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WALL PROXIMITY CORRECTIONS FOR HOT-WIRE READINGS

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SUMMARY Recent literature on correcting hot wire readings for wall proximity effects is reviewed. Hot-wire measurements in laminar and turbulent flow regions on axial compressor blades are described, and available wall proximity correction methods are assessed in the light of this experience. It is concluded that further investigations are required to resolve remaining doubts about the influence of wire diameter on the additional heat loss near a wall.

1 INTRODUCTION

The proximity of a solid boundary to a hot-wire probe alters the temperature and velocity fields so as to increase the rate of cooling. Uncertainties in correcting for wall proximity effects mean that the high spatial discrimination of a hot wire sensor cannot be used to full advantage in this situation. The increase in apparent velocity due to wall cooling also carries the risk of damaging the probe by inadvertent contact with the solid boundary, in cases where the wall position is not determined independently.

The possible magnitude of wall proximity effects can be judged from Fig. 1, which shows some typical measurements in a laminar boundary layer with total thickness $\delta \simeq 0.8$mm and free stream velocity $U \simeq 17\ \mathrm{ms}^{-1}$. At $y/\delta = 0.6$, the error in velocity from neglecting wall proximity effects is about 0.1 U (or about 100% of the local velocity u), which leads to an error of about 100% in the wall shear stress τ_w. The uncorrected velocity profile gives values of boundary layer displacement thickness and momentum thickness which are too low by 8% and too high by 5%, respectively. The apparent wall position obtained by extrapolating the uncorrected profile is at $y \simeq -0.1$.

Section 2 of this paper reviews published methods for applying wall proximity corrections to hot-wire readings. Section 3 outlines some previous hot-wire measurements by the author in laminar and turbulent boundary layers on axial compressor blading; the application of wall proximity corrections in this situation is then reviewed in the light of more recent publications. Finally, some comments are made about the validity of currently available correction methods and the need for further work on this subject.

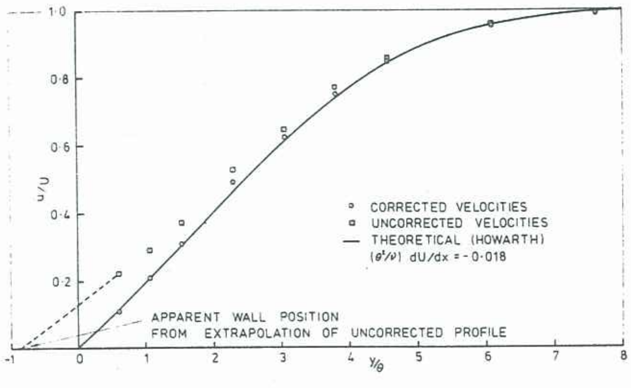

Figure 1 Wall Proximity Effects in Laminar Flow Over a Compressor Blade - Walker (1971). ($U \simeq 16.7\ \mathrm{ms}^{-1}$, $\theta = 0.0945$ mm)

2 PUBLISHED CORRECTION METHODS

2.1 Introduction

Factors previously observed to influence wall proximity corrections to hot-wire readings include:

(a) the probe geometry and distance of the sensor from the solid boundary;
(b) the fluid properties and thermal conductivity of the wall;
(c) the distribution of mean and fluctuating velocity components in the wall layer.

Only a brief outline of published correction methods will be given here. A more detailed summary can be found in Vagt (1979).

2.2 Van der Hegge Zijnen (1924) and Dryden (1936).

These workers assumed wall proximity effects to depend only on thermal conduction. The additional cooling effect measured in still air was used to correct experimental velocity measurements. This correction depends only on the distance from the wall, y, and not on the local velocity, u.

The unsatisfactory aspect of this approach is that the heat transfer from a hot-wire sensor most commonly occurs by forced convection. In still air conditions and at very low Reynolds numbers heat transfer by natural convection predominates. The range of conditions for which buoyancy effects are significant has been discussed by Collis and Williams (1959).

2.3 Wills (1962)

This method has been widely cited, and was used by the present author to correct the hot-wire measurements which will be described in Section 3.

From observations in incompressible laminar flow over a metal plate using a 4μm diameter wire about 700 d long, where d is the wire diameter, Wills found that the rate of heat loss could be expressed as

$$Nu(T_w/T_a)^{-0.17} = A + B\,Re_w^{\,0.45} \qquad (1)$$

provided that buoyancy effects were negligible. Here the Nusselt number Nu and wire Reynolds number Re_w are based on wire diameter, with fluid properties evaluated at temperature T_m which is the mean of the wire temperature T_w and ambient temperature T_a. The parameter A in Eqn. (1) depended only on y/d; as shown in Table 1, the additional cooling effect of the wall was significant to about y = 50d. At large values of y Eqn. (1) approximates the heat transfer relation for infinite wires suggested by Collis and Williams (1959).

According to these observations, the effect of the wall is to cause an increase in dimensionless heat loss parameter Nu $(T_m/T_a)^{-0.17}$ which is independent of Reynolds number. Thus Wills suggested that measurements in laminar flow could be corrected for wall proximity by subtracting a constant (dependent on y/d) from the apparent value of $Re_w^{0.45}$ regardless of the value of Re_w, in the forced convection range.

TABLE I

WALL PROXIMITY EFFECTS IN LAMINAR FLOW- AFTER WILLS (1962)

y/d	$\Delta Nu(T_m/T_a)^{-0.17}$
5	0.228
10	0.122
25	0.041
50	0.010

Wills also investigated the wall proximity correction required when the flow near the wall was turbulent, and found this to differ markedly from the laminar flow correction. From meaurements of turbulent flow in a two-dimensional channel of constant width, Wills suggested that the extra heat loss to the wall in this case should be of the same sign as that occurring in laminar flow, but smaller in magnitude by a factor of 0.5 ± 0.1. He was unable to explain why this factor was less than unity, except to suggest that the turbulent motion would convect heat away from the wall on average to a greater extent than the laminar motion, and might thereby reduce the total heat loss to the wall. Wills only expected the turbulent flow correction to apply in the viscous sublayer, where the laminar and turbulent velocity profiles are generally similar.

2.4 Repik and Ponomareva (1970)

These workers reported the influence of wall proximity to depend only on distance from the wall and not on wire diameter. The additional heat loss in turbulent flow was found to vary between 1.0 and 0.5 times that in laminar flow, and to depend on both y and $Re_y = u\,y/\nu$.

Very little experimental detail was published, making it impossible to determine the mode of heat transfer from the wire, the dimensionless heat transfer relation close to the wall, or the values of dimensionless position $y^+ = yu^*/\nu$, where $u^* = (\tau_w/\rho)^{\frac{1}{2}}$ is the wall friction velocity. Although the conclusions conflict with those of Wills, a direct comparison is not possible.

An interesting feature of this paper is a comment that the probe support geometry significantly influenced the measurements in the wall region.

2.5 Oka and Kostic (1972)

Oka and Kostic reported measurements in a turbulent boundary layer made with a 5 μm diameter sensor 1 mm long. Their uncorrected measurements collapsed onto a single curve of $u^+ = u/u^*$ against y^+, with the influence of the wall becoming negligible at about $y^+ = 6$. The difference between the apparent and true velocity was expressed as

$$\Delta y^+ = \Delta u/u^* = f(y^+) \qquad (2)$$

Once again, the limited experimental data does not permit a comparison with Wills' results.

2.6 Alcaraz and Mathieu (1975)

Alcaraz and Mathieu investigated the influence of wall proximity in turbulent pipe flow and a turbulent wall jet, using wires of 2, 3 and 4 μm diameter from 0.5 to 0.8 mm long. After making allowance for calibration non-linearity, which was found to be significant, the method of Wills was used to correct the hot wire readings. The weighting of 0.5 times the laminar flow correction suggested by Wills was found to be insufficient, and a factor of 1.0 to 1.2 was recommended as being more appropriate.

These workers found that wall conductivity influenced the heat loss from the wire up to y/d = 15.

2.7 Zemskaya et al. (1979)

Zemskaya et al. noted the lack of systematic variation of important physical parameters in previous observations of wall proximity effects. They carried out a more comprehensive series of experiments in both laminar and turbulent boundary layers using a range of sensor diameters and free-stream velocities.

Their results could not be collapsed onto a single curve of $\Delta u/u^+ = f(y)^+$ as suggested by Oka and Kostic (1972). The results were finally correlated using

$$\Delta\tilde{u}^{+} = f(\tilde{y}^{+}) \qquad (3)$$

where $$\Delta u^{+} = (\Delta u/u^{*})(d^{*}/d)^{0.15} \qquad (4)$$

and $$\tilde{y}^{+} = y^{+}\,(d^{*}/d)^{0.15} \qquad (5)$$

with d^* a reference value of wire diameter. Equation (3) is approximated by

$$\Delta\tilde{u} = C(\tilde{y}^{+})^{m} \qquad (6)$$

with $m \simeq -1$ for $\tilde{y}^{+} < 2$ and $m \simeq -2$ for $\tilde{y}^{+} > 2$. The breakpoint approximates that observed by Oka and Kostic. The observed relation implies $\Delta u^+ \propto d^{0.3}$ for $y^+ < 2$ and $\Delta u^+ \propto d^{0.45}$ for $y^+ > 2$. The influence of wire diameter on the wall proximity corrections is therefore significantly weaker than suggested by the data of Wills (1962), which indicates a dependence on $d^{0.5}$, approximately, for y/d small.

Zemskaya et al. also plotted dimensionless heat loss data in the form $\Delta Nu \sim Re_w$. They found ΔNu to decrease with increasing Re_w, rather than to remain constant as suggested by Wills. However, there is no indication of the boundary layer state for which these measurements were obtained, and the observed reductions in ΔNu could quite possibly be due to the effects of turbulence.

3 COMPRESSOR BLADE BOUNDARY LAYER MEASUREMENTS

3.1 Experimental Detail

The author (1971) reported an extensive series of hot wire measurements in laminar and turbulent boundary layer regions on the aluminium stator blades of an axial compressor. Details of this machine have been given by Oliver (1961). Observations were made in a wide range of pressure gradients over a 5:1 speed range.

The hot wire probes consisted of 8μm diameter tungsten wire spot-welded to 0.5mm diameter supporting prongs which had been sharpened at the tips. The sensing wires were typically 5mm long, giving a length/diameter ratio of about 600; the supporting prongs were at a slight angle to the blade surface. The probe head was fitted into a cylindrical sleeve and a screw adjustment against a retaining spring was used to align the wire parallel to the blade surface. The alignment was carried out by viewing tangent to the blade with the wire a few diameters from the surface; an accuracy of better than one wire diameter over the wire length is thought to have been achieved by this means.

Movement of the probe relative to the blade surface was achieved by rotating the whole stator row. Displacement of the stator supporting ring was measured with a dial gauge graduated to 0.0025mm. The position reading corresponding to the wire touching the blade surface was determined by an electrical contact method. Due allowance was made for the deflection of the stator blade under aerodynamic forces;these movements were measured separately to an accuracy of 0.0025mm, and the maximum observed displacement was about 0.05mm.

The probes were operated at constant currents from 40 to 65 mA over a velocity range of 0 to 50 ms^{-1}. Probe resistance could be determined to 0.001Ω under optimum conditions, but reading accuracy was significantly lower in unsteady flow situations. Probe calibrations were smoothed by fitting the curve

$$Nu(T_m/T_a)^{-0.17} = A + B\,Re_w^{0.45} + C\,(Re_w^{0.45})^2 \qquad (7)$$

This is a modified form of the heat transfer relation suggested by Collis and Williams (1959), who use A = 0.24, B = 0.56, C = 0 for wires of infinite length. Addition of the quadratic term makes a desirable allowance for variable end-conduction losses in wires of finite length; end conduction losses for the probes used typically amounted to 20% of the total heat loss. Continuous monitoring of pressure and temperature and the use of Eqn. (7) in reducing velocity measurements automatically allowed for effects of changing atmospheric conditions on the probe calibration.

Hot wire probes were operated for some 20 hours of running in the compressor between calibrations, and calibration drifts of 5 to 10% over this period were typically obtained. This drift was measured by checking suitable reference velocities at regular intervals and a corresponding correction was applied. The hot wire calibrations could be repeated to 1% of velocity, and Eqn. (7) was found to fit the calibration data to rather better than this accuracy, in general. However, the overall accuracy of absolute velocity measurements is considered to be around 3% due to additional uncertainties in correcting for calibration drift. Further errors of unknown magnitude may have arisen from flow unsteadiness associated with the passage of rotor blade wakes. Free stream velocity values obtained from the hot wire were typically 5% lower than the corresponding values obtained from surface pressure tappings.

3.2 Wall Proximity Correction in Laminar Flow

Measurements in laminar flow regions were corrected for the effects of wall proximity by subtracting the additional heat loss given in Table 1 from the observed value of $Nu(T_m/T_a)^{-0.17}$. This procedure is not exactly the same as Wills' suggested method of correcting the observed value of $Re_w^{0.45}$. The different approach is necessitated by the non-linearity of the probe calibration, Eqn. (7), for sensors of finite length.

This technique was very successful, and as indicated by Fig. 1 the non-dimensional velocity profiles consistently agreed with the corresponding theoretical solutions to within ± 0.01 in u/U. In all cases they were smooth curves passing quite close to zero velocity on extrapolation to the measured wall position y = 0.

As shown in Fig. 2, the maximum wire Reynolds number in these tests varied from $Re_w \simeq 4$ at $y/r_w = 10$ to $Re_w \simeq 16$ for $y/r_w = 100$, where r_w is the wire radius. Evidently, the laminar flow correction is more widely valid than indicated by Wills' investigation, which only ranged up to $Re_w \simeq 0.2$ at $y/r_w = 10$ and $Re_w \simeq 1$ at $y/r_w = 100$.

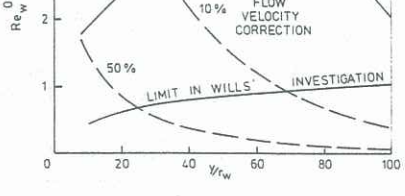

Figure 2 Range of Wall Proximity Effects for Compressor Blade Measurements - Walker (1971)

3.3 Wall Proximity Correction in Turbulent Flow

Following Wills' suggestion, all hot wire readings in the turbulent boundary layer regions were initially corrected by assuming the additional heat loss to the wall to be half of that occurring in laminar flow. However, the corrected velocity profiles did not appear physically reasonable with regard to the variation of mean vorticity $\zeta = \partial u/\partial y$ through the viscous sublayer. The theoretical variation obtained by dropping all the inertia and Reynolds stress terms in the two-dimensional boundary layer momentum equation is given by

$$\partial\tau/\partial y = \mu(\partial^2 u/\partial y^2) = \mu(\partial\zeta/\partial y) = dp/dx \qquad (8)$$

$$\text{or} \quad \partial(\zeta\theta/U)/\partial(y/\theta) = -(\theta^2/\nu)(dU/dx) \qquad (9)$$

where θ is the boundary layer momentum thickness. This indicates that in a positive pressure gradient ζ should increase monotonically with y through the inner part of the viscous sublayer. In the outer part of the sublayer, where the turbulent shear stress increases very rapidly, ζ should decrease monotonically with y. The foregoing considerations require that ζ reaches a maximum somewhere within the viscosity-dependent region of the wall layer; the theoretical model of McDonald (1969) predicts this maximum close to $y^+ = 4$ for pressure gradients similar to those obtained on the stator suction surface.

Fig. 3 shows some typical measurements of vorticity variation through the viscous sublayer in turbulent flow regions on the compressor blade. Using one half of the laminar flow wall proximity correction as suggested by Wills is seen to result in the vorticity decreasing monotonically through the wall layer; ζ has no maximum away from the wall, and $\partial\zeta/\partial y$ is of the wrong sign at the wall. Using the full laminar flow correction, however, gives vorticity profiles which have the expected positive slope at the wall and reach a maximum quite close to $y^+ = 4$ before decreasing monotonically at greater values of y. The values of $(\partial\zeta/\partial y)_{y=0}$ are smaller than those predicted from Eqn.(9) by a factor of 2 or 3; this could either be due to the neglected inertia and Reynolds stress terms, or to remaining inaccuracies in the applied wall proximity correction. Measurements by other workers in the fully turbulent regions of wall layers subjected to strong positive pressure gradients typically give values of total stress gradient $\partial\tau/\partial y$ around 50 to 70% of the streamwise pressure gradient dp/dx.

Because of the more satisfactory results obtained, the full laminar flow wall proximity correction was applied to all of the hot wire readings from turbulent flow regions on the compressor blade. Some doubts remained, however, as to the required magnitude of wall correct-

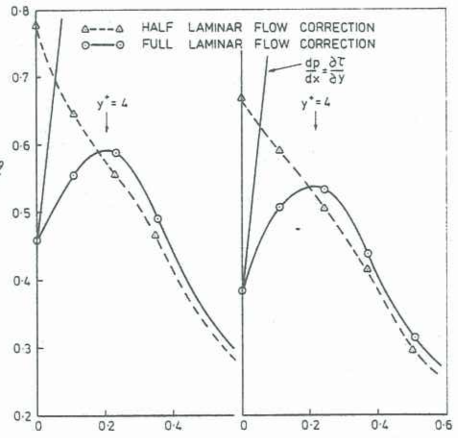

Figure 3 Wall Proximity Effects in Turbulent Flow Over a Compressor Blade - Walker (1971). (Left: $U = 18.9\ ms^{-1}$, $\theta = 0.668$ mm, Right: $U = 20.8\ ms^{-1}$, $\theta = 0.630$ mm)

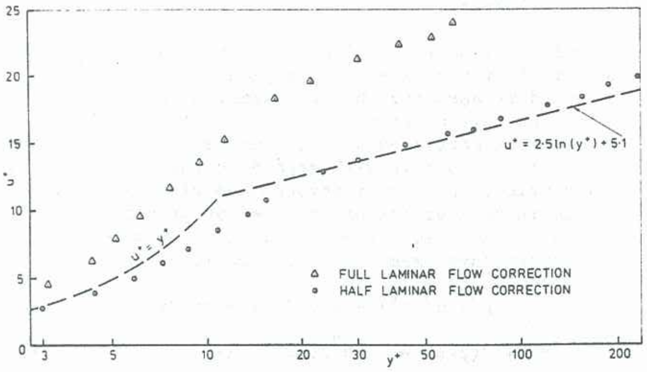

Figure 4 - Wall Proximity Effects in Turbulent Flow Over a Plate - Walker (1971). ($U = 20\ \mathrm{ms}^{-1}$, $U\theta/\nu = 1590$, u_* evaluated from corrected velocity profiles).

ions in the general case. An attempt to resolve these problems was made by measuring the turbulent boundary layer on a metal plate in conditions of low pressure gradient, using the same experimental techniques as applied in the compressor. In this case excellent agreement with the conventional law of the wall was obtained by applying one half of Wills' laminar flow wall correction, as shown in Fig. 4. The author (1971) therefore concluded that in positive pressure gradients the extra heat loss from a hot wire near a solid boundary in turbulent flow should vary between 0.5 and 1.0 times the corresponding loss in laminar flow, depending on the magnitude of the streamwise pressure gradient. Such a variation would be consistent with Wills' suggestion that the mean heat transfer path from the wire in turbulent flow is altered by the fluctuating component of velocity normal to the wall, v'. Since the values of v' near the wall are much lower in an adverse pressure gradient (see Spangenberg et al.) (1967) it would be reasonable to expect a smaller amount of heat to be convected away from the wall on the average in this case; this would presumably result in a smaller difference between the laminar and turbulent flow wall proximity corrections.

4 DISCUSSION

4.1 General Remarks

The literature on hot-wire wall proximity correction methods is superficially very contradictory, but many of the apparent problems arise from different methods of presenting the results. The dependence on wire diameter, for example, is necessarily different in the velocity and heat loss corrections. Further difficulties may arise from a lack of published experimental detail or a limited range of investigation. This often prevents an adequate comparison of different methods and in some cases has produced erroneous conclusions.

4.2 Laminar Flow Corrections

There is broad agreement on the corrections to be applied in laminar flow, except for the influence of wire diameter. The compressor blade observations described in Section 3 and the work of Alcaraz and Mathieu (1975) strongly support the hypothesis of Wills (1962) that the additional heat loss due to wall cooling should vary with the wire diameter ($\propto d^{-1}$), approximately). It is difficult to visualise how agreement between these three investigations, which used sensors of several different diameters, could have been achieved if the postulated dependence on wire diameter was substantially incorrect.

Wills' results were based on a single wire diameter, however, and the more comprehensive tests of Zemskaya et al. (1979) with a range of sensor diameters showed a somewhat different dependence on this variable. Further extensive investigations are needed to resolve this problem, and these should preferably be conducted with systematic variations in wire temperature.

4.3 Turbulent Flow Corrections

The recent literature on wall proximity corrections in turbulent flow over a smooth wall indicates a strong influence of dimensionless position y^+ on the additional wall cooling effect. Up to $y^+ = 2$, the laminar flow correction seems appropriate; for $y^+ > 2$ the required correction falls below the laminar flow value. This is physically reasonable, as increasing turbulent fluctuations in the latter region might convect heat away from the wall to a greater extent and reduce the wall's influence on the heat loss.

Having considered this data, the author now recommends that measurements in the viscous sublayer ($y^+ < 2$) be corrected using the full laminar flow correction regardless of pressure gradient. The author's earlier conclusion (1971) concerning the correction needed in zero pressure gradient was based on a single velocity profile measurement with the innermost data point at $y^+ \simeq 3$ (see Fig. 4); here, recent studies would indicate a correction significantly less than the laminar flow value in order to obtain the true values of u and u^+. Wills' (1962) recommendation of using half the laminar flow correction in turbulent flow was similarly based on an isolated observation with, by chance, the innermost point at about $y^+ = 3$. This provides a plausible explanation for the apparent agreement between these two observations and the disagreement with later publications by either workers.

It is encouraging to note that decreasing the wall correction for $y^+ > 2$ would significantly reduce the imbalance between the pressure gradient and measured stress gradient at the wall for the turbulent boundary layer profiles shown in Figure 4.

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