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Design of a Hot-wire Rake for Measurements in Temperature-varying Flow Fields

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Abstract

The present work deals with the design of a multi-probe support for simultaneous multi-point measurements. The article analyses the effects of the insertion of a hot-wire rake in a test section where the flow shows not constant temperatures. The constant temperature anemometry technique is known to have a relevant sensibility to both fluid temperature variations during the measurements and temperature differences between calibration and testing conditions. Therefore a technique to take into account for the flow temperature drifts influence is proposed and validated. The temperature correction presented allows reducing the influence of temperature variations on the measured velocity. This is achieved introducing a correction term, namely the temperature-loading factor that can be optimized for the individual probe and measurement conditions. The correction also takes into account for variations in fluid property values (Prandtl number, dynamic viscosity, heat conductivity and density) with temperature.

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Keywords: Constant temperature anemometry; non-uniform temperature flow field; temperature correction calibration; probes rak

1. Introduction

The simultaneously measuring the velocity at different points in a test section requires the use of rakes for simultaneous multi-point measurements [1] even for a large amount of probes [2]. A probes rake is commonly conceived and manufactured according to a specific experimental set-up and a specific need.

The measurement technique chosen to characterize the flow field in the test section is the Constant Temperature Anemometry (CTA) [3–5].

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Nomenclature

A, B, n	King's law coefficients
CTA	Constant Temperature Anemometry
E	measured voltage
Tw	wire temperature of the probe
$\boldsymbol{T_a}$	ambient temperature
$\boldsymbol{T_{ref}}$	reference temperature
$\boldsymbol{T_{f_a}}$	film T with respect to the ambient T
$\boldsymbol{T_{f_0}}$	film T with respect to a reference T
Nu	Nusselt number
Pr	Prandtl number
D	probe wire diameter
R	CTA bridge resistances
Θ	temperature difference
U	velocity
U_corr	corrected velocity
U_act	actual (known imposed) velocity
m	temperature-loading factor
α_ref	hot-wire probe specific parameter
OHR	Over Heat Ratio
r	recovery factor

2. Multi-probe rake design

The designed support is a hot-wire rake shaped out as a symmetrical 4-digits NACA profile, in which it is possible to insert up to five probes and up to two thermocouples.

After the validation of a three probes support [6] shown when installed in the test section in Figure 1 a five probes support is proposed. This latter could grant the measure of the whole velocity profile in test section at once.

The conceived rake is a NACA 0026 profile with a maximum thickness (t) of 12 mm, a chord length (c) of 46.15 mm and a total height (h) of 59 mm as shown in Figure 2.

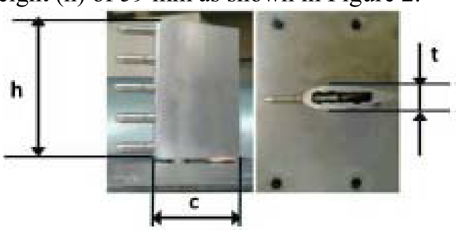

Fig.1. Dimensions of the hot-wire rake

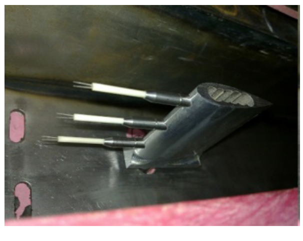
Fig.2. Manufactured three-probes rake

To improve the manufacture process and the adaptability of the rake, different materials and manufacturing procedures are tested. A short summarize in pictures is reported in Figure 3.

Eventually the best compromise resulted to be a rake of polyurethane, milled out by means of a "Computer Numerical Control" (CNC) machine. The probe holders are installed at a distance of 12.5 *mm* from each other. The material chosen for the manufacture is the Obomodulan® 500, which is a polyurethane based material for model, tool making, manufacturing of checking fixtures and test units and it is widely used in the field of rapid proto-typing.

The Obomodulan® 500 is characterized by homogeneous and smooth surfaces, an even and fine cell structure, a high edge strength and a low coefficient of thermal expansion additionally it grants free machining with low dust generation and machine time and an improved economic efficiency by reduced material consumption besides being ready for any gluing without the need of surface polish.

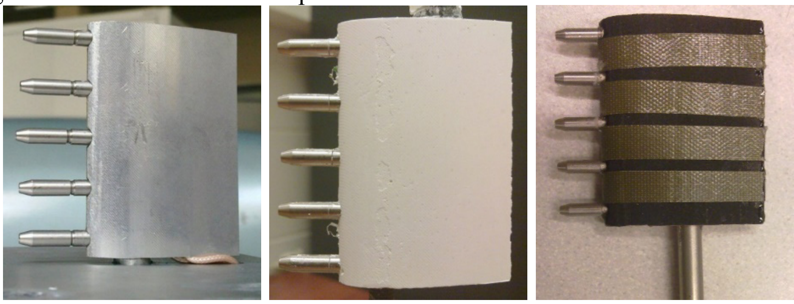

Fig.3. Material evolution of the manufactured probes rake. Steel, Plaster and Polyurethane from left to right

3. Flow temperature drift correction

The CTA technique is non-direct measurement technique and therefore to obtain meaningful measurements a calibration law is required. Calibration units are available for this purpose, letting us associate to a known velocity the voltage measured by the hot-wire probe. Unfortunately, this procedure cannot be exploited to analyze the data when the temperature varies during the measurements. Variation in fluid temperature is a major error source in hot-wire anemometry. The effect of the temperature on probe characteristics has been thoroughly investigated over the years and a variety of temperature correction schemes has been proposed. The plot in Figure 4 shows calibration curves of a Dantec 55P11 hot-wire probe operated at a wire temperature of 250 °C performed at a fluid temperature of 22 °C and 44 °C respectively.

Without temperature correction, the error in measuring the velocity in air is around -1.9 % per 1 °C increase in fluid temperature. The environment in which the hot-wire probe is placed is characterized by rather significant temperature variations, 6-10 K keeping the same velocity and from 320 K to 295 K varying the velocity from 30 m/s up to 180 m/s. Therefore, rather than a calibration curve a calibration surface with the temperature as additional variable would be required. The biggest issue to obtain such a calibration surface is that a dedicated wind tunnel should be exploited, where both the velocity and the flow temperature can be con-trolled. A wind tunnel of this kind is available at the Royal Military Academy but it is limited to a maximum velocity of 30 m/s under controlled temperature conditions, which is outside of the range of interest for the high-speed experiments that are performed at velocities ranging from 30 m/s to 230 m/s. Therefore, a different way to take into account for the fluid temperature variations has to be exploited.

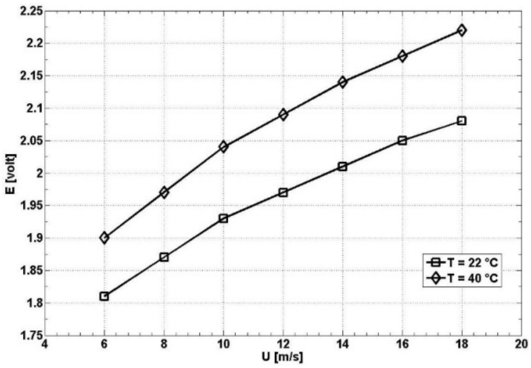

Fig.4. Influence of fluid temperature variation

The simplest procedure to apply a temperature correction, proposed by [7], assumes direct proportionality between the squared probe voltage and the heat transfer from the probe and neglects the temperature influence on the calibration constants A and B in King's law:

$$E^2 = (T_w - T_a)(A + B\,U^n) \tag{1}$$

In equation 1 the term T_w indicates the wire temperature while T_a is the ambient temperature. Procedures that are more sophisticated not only take the temperature influence on the fluid properties into account but also introduce a temperature-loading factor in the Nusselt number [8]. In equation 2 the term T_{f_a} is the film temperature defined as $(T_w + T_a)/2$.

$$Nu\left(\frac{T_{fa}}{T_a}\right)^{\{-0.17\}} = A + B \cdot Re^n \tag{2}$$

The proposed correction procedure is partly based on the work presented in [8]. The effect of fluid temperature on CTA probe characteristics can be deducted from the heat transfer equation 3 proposed by [9] which holds true for hot-wires with large length-to-diameter ratios:

$$Nu = 0.42 \cdot Pr_{f_a}^{0.20} \cdot + 0.57 \cdot Pr_{f_a}^{0.33} \cdot Re^{0.50} \tag{3}$$

Defining the Nusselt number Nu, the Prandtl number Pr and the Reynolds number Re as follows:

$$Nu = \frac{h \cdot D}{k_{fa}} \tag{4}$$

$$Pr = \frac{\mu_{fa} \cdot cp_{fa}}{k_{fa}} \tag{5}$$

$$Re = \frac{\rho_{fa}}{\mu_{fa} \cdot D \cdot U} \tag{6}$$

Equation 3 is only valid in the ranges 0.01 < Re < 10000 and 0.71 < Pr < 1000. Applying the general equation for the heat transfer from a heated body to the heated wire of a probe one obtains the expression in 7:

$$P = h\left(T_w - T_a\right)A \tag{7}$$

that for a constant temperature anemometer can be expressed in terms of the bridge top voltage E and probe and bridge resistances obtaining:

$$P = I^2 R = E^2 \cdot \frac{R_W}{(Rw + Rl + Rc + Rb)^2} \tag{8}$$

In equation 8 the terms R_w, R_l, R_c and R_b are respectively the wire, probe leads, cable and bridge resistances. Introducing the definitions from Kramers' equations 3, 4, 5, 6 and sending E^2 to the left hand side the probe characteristic can be re-arranged as in equation 9:

$$E^2 = (T_w - T_a) \cdot k_{f_a} \cdot \left(a \cdot Pr_{f_a}^{0.20} + b \cdot Pr_{f_a}^{0.33} \cdot \left(\frac{\rho_{fa}}{\mu_{fa}}\right)^n \cdot U^n\right) \tag{9}$$

where a and b are constants related to the specific sensor geometry and sensor-bridge resistances. In condensed form, the relationship in equation 9 can be expressed as follows:

$$E^2 = \left(T_w - T_a\right)(A + B \cdot U^n) \tag{10}$$

Still the temperature correction proposed by equation 1 neglects the temperature influence on the calibration constants A and B.

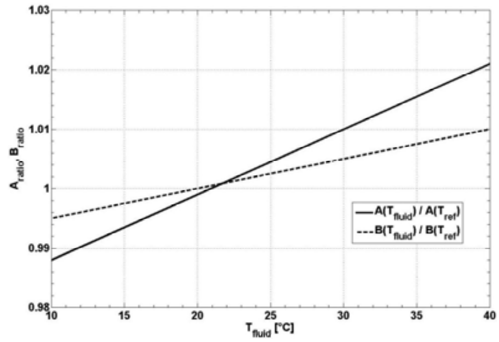

Fig.5. T_{fluid} drifts influence on the calibration constants

As visible from the analysis presented in Figure 5 the calibration constants A and B increase with approximately 0.1 % and 0.05 % per °C of variation, respectively. If not accounted for this dependency will systematically give too high readings of the velocity. Therefore, the proposed approach to account for fluid temperature variation includes a correction to be applied directly to the calibration constants. To obtain the actual velocities the reference calibration King's law coefficients are modified according to the measured fluid temperature. The corrected King's law coefficients are computed as described in equation 11:

$$\begin{cases} A_{corr} = \Theta^{1 \pm m} \cdot Ph_A \cdot A_{ref} \\ B_{corr} = \Theta^{1 \pm m} \cdot Ph_B \cdot B_{ref} \end{cases} \tag{11}$$

where the terms PhA and PhB are correction parameters linked to the physical properties of the fluid and Θ is a temperatures ratio term. Their explicit expressions are reported in equations 12, 13 and 14 respectively.

$$Ph_A = \frac{K_{f_a}}{K_{f_0}} \cdot \left(\frac{Pr_{f_a}}{Pr_{f_0}}\right)^{0.2} \tag{12}$$

$$Ph_B = \frac{K_{f_a}}{K_{f_0}} \cdot \left(\frac{Pr_{f_a}}{Pr_{f_0}}\right)^{0.33} \cdot \left(\frac{\rho_{f_a}}{\rho_{f_0}}\right)^{n} \cdot \left(\frac{\mu_{f_a}}{\mu_{f_0}}\right)^{-n} \tag{13}$$

$$\Theta = \frac{T_w - T_a}{T_w - T_0} \tag{14}$$

The terms composing the correction parameters Ph_A and Ph_B in equation 11 are computed at the temperatures T_{f_a} and T_{f_0} which are respectively the ambient and the reference film temperatures defined as follows:

$$\begin{cases} T_{f_a} = \frac{T_w + T_a}{2} \\ T_{f_0} = \frac{T_w + T_{ref}}{2} \end{cases} \tag{15}$$

After applying the temperature correction, the King's calibration law can be condensed as follows:

$$E^2 = A_{corr} + B_{corr} \cdot U^n \tag{16}$$

Eventually the velocity in the wind tunnel test section is computed as expressed by equation 17:

$$U = \left(\frac{E^2 - A_{corr}}{B_{corr}}\right)^{1/n} \tag{17}$$

The parameter m is called *Temperature Loading Factor* and the probe manufacturer Dantec suggests it should be kept between 0.2 and 0.3 and added or subtracted depending on whether T_a is bigger or smaller than T_{ref} respectively. This is confirmed by the performed analysis that also shows that an optimal value for m can be found. In order to apply the temperature correction the wire temperature T_w has to be known. This is possible from the following relationship:

$$R_w = R_{ref} \cdot \left[1 + \alpha_{ref}\left(T_w - T_{ref}\right)\right] \tag{18}$$

where α_{ref} and R_{ref} are known values, given by the probe manufacturer. To retrieve T_w the only missing value is the actual wire resistance R_w. This latter can be obtained once the Over Heat Ratio (OHR) is chosen during the acquisition system set-up. Since the following relationship holds true:

$$OHR = \frac{R_w - R_{ref}}{R_{ref}} \tag{19}$$

one can easily obtain the wire resistance as:

$$R_w = R_{ref} \cdot (1 + OHR) \tag{20}$$

Thence the expression for the wire temperature becomes:

$$T_w = T_{ref} + \frac{R_w - R_{ref}}{\alpha_{ref} \cdot R_{ref}} \tag{21}$$

It is therefore important, to properly apply the proposed temperature correction, to keep the same OHR value during the calibration operation and the testing phase. Moreover, regularly perform calibrations to have up to date reference calibration constants is also a good practice to follow.

Summarizing to apply the temperature correction, analytically correcting the transfer function as depicted by the set of equation in 11, it is enough to respect the following rules:

- operate the probe with the same sensor temperature as during calibration, i.e. keep a fixed decade resistance
- acquire the ambient fluid temperature simultaneously with a temperature sensor which is fast enough to follow the temperature variations
- acquire the bridge voltage without any correction

The plot in Figure 6 shows a comparison between actual and corrected velocities measured at 38 °C with a probe calibrated at 22 °C.

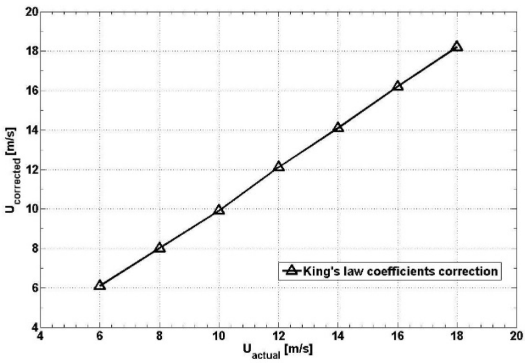

Fig.6. $U_{corrected}$ vs U_{actual}

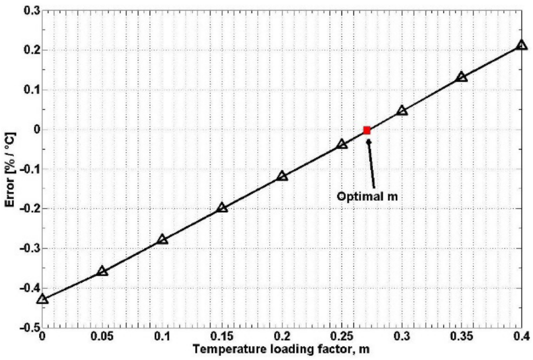

Fig.7. Optimal value of temperature-loading factor

The correction method, when an optimal temperature-loading factor is found, may exhibit a small residual error. Since m resulted being slightly velocity dependent the plot presented in Figure 7 is an average of the results obtained for the velocities in the range of interest.

Conveniently defining the error as in equation 22, one obtains errors of the order of ± 0.06% per °C:

$$e_{res} = \frac{(U_{corr} - U_{act})}{U_{act} \cdot (T_a - T_{ref})} \cdot 100 \tag{22}$$

Exploiting the definition given for the residual error it is possible to search for an optimal value of the temperature-loading factor. In the velocity range of interest the residual error remains below 0.08 % per °C once the optimal temperature loading-factor found.

4. Flow temperature measurements

It is therefore clear as knowing the temperature of the flow in the test section is of crucial importance in order to correctly measure the velocity by means of the hot-wire probes. At high speed, especially since the fluid compressibility starts playing an important role, the flow temperature evaluation requires higher care with respect to low speed. Pitot-static probes were chosen for the wind tunnel commissioning and since they remain inserted in the test section as controlling sensors during the experimental campaign the choice to install probes with embedded thermocouple is taken. This kind of Pitot tube allows both pressure and temperature measurements at once reducing of course the flow blockage in the testing chamber. A sketch of the installed probes is reported in Figure 8. The Pitot-tube is instrumented with a K-type thermocouple which is installed on the probe nose. To be able to perform stand-alone temperature measurements other thermocouples are placed in the wind tunnel. Seen the high velocities obtainable in test section the inserted K-type thermocouples, with a 0.5 mm diameter, are prepared by stiffening the first part of the sensor and leaving free to the flow the last 1.5 cm including the sensing element. A picture of a so prepared thermocouple is shown in Figure 9. The high velocities involved in the experiments may cause high readings error in the temperature measurements performed with thermocouples. Indeed, according to the *Manual on the use of thermocouples in temperature measurement* [10], whenever a gas moves with an appreciable velocity, in addition to the thermal energy in the form of random translational kinetic energy of the molecules, some of its thermal energy is in the form of directed kinetic energy of fluid flow. The static temperature is a measure of the random kinetic energy, while the dynamic temperature is a measure of the directed kinetic energy.

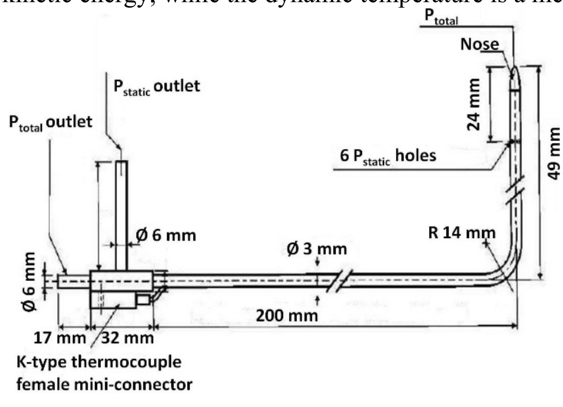

Fig.8. Pitot-static tube with embedded thermocouple

Fig.9. stiffened K-type thermocouple

The total temperature is a concept (and not a measurement) which sums the static and the dynamic temperatures. Such a total temperature would be theoretically sensed by an adiabatic probe which completely stagnates an ideal gas. The gas flowing around a thermocouple immersed in the gas is slowed down, but not stopped and not adiabatically: for this reason a measurement error, called velocity error, arises. It is therefore clear that when temperatures in high-speed environments have to be evaluated a correction is needed. The correcting parameter or recovery factor can be expressed as in equation 23:

$$r = \frac{T_{measured} - T_{static}}{T_{total} - T_{static}} \tag{23}$$

It allows taking into account for conduction, radiation and velocity error. By means of a dynamic calibration it is possible to retrieve the recovery factor as a function of the Mach number. Once the recovery factor evolution known, one can compute the total temperature from the expression reported in equation 24:

$$-T_{measured} = T_{total} \cdot \left[1 - (1-r) \cdot \frac{(\gamma-1)M^2}{2+(\gamma-1)M^2}\right] \tag{24}$$

where the temperatures are expressed in K, M is the Mach number, r the recovery factor and γ the air specific heats ratio. To perform the sensor dynamic calibration the procedure proposed in [11] is followed and the actual installation used in the article for the calibration is exploited. Indeed the calibration experiments are performed at the von Karman institute and exploit the specifically designed installation. A sketch of the calibration instrumentation is shown in Figure 10.

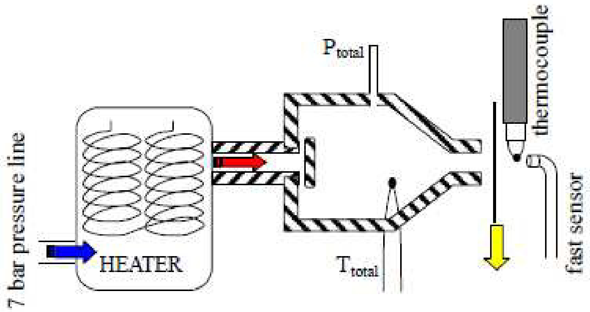

Fig.10. thermocouple dynamic calibration installation [11]

The installation is composed by a 25:1 contraction factor nozzle fed with high-pressure air, whose temperature can be managed by means of a heater. A thermocouple and a pressure sensor are placed upstream the reduction section in order to measure the flow total conditions. In the meanwhile the thermocouple to be calibrated is placed at the nozzle outlet. The knowledge of the ambient pressure, corresponding to the static pressure surrounding the tested sensor, allows to subsequently retrieving the Mach number, the static temperature and eventually the recovery factor. The calibration procedure is performed for both the stiffened thermocouple and the Pitot-tube embedded thermocouple. The obtained calibration curves, reporting the recovery factor as a function of the Mach number are shown in Figure 11.

5. Conclusions

The CTA technique applied exploiting hot-wire probes resulted to be the most suitable for the use required by the proposed analysis. Since the fluid temperature in the test section is not constant and often far from the hot-wire probes calibration conditions it becomes crucial the problem of taking into account for the flow temperature variation influence on the measurements performed by means of hot-wire anemometers. Therefore a study to take into account for the flow temperature drift effects is performed. The temperature correction presented makes it possible to reduce the influence of temperature variations on the measured velocity to typically less than ± 0.1%/C thanks to the temperature loading factor a parameter optimized for the individual probe and measurement conditions.

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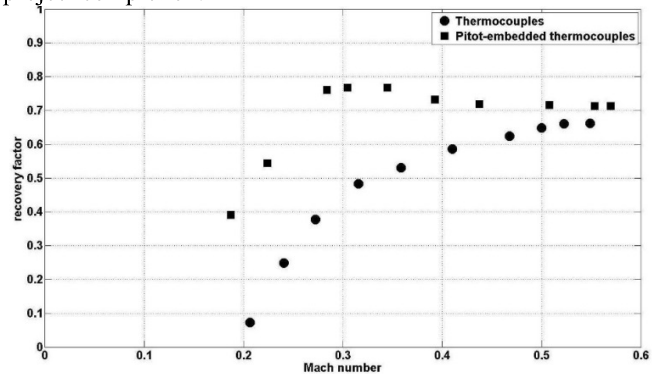

Fig.11. Thermocouples recovery factor - r = f (M)

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