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ON THE DIRECTIONAL SENSITIVITY OF HOT-WIRE AND HOT-FILM PROBES

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ABSTRACT

When hot-sensor anemometry is used in complex turbulent flows, the relative positioning sensor-velocity vector is usually not known a priori. Therefore, the anemometer output will most likely reflect the result of lateral cooling of the sensor causing an effective value to be recorded. The effect of the deviation of the measured flow velocity from the true value is analyzed, accounting for geometric inclination of the main flow with respect to the wire. An experimental study on the overall directional behavior of a single-wire probe (l/d = 300) was performed. It was found that for angles up to 45 degrees, no correction is necessary if high accuracy is not desired. Also, the error between the true and measured velocities increases rapidly for angles higher than those for which the correction was done. In addition, this correction should be based on the maximum expected angle between the velocity vector and the wire. These results are in agreement with the literature.

INTRODUCTION

The use of hot-wire and cylindrical hot-film anemometry to measure turbulent shear stresses and turbulent intensities requires the knowledge of the directional sensitivity of the probe [1]. In complex turbulent flows, the relative positioning sensor-instantaneous velocity is not known, and the anemometer output will reflect the result of lateral cooling of the sensor, causing an effective signal to be recorded.

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The literature usually refers to the directional sensitivity problem as when the instantaneous velocity vector is not perpendicular to the sensor.

Two cases can be identified under this circumstance:

1. The velocity vector has no mean component parallel to the wire, but has sufficient large turbulent components, and

2. The velocity vector makes an angle with the wire direction and turbulent intensities are considered negligible.

The first case is used to analyze the nonlinearity of the output signal due to the extra cooling by the fluctuating components. This approach permits quantifying experimental errors when measuring large-scale turbulence. The second case is usually presented to investigate probe geometrical properties, such as length-to-diameter ratio and end-losses, causing departure from the cosine or normal component cooling law.

The present work is concerned with the latter case, or when a low turbulent intensity stream has a mean component aligned to the wire. The purpose of this paper is to report the experimental investigation on the overall directional characteristics of a single-wire probe, which was used in another set of experiments [2].

It should be pointed out that in the actual case, as might occur when measuring complex flows, the velocity has a component in the wire direction in addition to non-negligible fluctuations. This situation is difficult to handle analytically, and some details will be shown later.

LITERATURE REVIEW

Several empirical correlations have been presented by the investigators. Hinze [3] proposed the relation

$$U^2_{eff} = U^2 \left(\cos^2\beta + K^2 \cdot \sin^2\beta\right) \tag{1}$$

where

U_{eff} = effective cooling velocity correspondent to the anemometer output.

U = mean bulk flow velocity in a plane containing the wire.

β = angle between U and the normal to the wire.

K = parameter of directional sensitivity.

Equation (1) states the deviation from the cosine law due to lateral cooling effect. Schubauer and Klebanoff [4] tested the validity of the cosine law for $\beta < 70°$. Their results for the Nusselt number are presented in the form

$$Nu = A + B\left(Re \cdot \cos\beta\right)^{1/2} \tag{2}$$

where

A, B = constants

Re = Reynolds number based on the wire diameter.

Newman and Leary [5] proposed a modification in Eq. (2) as follows

$$Nu = A + BRe^{1/2}(\cos\beta)^n \quad (3)$$

with n = 0.457, whereas Sandborn and Laurence [6] found different values for the exponent 'n' using different probes. The latter work also found that the effect of length-to-diameter ratio l/d, on the rate of heat loss from wires normal to the flow could be eliminated by end-loss corrections. The authors proposed an empirical relation of the form

$$Nu = \left[A + B(Re\cos\beta)^{1/2}\right]\cos + \left[C + D(Re\sin\beta)^{1/2}\right]\sin. \quad (4)$$

Equation (4) is based on the weighted addition of the heat losses of normal and parallel wires. Kronauer [7] suggested dependence on the length-to-diameter ratio of the wire and independence of the Reynolds number, and proposed

$$U_{eff} = U\cos\beta + 1.2(d/l)^{1/2} \cdot \sin^2\beta \quad (5)$$

The shifting in the temperature profile in yawed wires is well documented by Champagne and Schleicher [1]. Also reported in that work is that K is approximately 0.2 for l/d = 200, decreases with increasing l/d and becomes effectively zero at l/d = 600. These experiments were performed in air at low subsonic velocity, and Equation (1) agreed with these results for 25° < β < 60°. Jorgensen [9] used an equation different from Equation (1), accounting also for the velocity component perpendicular to the wire. He proposed the following equation

$$U^2_{eff} = U^2_x + K^2_1 \cdot U^2_y + K^2_2 \cdot U^2_z , \quad (6)$$

where K_1 is similar to K, and K_2 has the same significance for U_z.

The factor K_2 was found to be not as important as K_1 due to the fact that K_2 only accounts for probe geometric aspects such as support interference.

According to the foregoing summary, it is evident the disagreement in the literature as to the directional sensitivity of hot-wire probes and inaccuracy of measurements made with inclined wires. Yet, all the constants in those equations depend on the l/d ratio because the non-uniform wire temperature distribution affects the directional response.

THEORETICAL BACKGROUND

The actual case when the instantaneous velocity vector U_i has a component normal to the wire and the three turbulent components u, v, and w is shown in detail in Figure 1.

The magnitude of the instantaneous velocity U_i is

$$U_i = [(U + u)^2 + v^2 + w^2]^{1/2} . \tag{7}$$

The instantaneous effective cooling velocity is given by

$$U_{eff}^2 = U_i^2 (\cos\alpha + K^2 \sin^2\alpha) \tag{8}$$

Equation (7) is equivalent to Equation (1) and describes now the instantaneous velocity U_i, rather than time averaged value U. The angle α can be expressed in terms of β (the angle between the normal to the wire and the mean flow direction) and the velocity components as follows. Applying the cosine law of trigonometry yields:

$$- \sin\alpha = - \frac{U + u}{U_i} \sin\beta + \frac{v}{U_i} \cos\beta . \tag{9}$$

Squaring Equation (9) gives

$$\sin^2\alpha = \left(\frac{U}{U_i}\right)^2 \left[\left(\frac{U + u}{U}\right)^2 \sin^2\beta + \left(\frac{v}{U}\right)^2 \cos^2\beta - 2\sin\beta \cos\beta \left(\frac{v}{U} + \frac{uv}{U^2}\right)\right] . \tag{10}$$

Thus,

$$\cos^2\alpha + K^2 \sin^2\alpha = 1 + (K^2 - 1) \left(\frac{U}{U_i}\right)^2 \left[\left(\frac{U + u}{U}\right)^2 \sin^2\beta + \left(\frac{v}{U}\right)^2 \cos^2\beta \right.$$

$$\left. - 2\sin\beta \cos\beta \left(\frac{v}{U} + \frac{uv}{U^2}\right)\right] . \tag{11}$$

Substituting Equation (11) into Equation (8) gives

$$U_{eff} = U \left\{\left(\frac{U}{U_i}\right)^2 + (K^2 - 1) \left[\left(\frac{U + u}{U}\right)^2 \sin^2\beta + \left(\frac{v}{U}\right)^2 \cos^2\beta \right.\right.$$

$$\left.\left. - 2\cos\beta \sin\beta \left(\frac{v}{U} + \frac{uv}{U^2}\right)\right]\right\}^{1/2} , \tag{12}$$

and from Equation (7)

$$\left(\frac{U_i}{U}\right)^2 = 1 + 2 \frac{u}{v} + \frac{u^2 + v^2 + w^2}{U^2} . \tag{13}$$

By means of power series expansions, Champagne et al [8] used Equation (12) to calculate the corrections on the output signal for an ideal X probe.

For a linearized constant temperature operation they presented errors on the order of 17% in turbulence measurements due to sensors slanted 45° with respect to the wires.

EXPERIMENTAL WORK

Scope and General Procedure

Since the directional sensitivity of probes is essentially dependent on the probe type used, the experiments presented here were performed as a preliminary study on the characteristics of the apparatus used to obtain the data reported in Ref. 2.

Due to the particular case of the test section used in Ref. 2, the hot-wire probe had to be positioned with the prongs perpendicular to the main flow direction. This, however, would introduce errors not only due to the slanting hot-sensor, but also due to interference of the prongs on the point of measurement. It was then mandatory to carry out a study to qualitatively determine the errors introduced by this particular probe positioning as well as correction factors to overcome them.

The present work consisted in the measurement of the effective velocity U_{eff}, for three different known velocities U and for ten different angles β in an arrangement similar to the one used in the above mentioned work. This way it was possible to analyze the directional sensitivity of the probe positioned perpendicular to the mean flow.

According to Equation (1), the factor K^2 for a known set of U_{eff}, U, and β can be calculated as

$$K^2 = \frac{1}{\sin^2\beta}\left[\left(\frac{U_{eff}}{U}\right)^2 - \cos^2\beta\right] \tag{14}$$

Equation (14) indicates that for a certain probe type, K^2 is a function of U and β. This fact poses the question what value of K^2 should be used in Equation (1) to get the corrected velocity U.

From Equation (14), for a given set of K^2, U_{eff}, and β, the velocity U can be calculated as

$$U^2_{calc.} = U^2_{eff}\left(\cos^2\beta + K^2\sin^2\beta\right)^{-1} . \tag{15}$$

To investigae the influence of β of U_{calc}, Equation (15) was computed taking into account the angular dependence of K^2. Results were compared to the known value U, defining the error $\underline{e}$, as follows:

$$e\ (\%) = \frac{U - U_{calc.}}{U} \times 100 \tag{16}$$

The error $\underline{e}$, is then a function of K, U, and β.

The instrumentation and experimental set-up used are briefly described below. The results for K^2 and $\underline{e}$ are presented in the following section.

Instrumentation

The instrumentation basically consisted of a calibrator coupled to a probe rotating device and an anemometer system.

The low turbulent intensity stream was provided by a probe calibrator model 1125TSI, giving the known velocity U. A pointer, attached to the probe body and referred to a scale, was set to measure the probe rotation angle β. A schematic is shown in Figure 2.

The anemometer system was composed basically of the 1050 TSI Hot-Wire Anemometry Series and was used to obtain U_{eff}. The main units can be shortly described as follows:

- hot-wire probe model 1210-TSI, repaired with 6 μ diameter tungsten wire.
- 1050TSI Constant Temperature Anemometer with a low noise equivalent to 0.007% of intensity of turbulence.
- 1052TSI linearizer. Using a 4th degree polynomium, the CTA output is linearized. Average precision of $\pm$ 0.2%.
- 1057TSI Signal Conditioner.
- 8000A-FLUKE digital voltmeter. Precision of $\pm$ 0.1% $\pm$ 1 digit.
- 1125TSI Probe Calibrator. Gives intensity of turbulence less than 0.1%.

RESULTS AND CONCLUSIONS

The values of K^2 for the three velocities U (30, 60, 90 m/s) and calculated according to Equation (14) are shown in Figure (3). The negative K^2 for small angle β shows U_{eff} as being lower than U (see Equation (1)). Possibly, this is due to the probe aerodynamic behavior when positioned perpendicular to a low velocity field. Nevertheless, this negative contribution is small, since the product $(K^2 \sin^2\beta)$ is taken into account. The maximum positive value of 0.2 for K^2 is in accordance with the one suggested by Jorgensen [9]. Also in accordance with Ref. 9 is that K^2 decreases with increasing β, for $20° < \beta$ 80°.

Figure 4 presents results for $\underline{e}$ when $K^2 = 0$, or say, when no correction is introduced in Equation (1). The figure shows the departure from the cosine law as β increases. Also indicated is that for angles of attack less than 45°, no correction is necessary if errors on the order of 5% are considered within experimental uncertainty.

Figures 5 to 10 present results for $\underline{e}$ using K^2 correspondent to different values of β, or using $K^2 = K^2(\beta)$. The purpose of these figures is to obtain an overall view of the probe directional characteristics. The figures indicate that the errors increase rapidly for angles higher than those for which the correction was done, or say, for $\beta > \beta^*$ when using $K^2 = K^2(\beta^*)$ in Equation (1). As expected, the error $\underline{e}$ vanishes for $\beta = \beta^*$. In addition, the figures show that for $\beta^* < 50°$, the error between 0° and β^{-} can be considered negligible. These results are also in agreement with Ref. 9.

Based on the foregoing considerations, it is concluded that to minimize the measuring errors, the sensor should be positioned at angles up to 45° with respect to the estimated direction of the velocity vector. This procedure was used in the measurements presented in Ref. 2.

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NOMENCLATURE

d	Wire diameter
e	Error percent due to directional sensitivity correction
K	Directional sensitivity parameter
l	Wire length
U	Time averaged flow velocity
U_i	Instantaneous flow velocity
U_{calc}	Calculated flow velocity
U_x, U_y, U_z	U component in x, y, and z directions respectively
u, v, w	Fluctuating components in the U, normal and binormal directions, respectively
Nu	Nusselt number
Re	Reynolds number based on the wire diameter

Greek Letters

β	Angle between U and normal to the wire
α	Angle between U_i and normal to the wire

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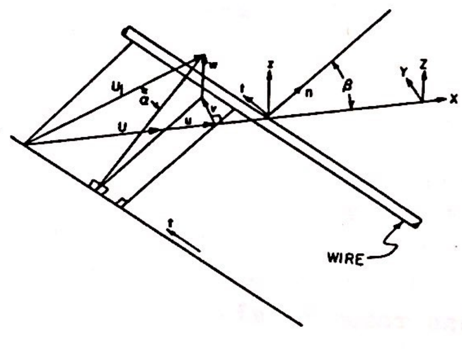

Figure 1. Actual Flow, Mean and Turbulent Components in the Wire Direction.

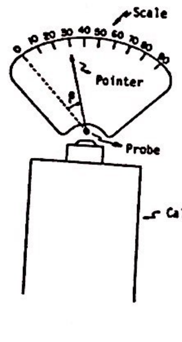

Figure 2. System for Studying the Parameter K^2

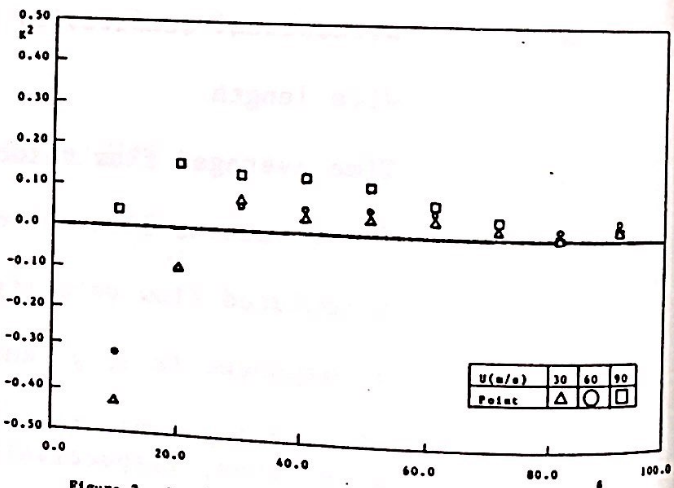

Figure 3. Results for K^2 for the Used Probe ($\ell/d = 300$)

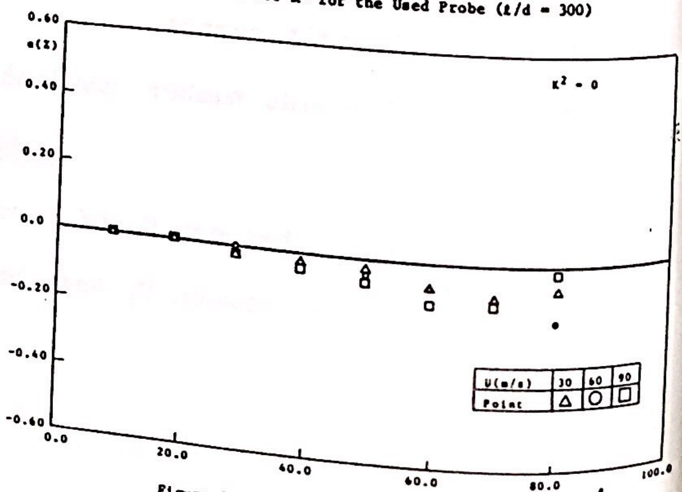

Figure 4. Results for e Using $K^2 = 0$

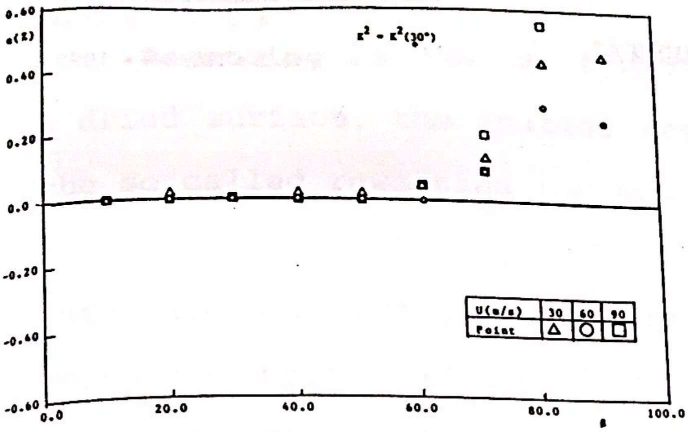

Figure 5. Results for e Using $K^2 = K^2$ (30°)

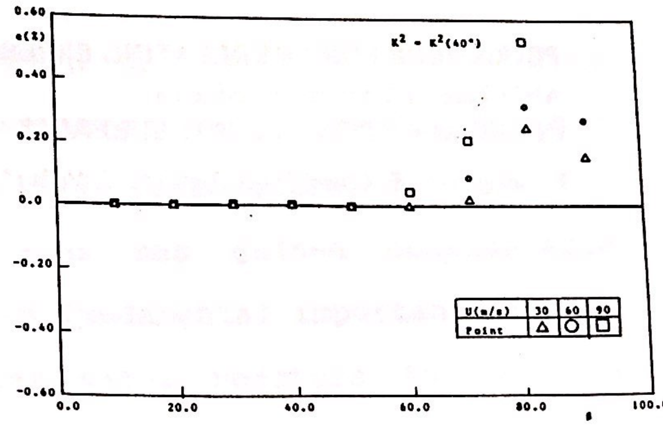

Figure 6. Results for e Using $K^2 = K^2$ (40°)

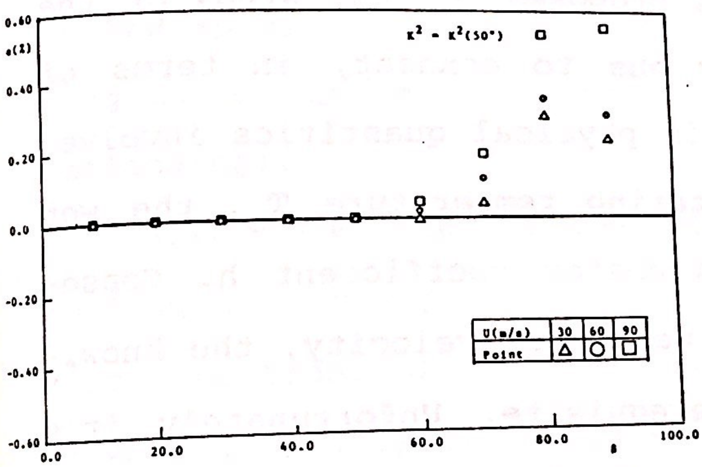

Figure 7. Results for e Using $K^2 = K^2$ (50°)

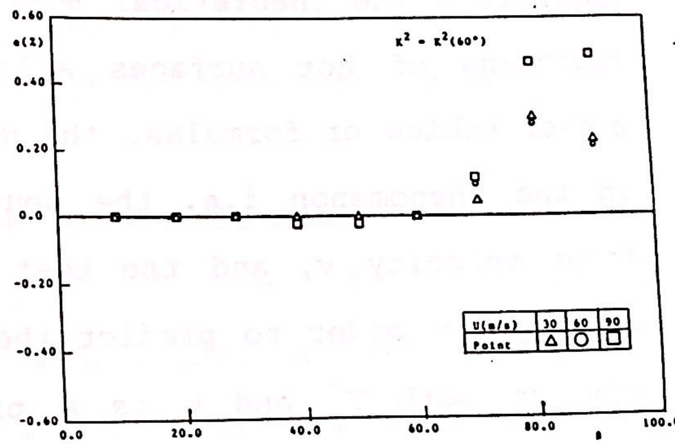

Figure 8. Results for e Using $K^2 = K^2$ (60°)

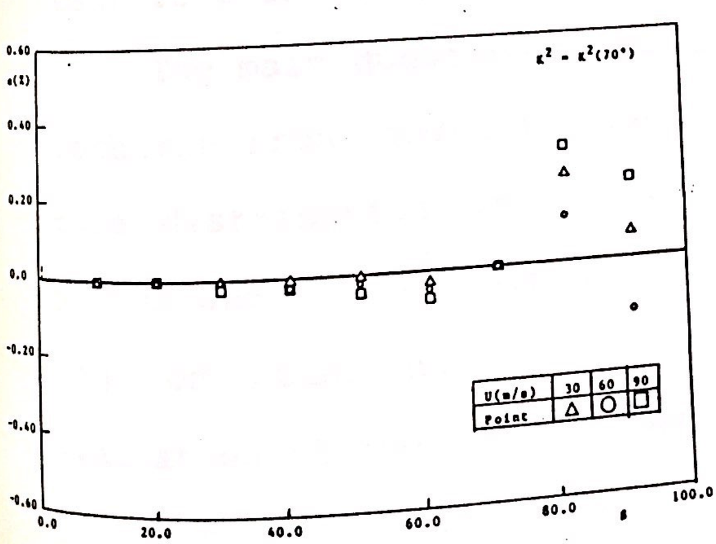

Figure 9. Results for e Using $K^2 = K^2$ (70°)

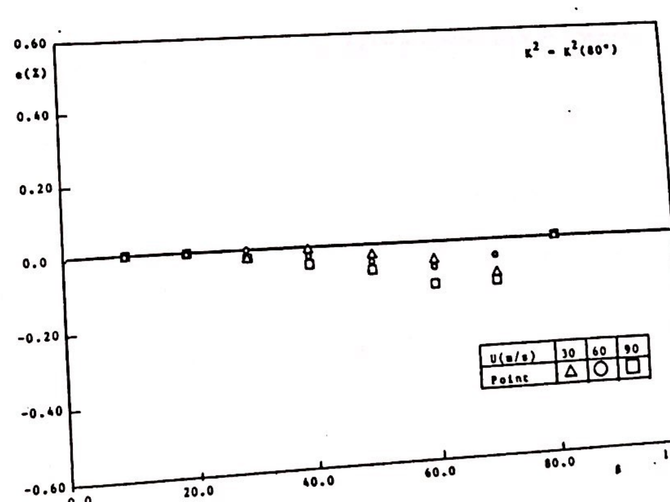

Figure 10. Results for e Using $K^2 = K^2$ (80°)