerations can be extended to measurements near walls in turbulent-flow situations. Assuming a linear velocity profile to exist between the wire location Y and the wall, the following expression holds:

$$\hat{U}_\tau^2 = \frac{\hat{\tau}_w}{\rho} \equiv \frac{1}{\rho}\mu\left(\frac{\partial \hat{U}}{\partial Y}\right)_w \approx \nu\frac{\hat{U}}{Y}$$

where $\hat{U}$ is the instantaneous velocity that the hot wire experiences. Of course, this velocity differs from the velocity *that is measured* at this location because of the wall influence.

In accordance with the above equation, the dimensionless distance $\hat{Y}^+$ of the wire from the wall, can be expressed in the form

$$\hat{Y}^+ = \frac{Y\hat{U}_\tau}{\nu} = \left(\frac{\hat{U}Y}{\nu}\right)^{\frac{1}{2}}.$$

The fast frequency response of constant-temperature hot-wire anemometers permits the laminar correction to be applied to the instantaneous velocity records, for example, the general correction curve ($\Delta U/U_\tau$) computed in § 3 as a function of Y^+ has to be applied to each velocity sample from a turbulent flow field. For this purpose, the measured instantaneous velocity is taken, and the above formula is used to compute the friction velocity $\hat{U}_\tau$ and the dimensionless wall distance $\hat{Y}^+$. For these properties, the velocity correction ΔU is computed using the correction curve in figure 5. This correction yields an improved velocity measurement, which is used in a second step to recompute U_τ and Y^+. With these improved values, a new correction is computed, yielding a further improvement in the velocity measured by the hot wire. This procedure is repeated until the changes in the corrections are below a preset limit, e.g. 1 %. The resultant velocity is then taken as the measured and corrected instantaneous velocity. If the above procedure is applied to measurements in turbulent flow fields near metal walls, all instantaneously *measured* velocity components can be transferred into *corrected* values, and from the latter the correct mean and turbulence quantities can be computed. This has been demonstrated by the authors in many experiments, and in § 5.2.2 some examples are given and discussed.

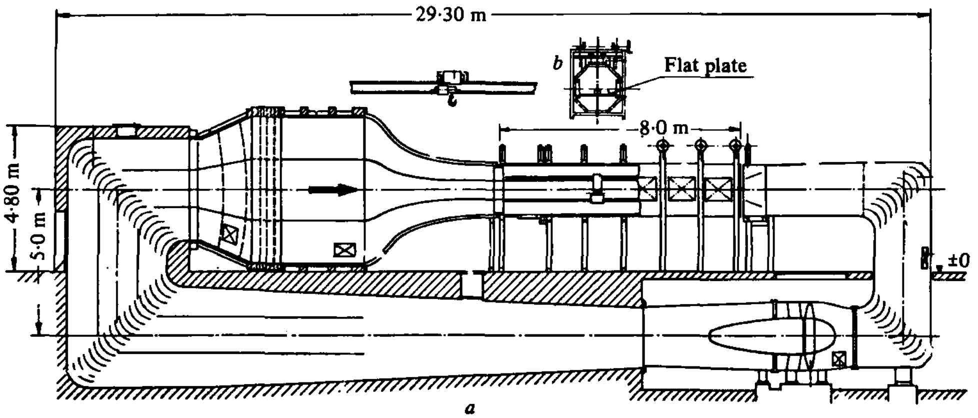
It is worth noting that the present suggestion to correct hot-wire measurements near walls differs from those suggested on the basis of experimentally obtained deviations from the postulated linear velocity profile in turbulent sublayer flows, as obtained by Oka & Kostic (1972), Hebbar (1980) and others. These corrections were only obtained for mean-velocity-profile measurements and already contain the effects of turbulence. The correction can therefore only be applied to mean-velocity records and not to instantaneous values. If probability-density measurements are attempted near walls, the corrections have to be applied to instantaneous values and the procedure suggested above has to be used. Differences between both procedures occur only close to the wall, e.g. for Y^+ values smaller than 3. This can be seen readily from figure 14.

5. Experimental investigations

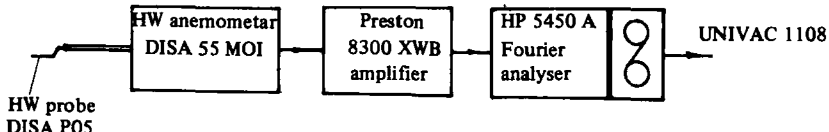
5.1. *Experimental equipment*

The present theoretical study was carried out as a basis for hot-wire anemometer investigations of flow structures in wall boundary layers. The theoretical results suggest the application of wall corrections for measurements close to metal walls, whereas no corrections are suggested in the vicinity of non-conducting walls. In order to verify these results, two sets of experiments were carried out employing the experimental equipment described below.

The measurements were performed in the large wind tunnel of the Institut für Hydromechanik of the Universität Karlsruhe. This tunnel is shown schematically in figure 6 together with a block diagram of the employed hot-wire equipment. This figure indicates the major parts of the closed-loop low-speed low-turbulence-level wind tunnel, designed with an octagonal test section of 2 m^2 cross-sectional area and a length of 8 m. The flow entered the test section from a plenum chamber through mounted wire meshes and a contraction nozzle of an area-contraction ratio of approximately 10–1. The tunnel is well designed to yield a low turbulence level at all flow speeds, approaching approximately 0·1 % at the maximum freestream speed of 45 m/s.



Wind tunnel and test section



Block diagram of hot-wire anemometer set-up

FIGURE 6. Test section and hot-wire equipment.

Figure 6 indicates that a flat plate was mounted inside the test section, along which a boundary layer developed. Plates of various materials can be inserted into the test section up to a length of approximately 6 m. In the present study, plates made of plastic material (PVC) were inserted into the wind tunnel for the non-conducting wall measurements and metal strips of copper and brass of approximately 10 cm width were flash-mounted on these plates, in the middle of the test section of the tunnel, to carry out the experiments near metal walls.

The hot-wire equipment used for measuring the streamwise velocity consisted of a constant temperature DISA-55MOI anemometer unit operated with DISA-55PO5 boundary-layer probes. The nominal overheat ratio of the hot wire was 1·8 for the main part of the measurements, and the wires were calibrated for this value in the range of 0·5–20 m/s using the modified DISA 55D90 calibration equipment described by Bruun & Tropea (1979). However, a Baratron 3 mmHg pressure transducer was used in the equipment employed in the present study.

To determine the absolute distance of the hot wire from the wall, the anemometer output voltage was measured and calibrated against distance. This calibration was performed in still air outside the wind tunnel by approaching a plate made of the same material as the test-section plates of the tunnel. A typical calibration curve is presented in figure 7 showing output voltage against distance from the plate. The latter was read by an optical microscope of 2 μm accuracy.

For data acquisition the signal from the anemometer was first passed through a Preston 8300 XWB amplifier, which also filtered the signal at a cut-off frequency of 10 kHz. The output of the amplifier was fed to a Hewlett–Packard 5450A Fourier Analyser operating at a sampling frequency of 10 kHz and storing the recorded

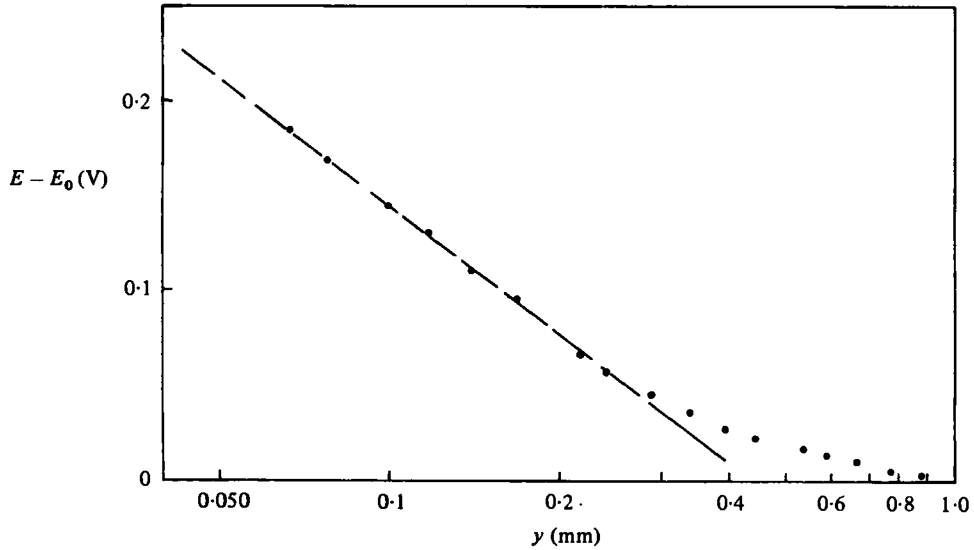


FIGURE 7. Calibration curve for determining the distance of the hot wire from the wall.

signals on digital magnetic tape. Records of 40 s length were taken for every measuring point giving sufficient readings for the statistical analysis of the data not only to yield correct mean velocity measurements and r.m.s. values of the turbulent fluctuations but also to permit the evaluation of probability-density measurements. As figure 6 indicates, no linearizer was employed, and the transformation of the hot-wire anemometer data into velocity was performed inside the computer using stored information for the hot-wire calibration.

For data evaluation, a computer program for statistical analysis of hot-wire anemometer signals was developed that performs computations of the major quantities of interest in the amplitude and frequency domain. The details of the computer program are reported by Andreopoulos, Durst & Jovanovic (1981). All experimental data, stored on magnetic tape, were evaluated on the UNIVAC 1108 digital computer of the University of Karlsruhe.

5.2. *Experimental results*

5.2.1. *Non-conducting wall.* Measurements were first carried out for the plate of non-conductive wall material and for two wind velocities 6·22 m/s and 10·76 m/s approximately 4·5 m from the leading edge of the flat plate. Various integral parameters of the boundary layers at these velocities were measured by Pitot tube and are given in table 2.

For these boundary layers, average velocity profiles and turbulence-intensity distributions across the whole boundary were measured by hot-wire anemometers and are presented in normalized coordinates in figures 8 and 9, indicating that the boundary layer has common well-established properties.

The profiles of average velocity in close proximity to the wall are given in figure 10. These data do not show a deviation from the linear velocity profile down to $Y^+ \approx 2{\cdot}5$. Closer to the wall, higher velocities are detected, probably because of distortions of the velocity profile by the wire (see Piercy *et al.* 1957) and due to prong interference. Because of the thickness of the hot-wire prongs ($d = 300\,\mu$m at the tip), smaller

U_e (m/s)	U_τ (m/s)	θ (mm)	R_θ
6·22	0·250	8·66	3620
10·76	0·410	7·65	5540

TABLE 2

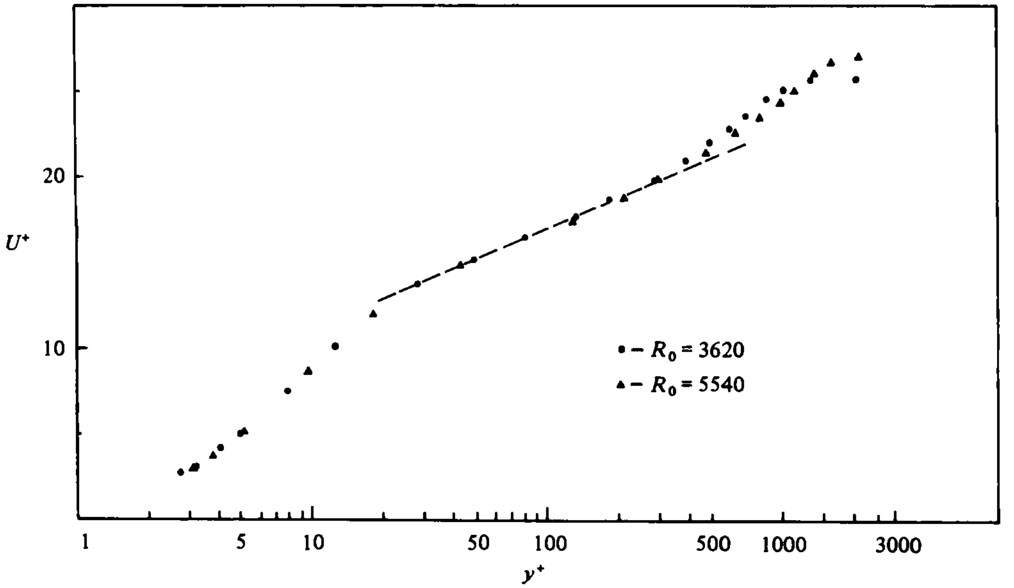


FIGURE 8. Normalized mean-velocity profiles across boundary layers.

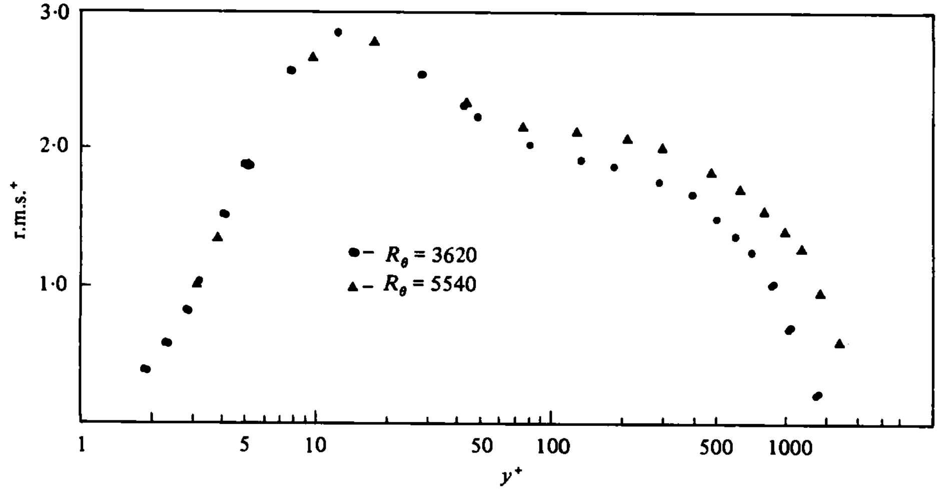


FIGURE 9. Normalized r.m.s. values across boundary layers.

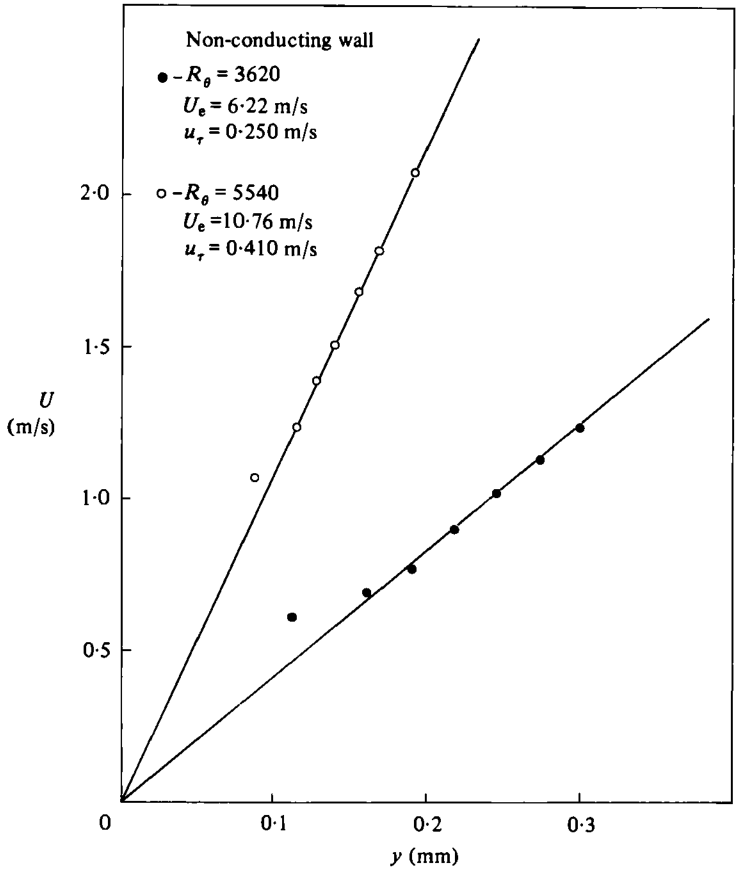


FIGURE 10. Hot-wire anemometer measurements of mean velocity near a wall of non-conducting material.

distances to the wall could not be reached even by inclining the probe holder. According to Polyakov *et al.* (1978), the small angle of 3° chosen in these experiments has a negligible effect on hot-wire readings in regions with high velocity gradients. Nevertheless, keeping in mind that at $Y^+ = 3$ the excess velocity for metal walls is already $\Delta U/U_\tau = 0{\cdot}62$, the present agreement between expected and measured results can be taken as an experimental proof that the presence of non-conducting walls does not require any wall corrections to hot-wire anemometer data.

Using the aforementioned information, Durst and Jovanovic are presently utilizing the experimental test section and hot-wire equipment described above to study turbulent boundary-layer flows. Examples of probability-density measurements in the near-wall region are presented in figure 11 in the range up to $Y^+ \approx 6$ where wall corrections would be required close to metal walls. The present data are in excellent agreement with measurements obtained by Eckelmann (1970), who carried out his study in oil flows. Wall corrections are less severe if liquids are taken as test fluids owing to the smaller overheat ratio applied to the hot film.

5.2.2. *Conducting wall.* Conductive-wall measurements were performed approximately 3 m from the leading edge of the flat-plate where a 10 cm wide metal strip was flash-mounted onto the PVC plate. The data for this set of experiments were taken

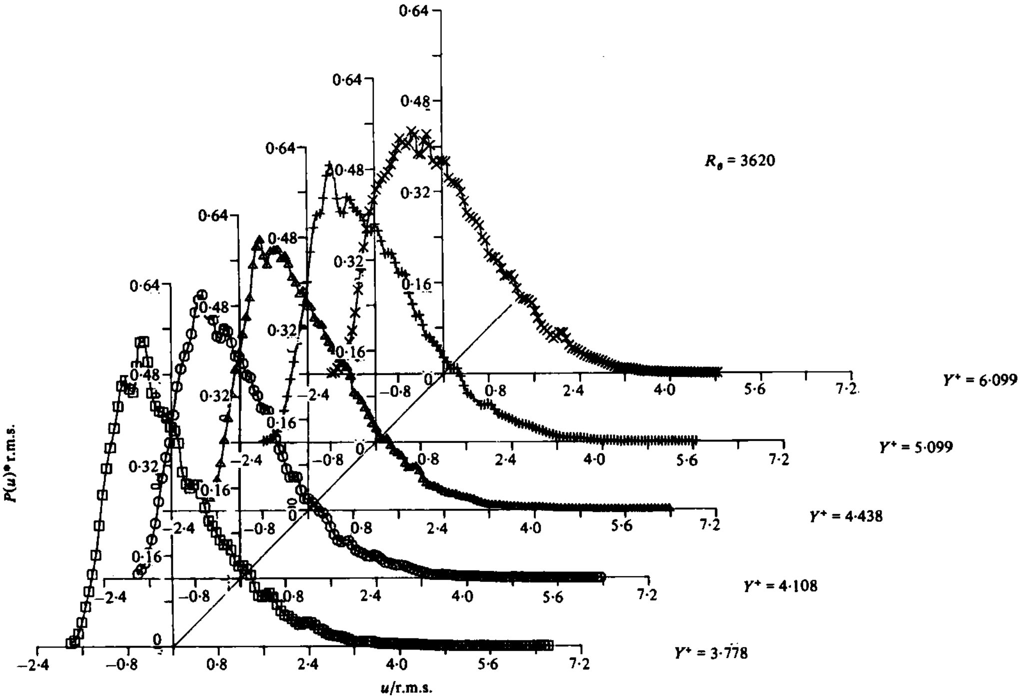


FIGURE 11. Probability-density distributions in viscous sublayer.

with nearly the same freestream velocities used for the non-conductive-wall measurements. At this measuring location, the integral parameters of the two boundary layers studied are given in table 3.

In order to apply the obtained theoretical results for instantaneous hot-wire corrections, the theoretical results in figure 5 were fitted by a suitable analytical function in order to simplify the data evaluation. Among many possibilities, the authors chose a seventh degree polynomial (10) that fitted the data with better than 1% accuracy:

$$\frac{\Delta U}{U_\tau} = \sum_{i=0}^{i=7} a_i (Y^+)^i \quad (0 < Y^+ < 5), \tag{10}$$

with $a_0 = 6{\cdot}16419$, $a_1 = -6{\cdot}47566$, $a_2 = 2{\cdot}90740$, $a_3 = -0{\cdot}42809$, $a_4 = -0{\cdot}05759$, $a_5 = 0{\cdot}01560$, $a_6 = 0{\cdot}00105$, $a_7 = -0{\cdot}00027$.

A computer program for data evaluation was written to employ the data from the correction curve in figure 5 for every instantaneous value, as described in § 4. The correction procedure described there was applied to every value of the recorded velocity data. The first iteration starts with the uncorrected velocity value, which is used to compute U_τ and Y^+ assuming an instantaneous linear velocity profile across the sublayer and correcting the data employing the polynomial (10). Subsequent iterations utilize previously corrected data until the procedure is terminated by an accuracy condition. Typically between 2 and 5 iterations are required to obtain a convergence to 1 %.

Uncorrected and corrected velocity profiles in the proximity of metal walls are presented in figures 12(*a*, *b*). For both Reynolds numbers, the correction procedure provided improvement of the data except for points very close to the wall. Reasons

U_e (m/s)	U_τ (m/s)	θ (mm)	R_θ
6·14	0·25	6·54	2660
10·81	0·42	6·26	4480

TABLE 3

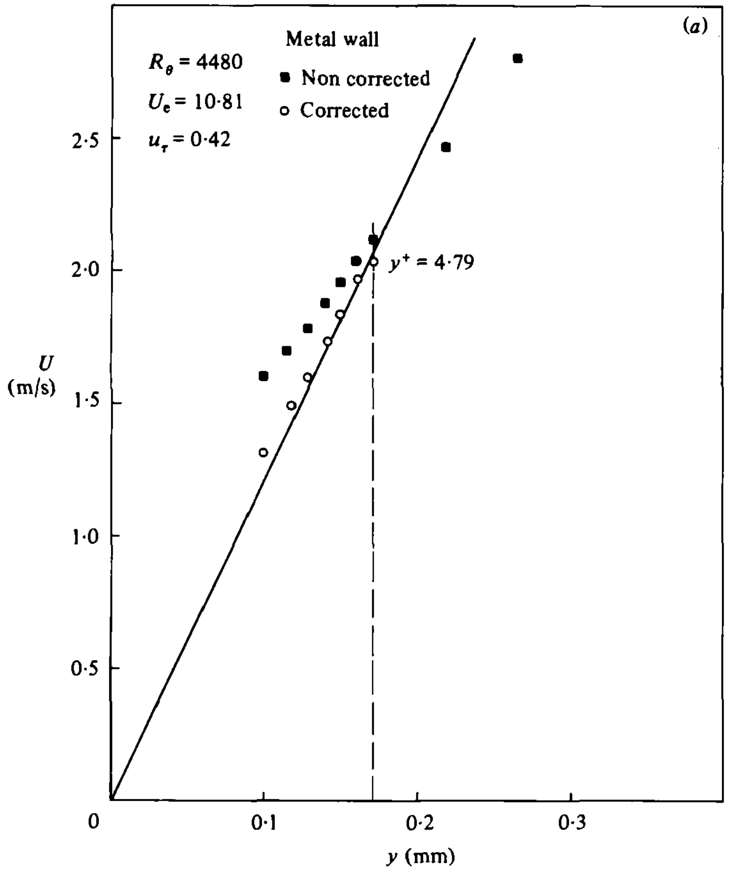


FIGURE 12(a). For caption see facing page.

for this can be sought in the experimental distortion of the linear velocity profile due to the presence of the wire near the wall, which was not considered in the computations in § 3. Leaving the last points out, the computed skin-fraction coefficient from corrected data agreed very well with Preston-tube measurements and the Blasius formula for zero-pressure-gradient boundary layers.

With the conductive wall material, some additional sets of measurements were performed in order to check the influence of the overheat ratio on the proposed instantaneous hot-wire correction. The data were recorded at each measuring position from the wall for different overheat ratios and then corrected with the appropriate correction curves. No significant influence of this parameter was found, and this suggests the present approach to be generally applicable for corrections of near-wall hot-wire anemometer measurements.

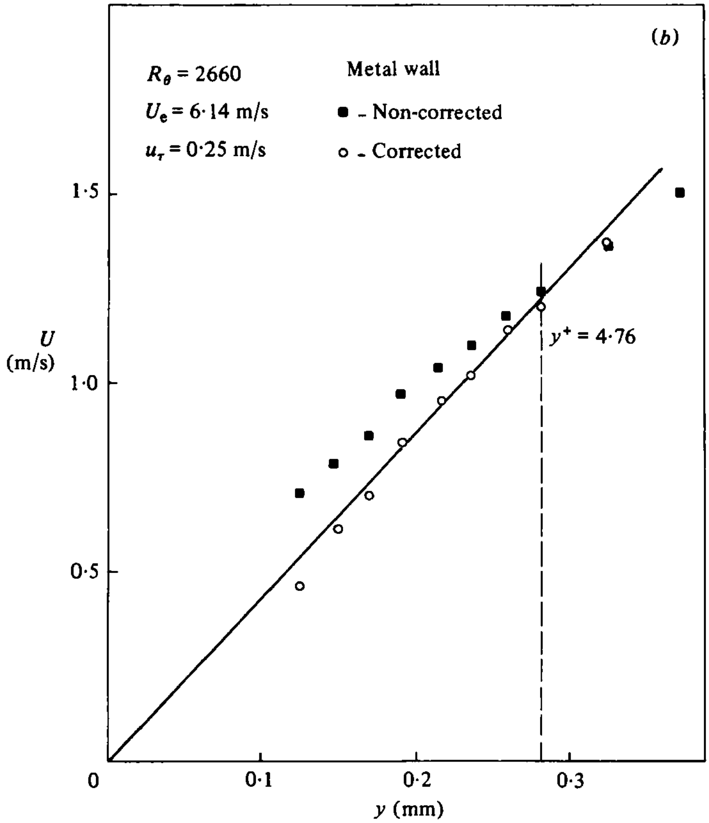


FIGURE 12. Hot-wire anemometer measurements of mean velocity near a wall of conducting material.

6. Conclusions and final remarks

A correction procedure for hot-wire anemometer measurements close to walls has been derived on the basis of a two-dimensional numerical study of the heat loss from a line source located close to a wall. The line source was positioned in a laminar flow field with a linear gradient perpendicular to the wall. To the authors' knowledge, this study is the first attempt to obtain theoretically a quantitative correction of the wall influence on hot-wires that takes into account the velocity profile close to the wall and also the effects the wall material has on the heat loss. The outcome of the numerical study can be summarized as follows.

1. The numerical results indicate that the physical cause of the additional heat loss from a hot-wire is the distortion of the temperature wake by a wall of high-conductivity material. For walls of high heat conductivity, this distortion causes an additional heat flux through the distorted wake. This additional heat flux is negligible for wall materials of low heat conductivity.

2. In agreement with the experimental findings of Polyakov & Shindin (1978) the numerical study indicates that the wall material has a large influence on the heat loss from the hot wire. This was also confirmed by verification experiments carried out by the authors. These experiments also confirmed that no corrections are necessary if the wall material is chosen to have a low heat conductivity (to obtain this result, it is

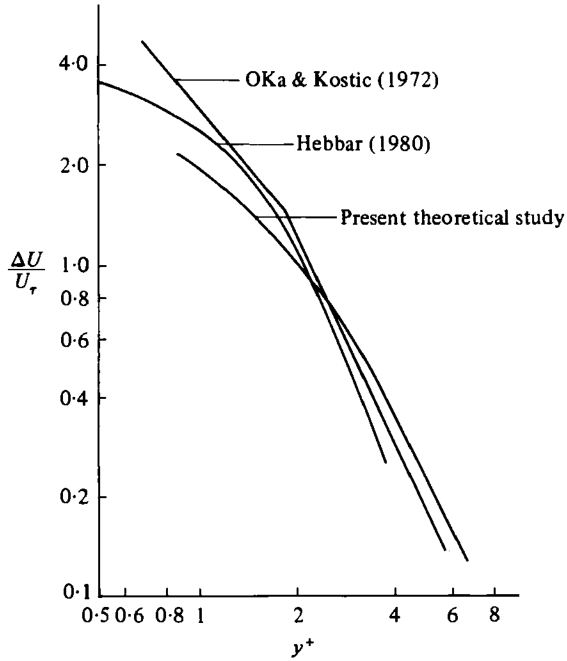


FIGURE 13. Comparison of computed corrections with experimental findings of Oka & Kostic (1972) and Hebbar (1980).

essential that plated boundary-layer probes be used and that the wall distance should not be varied by probe inclination).

3. The authors' numerical study confirmed experimental findings that suggest that the wall correction of hot-wire measurements results in a universal correction relationship $(\Delta U/U_\tau) = f(Y^+)$.

4. Although computations of wall corrections were carried out for laminar flows, the fast frequency response of constant-temperature hot-wire anemometers suggests their applicability also to turbulent flows. A procedure has been suggested that applies the computed wall correction to every instantaneous velocity component. This procedure can be applied on-line if digital signal-processing equipment is available.

5. Turbulence fluctuations and/or distortions of the velocity field by the wire have to be taken into account when applying the suggested corrections to mean-velocity measurements at distances $Y^+ \lesssim 2$. The computations show that, in this near-wall region, the correction applies to the instantaneous velocity record and is always smaller than the correction for the local mean velocity (see figure 13).

6. Experimentally obtained wall corrections already contain the effects of turbulence. They are only applicable to correct the mean-velocity field close to walls but are not applicable to instantaneous-velocity records.

The application of the computed results to turbulent flows also presumes that the scale of turbulence is such that the laminar velocity profile in the immediate vicinity of the wire is a good approximation. This is an assumption that is not only necessary for the proposed correction procedure but also for hot-wire anemometry measurements in general.

The present study is part of a collaborative program between the Sonderforschungsbereich 80 of the University of Karlsruhe and the Boris Kidrich Institute of Nuclear Sciences in Belgrade. The work has been carried out at the University of Karlsruhe and has been supported by the Deutsche Forschungsgemeinschaft and the Bundesministerium für Forschung & Technologie through the Internationales Büro in Jülich, BRD. An Alexander von Humboldt scholarship given to the third author is thankfully acknowledged.

The authors are grateful to the personnel of the Institute for Hydromechanics and the Sonderforschungsbereich 80 for all the support given to complete the work and the manuscript.

REFERENCES

ANDREOPOULOS, J., DURST, F. & JOVANOVIC, J. 1981 Computer program for statistical analysis of hot-wire signals. *University of Karlsruhe, SFB 80 Rep.* (in preparation).

ALCARAZ, E. & MATHIEU, J. 1975 Mesure des vitesses moyennes près d'une paroi par anémométrie à fil chaud. *C.R. Acad. Sci. Paris, Ser.* A, **280**, 737–740.

BRUUN, H. H. & TROPEA, C. 1979 The SFB 80 nozzle calibration facility. *University of Karlsruhe, SFB 80 Rep.* SFB 80/M/141.

CHAUVE, M. P. 1980 Determination des contraintes de frottement à là paroi par anémométrie à fil chaud. Communication presented at EUROMECH 132 Lyon, 2–4 July 1980.

CLARK, J. A. 1968 A study of incompressible turbulent boundary layers in channel flow. *Trans. A.S.M.E.* D, *J. Basic Engng* **90**, 455–468.

COMTE-BELLOT, G. 1965 Ecoulement turbulent entre deux parois parallèles. *Pub. Sci. et Tech.* no. 419, *Paris.*

ECKELMANN, H. 1970 An experimental investigation of a turbulent channel flow with a thick viscous sublayer. *Mitteilungen Max-Planck-Institut, Göttingen* nr. 48.

GUPTA, A. K. & KAPLAN, R. E. 1972 Statistical characteristics of Reynolds stress in turbulent boundary layer. *Phys. Fluids* **15**, 981–985.

HEBBAR, K. S. 1980 Wall proximity corrections for hot-wire readings in turbulent flows. *DISA Information*, no. 25, pp. 15–16.

LAUWERIER, H. A. 1954 Diffusion from a source in a skew velocity field. *Appl. Sci. Res.* A **4**, 153–156.

OKA, S. & KOSTIC, Z. 1972 Influence of wall proximity on hot-wire velocity measurements. *DISA Information* no. 13, pp. 29–33.

PIERCY, N. A. N., RICHARDSON, E. G. & WINNY, H. F. 1956 On the convection of heat from a wire moving through air close to a cooling surface. *Proc. Phys. Soc.* B **69**, 731–742.

POLYAKOV, A. F. & SHINDIN, S. A. 1978 Peculiarities of hot-wire measurements of mean velocity and temperature in the wall vicinity. *Lett. Heat Mass Transfer* **5**, 53–58.

REICHARDT, H. 1940 Die Wärmeübertragung in turbulenten Reibungsschichten. *Z. angew. Math. Mech.* **20**, 297–328.

SINGH, U. K. & SHAW, R. 1972 Hot-wire anemometer measurements in turbulent flow close to a wall. In *Proc. DISA Conf.*

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, pp. 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.

ZARIČ, Z. 1972 Wall turbulence studies. *Adv. Heat Transfer* **8**, 285–350.