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HOT WIRE ANEMOMETRY TEMPERATURE CORRECTION IN A FREE SHEAR LAYER

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ABSTRACT

A measurement procedure is proposed to take into account temperature drift for hot wire anemomentry measurements in conditions where the facility is not equipped with temperature control. The procedure consists in evaluating the wire sensitivity to the temperature by building a voltage-temperature curve. The voltages of both the calibration points and the measurement points are corrected shifting the voltage values to an arbitrary reference temperature. The results for a free shear layer evidence improvements with respect to the non corrected data and to the data corrected using the semi-empirical relation proposed by Jørgensen (2002).

1 INTRODUCTION

Hot wire anemometry is a robust experimental technique that allows to obtain time series of velocities in a turbulent field. A thin metallic element (diameter micrometers and length order of millimetres) is heated by an electric current for Joule effect and immersed in a flow field; the cooling of the probe or the voltage necessary to keep the temperature constant (thanks to a Wheatstone Bridge) are correlated with the velocity field through a calibration curve (Comte-Bellot, 1976).

Errors in the calibration strongly influence the overall accuracy of the measurements. A main source of calibration error is the temperature drift (Comte-Bellot (1976)). Temperature drift are linked with the variation of the flow temperature, T_a, during the measurements with respect to the flow temperature during the calibration.

Temperature drifts can be classified in slow drift due to the electrical heat generated by a motor in a closed-loop wind tunnel or fast drift due to the temperature fluctuations in a turbulent field (Bruun, 1995). When performing measurements in a facility not equipped with active temperature control both temperature drifts are present. The core of the jet will be at a higher temperature with respect to the ambient conditions, leading to a non-negligible temperature gradient through the turbulent shear layer that develops on the sides of the open jet. The temperature in the core of the jet will be function of the test velocity and of the ambient temperature. In figure 1 we report measurements of an open jet wind tunnel; it is worth underlining that an overall temperature variation of more than 20°C is achieved. As depicted in figure 1 a temperature drift is present for each point of the calibration (namely for each velocity) and the velocity-temperature relation strongly depends on the velocity at a particular measurement point and on the ambient condition that varies from one calibration to another (taken during different days). In addition, the relation velocity-temperature curve changes completely when a measurement is carried out along the turbulent shear layer due to the temperature fluctuations that generate an "instantaneous" temperature drift.

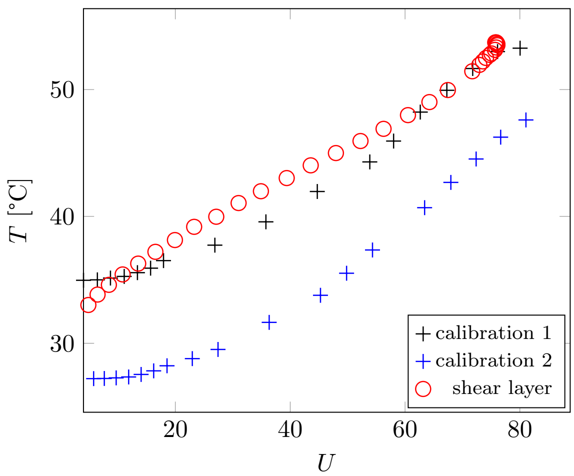

Figure 1. Temperature dependence on the streamwise velocity during two calibrations and in the shear layer.

The most common procedures to take into account temperature drifts relies on analytical corrections using the ambient temperature, T_a, acquired during each velocity measurement (Abdel-Rahman *et al.*, 1987). The corrections can be applied on the semi-empirical non-dimensional heat transfer relationship

$$Nu = A + BRe^{0.5} \tag{1}$$

where Nu is the Nusselt number, Re is the Reynolds number (Collis & Williams, 1959), or directly on the velocity and temperature calibration relation leading to a King's law modification

$$E^2_{\text{corr}} = (A + BU^n)(T_w - T_a) \tag{2}$$

where A and B are calibration constants and T_w is the wire temperature (Bruun, 1995; Tropea *et al.*, 2007). According to the procedure detailed by Jørgensen (2002), if the temperature of the flow where the hot wire is immersed varies with respect to the ambient temperature at the time the wire is conditioned, the output voltage has to be further corrected with the formula

$$E_{\text{corr}} = \left(\frac{T_w - T_0}{T_w - T_a}\right)^{0.5} \cdot E \tag{3}$$

where T_0 is the ambient reference temperature related to the overheat setup before calibration. Unfortunately, according to Jørgensen (2002) this correction is only valid for moderate temperature variations, within $5°C$. As shown in figure 1 the temperature gradient both during a calibration and during a measurements in the shear layer at high speed reaches values well above $20°C$ suggesting that the correction proposed by Bruun (1995); Jørgensen (2002) might lead to erroneous results.

Another common technique relies on multiple calibration curves obtained at distinct temperatures using interpolation schemes to cover the intermediate temperatures obtained during a measurement. Talluru *et al.* (2014) proposes a method to account multiple calibration drifts using ”intermediate single point recalibration”. The method is based on an accurate traversing system which is able to relocate the probe at the measurement position after the acquisition of a single point for an intermediate calibration. The method, however, requires further complications in the setup and in the traversing system that makes it non applicable in large-scale industrial contexts. In addition, the technique only considers conditions where each calibration curve or additional point is obtained at a constant temperature and the temperature gradient within the measurement domain is negligible, making it not applicable for instance on the test-case presented above.

Blair & Bennett (1987) detailed a multi-element constant temperature hot wire procedure that permits to simultaneously measure the temperature and velocity fluctuations. The hot wires needs to be closely spaced and conditioned with different over heat ratios. Lienhard V & Helland (1989), however, highlighted the complexity of the procedure proposed by Blair & Bennett (1987) and the limitations of the multi-element probe method that is only applicable for moderate mean temperature and velocity gradients and for moderate temperature fluctuations.

In the current paper we propose a novel technique based on the wire temperature sensitivity. Coupling hot wire anemometry measurement and temperature measurements it is possible to correct each calibration points, as well as each actual measurement point, taking into account any temperature drift. We will focus on the application of the sensitivity correction to turbulent shear layer measurements, as the one presented above, even if the technique is expected to work for other kinds of turbulent flow measurements. We will firstly report the correction when the the hot wire data are synced with time-resolved temperature measurements. We will highlight the differences in the results between our method and the correction proposed by Jørgensen (2002). Then we will detail a correction based on only the statistics of the temperature and not on their instantaneous measurements.

2 EXPERIMENTAL SETUP

The experiments are conducted in the anechoic open jet wind tunnel of the LMFA at the École Centrale de Lyon. The jet is equipped with a nozzle with contraction ratio of 1.25 ending with a square exit section that measures 0.5 m side. The maximum speed achievable is around 80 m/s. The measurements are carried out on the turbulent shear layer that develops from the side of the exit section, figure 2.

The setup consists in two probes, Dantec gold-plated hot wire 55P11 straight probe used as a constant temperature hot wire anemometer (CTA) and a constant current cold wire thermometer (CCA). The acquisition of the two probes is synced.

The cold wire is operated at very low overheat ratios so acting as a thermometer (Berson *et al.*, 2010); it allows to perform time-varying temperature measurements. A calibration for the CCA cold wire is performed against a thermocouple in a controlled environment where the temperature is varied within the range of interest of the current investigation; The calibration curve allows to link directly the output voltage with the flow temperature. For further details about the CCA the reader should refer to Tropea *et al.* (2007).

The hot wire CTA is conditioned using a Dantec Streamline; an overheat ratio of 0.8 is imposed. The wire temperature after the conditioning is approximately equal to $T_w = 238°C$. The frequency response of the system obtained from a square wave test is equal to 85 kHz and it is evaluated at the maximum test velocity. The velocity calibration is performed *in situ* in the core of the jet against a pitot tube; the calibration law is obtained using a forth order polynomial fit following (Perry, 1982). The distance between the two wires is $\Delta z \cong 2$ mm so that it can be considered that the temperature measurements are obtained at the same location with respect to the velocity measurements. Fixed to the cold wire support, a thermocouple is installed to give a further measurement for the mean temperature.

The tests are conducted at 35, 55 and 75 m/s. The temperature of the jet core is monitored through all the experimental campaign though a thermocouple located at the exit of the nozzle. The surveys are conducted at streamwise coordinates of 300, 500 and x =700 mm downstream of the nozzle where the shear layer is expected to be self-similar. Signals were sampled at 104 kHz by a National Instruments PXI-4472 acquisition system. The probes are traversed through the shear layer span in the y direction, the sampling time for each y-position is equal to 20 s in order to have the statistics converged. The minimum displacement of the traversing is 0.01 mm.

Planar PIV measurements at 35 and 55 m/s obtained during a separate experimental campaign are reported as reference for the streamwise standard deviation profiles. The measurement plane is horizontal (xy), the PIV plane is centred at the streamwise location of 500 mm. Two smoke generators are employed, one to seed the core of the jet and the second to seed the anechoic chamber in order to have sufficient particle density though the shear layer region. A double pulsed Continuum Mesa PIV laser is employed to illuminate the particles. The acquisition frequency is set to 5 kHz. A Phantom VEO1310L 12 bits CMOS camera equipped with a 60 mm f/2.8 Micro Nikkor lens is used as imaging tool. Lavision DAVIS 10.2 is used for the calibration, synchronisation, laser control and image acquisition. Each run consists in 4900 image pairs for a duration of 0.98 s. Almost 20 runs are acquired in order to have a sufficient convergence of the statistics allowing to resolve the largest flow features. The samples are processed using the 2D2C cross-correlation PIV algorithm of DAVIS 10.2. The interrogation window size was iteratively changed passing from 64×64 pixel to 8×8 with an overlap of 50%; this leads to a vector spacing of $\Delta x = \Delta y$ =0.665 mm and 34200 vectors. The field of view (FOV) is 158 mm × 212 mm ($2.2\delta_\omega \times 1.6\delta_\omega$, where δ_ω is the vorticity thickness).

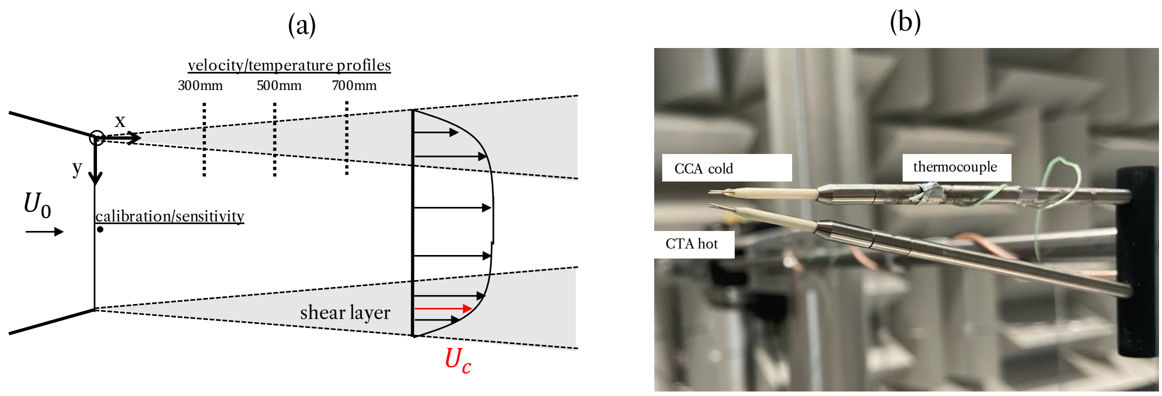

Figure 2. Experimental setup (a) sketch of the setup and the measurement locations, (b) photo of the two probe arrangement.

3 SENSITIVITY EVALUATION

The procedure for the evaluation of the temperature sensitivity of the wire, s, is based on decoupling the voltage output variation, due to the temperature variation in the flow, from the voltage output variation due to changes in the impinging velocity. The objective is to find a relation that links the voltage variation to the temperature variation for a fixed velocity.

The procedure can be performed easily by placing the hot wire and the thermometer in a jet in which the temperature varies due to electrical heat generated by the motor. The thermometer device has to be ideally located as close as possible to the hot wire in order to assume that the temperature measured is the same as the one of the hot wire position. It is important to keep the free-stream velocity fixed in order to have a voltage variation that is only due to the temperature variation in the flow. During the temperature variation, the hot wire voltage and the temperature are acquired. To keep the freestream velocity fixed through the whole procedure, a pitot tube and a thermocouple in the free-stream are necessary to constantly monitor the exact value of the free-stream velocity. The power of the motor is then adjusted in order to compensate for the changes in temperature (and by consequence in density). This can be done by an automated routine that reads the output values of the temperature and pressure difference and tunes the wind tunnel motor power to keep the free-stream velocity fixed.

The temperature-voltage curve is depicted in figure 3. A linear fit through the data allows to calculate the temperature sensitivity parameter, s, as the slope voltage-temperature curve. The procedure is carried out at two velocities (around 50 m/s and around 100 m/s). As illustrated in the figure, negligible variations in the slope of the curve, namely the temperature sensitivity, can be evidenced when changing the free-stream velocity and small differences are due to the temperature measuring device (not shown).

The sensitivity evaluation is repeated for the same wire and over-heat ratio in several experimental campaigns carried out in different facilities; the results are almost identical. Tests for a lower over-heat ratio (0.6) evidenced a decrease of the value of s, suggesting that the sensitivity needs to be measured each time the wire is conditioned. The sensitivity is further educed in correspondence of the maximum temperature fluctuations which is approximately located in correspondence of the peak of the velocity fluctuations. The results evidences an increase of the sensitivity of about 10% where the temperature fluctuations are the highest. This suggests that when correcting the velocity fluctuations, the peak location is expected to suffer from a larger uncertainty if the sensitivity measured in

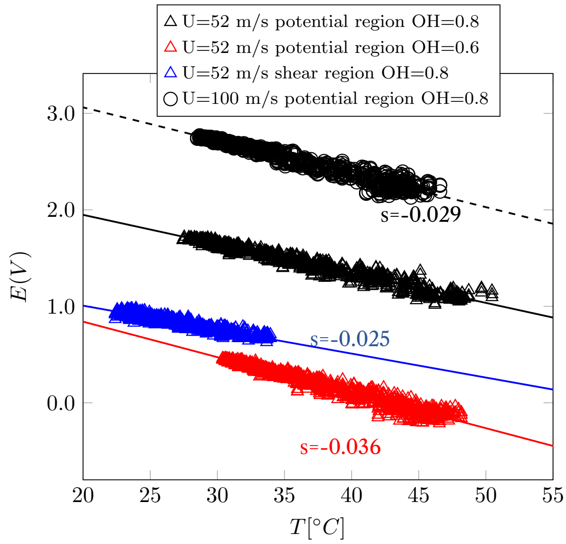

Figure 3. Temperature sensitivity evaluation for several velocities, effect of velocity, over-heat ratio and position, temperature data obtained with the CCA cold wire.

the potential region is applied to all the profiles, as done in the current investigation.

Once the sensitivity is calculated, during each hot wire anemometry acquisition, the temperature from the thermometer, T_{meas} needs to be acquired. The output voltage for each measurement point, E, associated with a specific T_{meas} is then corrected in order to compensate for the temperature drift; this is done by shifting the voltage to an absolute reference temperature value, T_{ref} which can be chosen arbitrarily. This makes the voltages as if they were acquired at a constant temperature equal to T_{ref} trough all the measurements

$$E_{\text{corr}} = E - (T_{\text{meas}} - T_{\text{ref}}) \cdot s. \tag{4}$$

This formula is valid both for the mean voltage and for the instantaneous voltages. In the latter case the temperature measurement needs to be time-resolved to instantaneously correct the voltage value

$$E'_{\text{corr}}(t) = E(t)' - (T'_{\text{meas}}(t) - T_{\text{ref}}) \cdot s. \tag{5}$$

It is fundamental to use the same reference temperature, as well as the same temperature measuring device, for the sensitivity, calibration and during the actual measurements.

4 RESULTS

4.1 Instantaneous correction

The sensitivity correction is performed instantaneously on the signal relying on the synced measurements of the CTA hot wire and the CCA cold wire, following the equation 5. It worth noticing that the corrections cannot be considered fully instantaneous because of the difference cut-off frequencies of the cold and hot wires. For this reason, the temperature fluctuations above a certain frequency (around 1kHz) cannot be taken into account in the instantaneous correction.

The efficacy of the correction will be evaluated against the correction proposed by Jørgensen (2002); it will be based on the evaluation of the values of the velocity statistics as well as the self-similar evolution of the shear layer when varying the free-stream velocity namely: linear growth of the shear layer vorticity thickness and the collapse of the profile of the statistics when plotted using reduced coordinates (Bell & Mehta, 1990). It is worth underlying that the vorticity thickness, $\delta_\omega(x) = \frac{U_0}{\left(\frac{\partial U(x)}{\partial y}\right)_{\max}}$, evolves linearly regardless the correction applied. The results are reported in figure 4 for 55 m/s together with the semi-empirical relation by Candel *et al.* (1976) and additional pitot measurements.

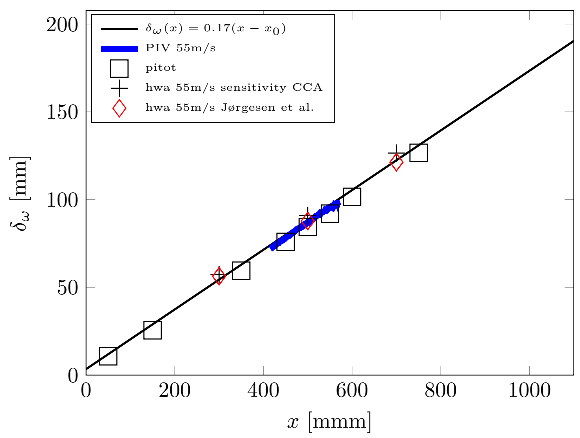

Figure 4. Streamwise evolution of the vorticity thickness at 55 m/s, comparison between the two correction methods, PIV and additional pitot measurements. Reported also the theoretical linear growth by Candel *et al.* (1976)

The mean, standard deviation and skewness profiles for the three free-stream velocities at $x = 500$ mm are reported in figure 5. To make non-dimensional the mean and standard deviation a reference value of U_0 is used. The value is measured with a pitot tube immersed in the core region of the jet and is independent on the correction method. This allows to highlight the absolute differences of the evaluation of the statistics for the two correction methods presented.

The non-dimensional mean velocity profiles follow a the theoretical error function proposed by Gortler (1942) $\frac{U(\eta)}{U_0} = \frac{1}{2}[1 + \text{erf}(\eta + \eta_0)]$ where erf() is the Gauss error function and the similarity variable is defined as $\eta = \sigma \frac{y}{x}$ where $\sigma = 11$ is the spreading parameter and $\eta_0 = 0.4$ is the expansion of the potential core.

The self-similarity of the mean velocity for the correction method by Jørgensen (2002) is acceptable except for the region close to the potential region of the jet, where the temperature differences becomes increasingly important. The free-stream value is underestimated leading to an error in the free-stream of approximately 5%. The sensitivity correction, instead, shows a non-dimensional value of the mean velocity in the core of the shear layer that is equal to one, meaning that the actual value of the free-stream velocity is correctly measured.

For the standard deviation, using the method of Jørgensen (2002), the profiles do not collapse especially in the peak region. The peak value increases when increasing the free-stream velocity suggesting a clear trend with the temperature increase. Similar considerations can be made for the skewness profile, that for the highest speed does not collapse through all the spanwise extent. This would lead to an erroneous assumption on the self similarity of the shear layer that instead is confirmed when the sensitivity correction is employed: a perfect collapse of the statistics is shown in figure 5.

Despite the perfect collapse of the standard deviation profiles when applying the sensitivity correction, the peak value shows a 6% difference with respect to the PIV results. The PIV results are in good agreement with the the results by Bell & Mehta (1990) and Rogers & Moser (1994). The discrepancies with respect to the PIV results as well as the literature results can be attributed to the higher value of the sensitivity in correspondence of the region where the temperature fluctuations are the highest. Another possible explanation is that the correction cannot be considered fully instantaneous, meaning that the velocity fluctuations due to smallest turbulent scales are not fully corrected.

The normalised velocity spectra in correspondence of the σ_U peak are presented in figure 6. The spectra, obtained for the correction methods collapse well, however, it is worth underlying that the inertial range is better resolved when the sensitivity correction is applied; the slope, in fact, is more close-fitting to the canonical -5/3.

4.2 Correction using the temperature statistics

The sensitivity correction can be applied relying only on the statistics of the temperature and not on the time-resolved values. In figure 7(a) the results for the mean velocity obtained using the mean temperature, $\overline{T}$, to correct the mean voltage, namely relying then on the equation 4 are depicted. One can notice that the results are indistinguishable from the instantaneous correction presented above. In addition, using the mean temperature measured by the thermocouple, gives the same results of using the CCA cold wire. In figure 7(b) the standard deviation of the velocity is presented. If the mean temperature profile is used to correct the instantaneous voltage (blue triangles) a further underestimation of the peak of the streamwise velocity standard deviation is found. The reason being that the correction accounts just for the mean temperature gradient but not for the temperature fluctuations due to the turbulent field.

To take into account the temperature fluctuations, we can relay on the statistics of the temperature field. The standard deviation of the corrected voltage, $\sigma_{E_{\text{corr}}}$, can be expressed as a function of the sensitivity, s, of the standard deviation of the non corrected voltage, σ_E, and of the standard deviation of the temperature, $\sigma_{T_{\text{meas}}}$

$$\sigma_{E_{\text{corr}}} = \sqrt{\sigma_E^2 + s^2 \sigma_{T_{\text{meas}}}^2} \quad (6)$$

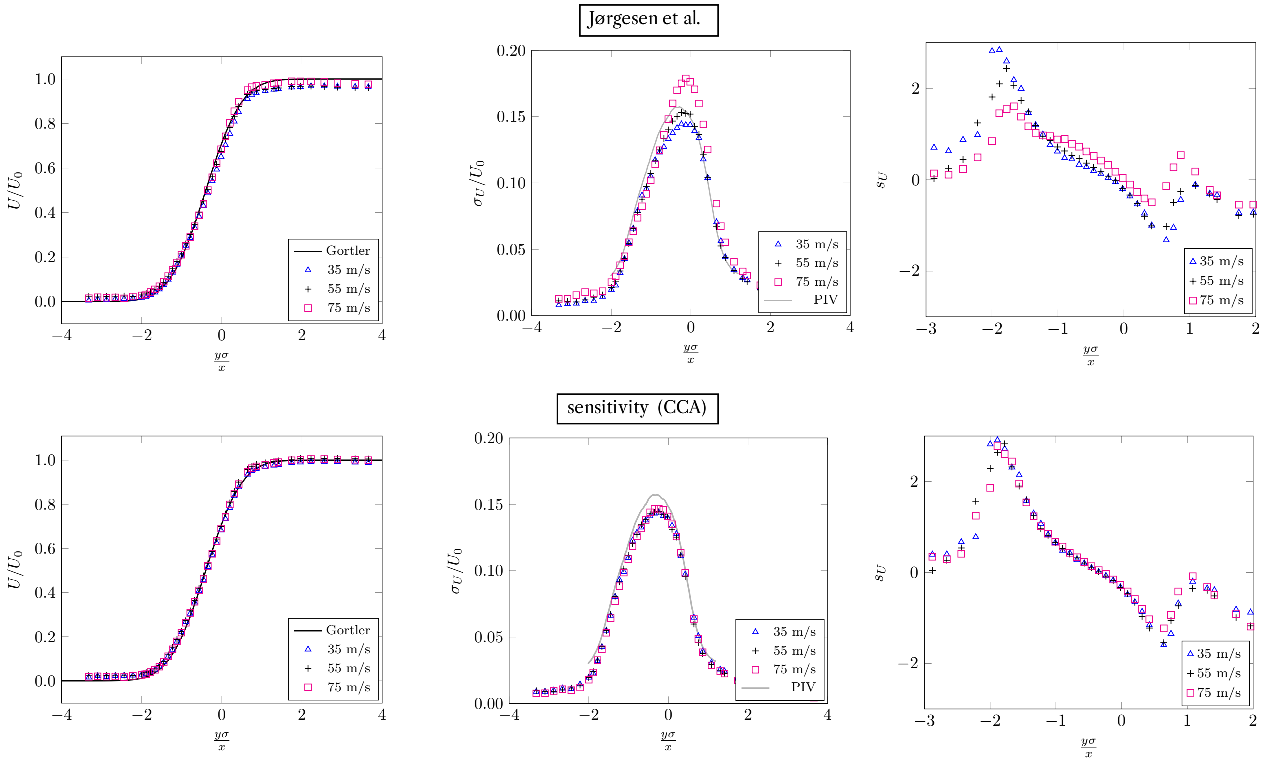

Figure 5. Mean velocity U/U_0, standard deviation σ_U/U_0 and skewness profiles. Effect of the free-stream condition U_0. Reference value of U_0 obtained with pitot used to normalise the profiles.

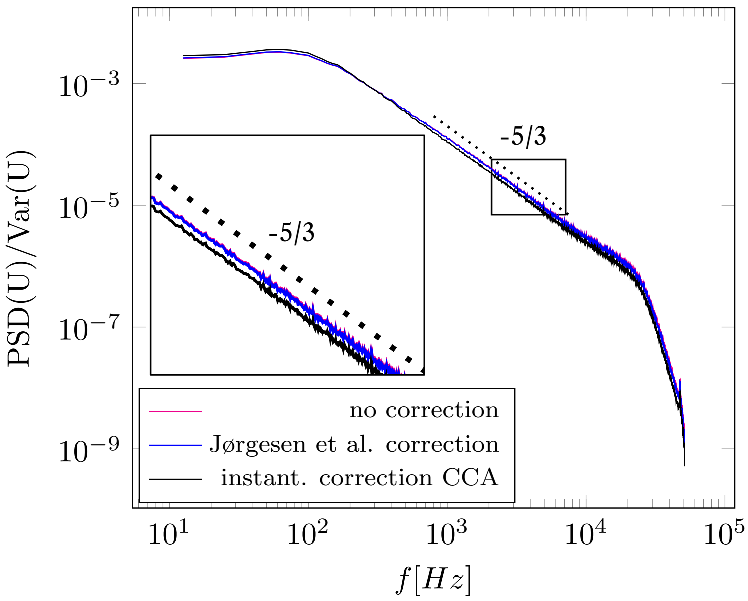

Figure 6. Velocity spectra at 55 m/s taken in correspondence of the σ_U peak, effect of the sensitivity correction.

Using the fourth order polynomial calibration equation to obtain the velocity as function of the voltage (Perry, 1982)

$$U = C_1 + C_2 E_{\text{corr}} + C_3 E_{\text{corr}}^2 + C_4 E_{\text{corr}}^3 \quad (7)$$

it is possible to express the standard deviation of the velocity, σ_U, as function of the standard deviation of the corrected voltage

$$\sigma_U = \sqrt{\left(C_2 + 2C_3 E_{\text{corr}} + 3C_4 E_{\text{corr}}^2\right)^2 \cdot \sigma_{E_{\text{corr}}}^2} \quad (8)$$

As depicted in figure 7(b) the results obtained expressing the σ_U as a function of the σ_T, are indistinguishable from the ones obtained correcting instantaneously the voltage. The self similarity is retrieved but it is not shown here for brevity.

5 CONCLUSIONS

A simple method to correct the hot wire temperature drift for turbulence measurements with large temperature gradients is proposed. The method relies on the measurement of the temperature sensitivity of the hot wire and is tested in a turbulent

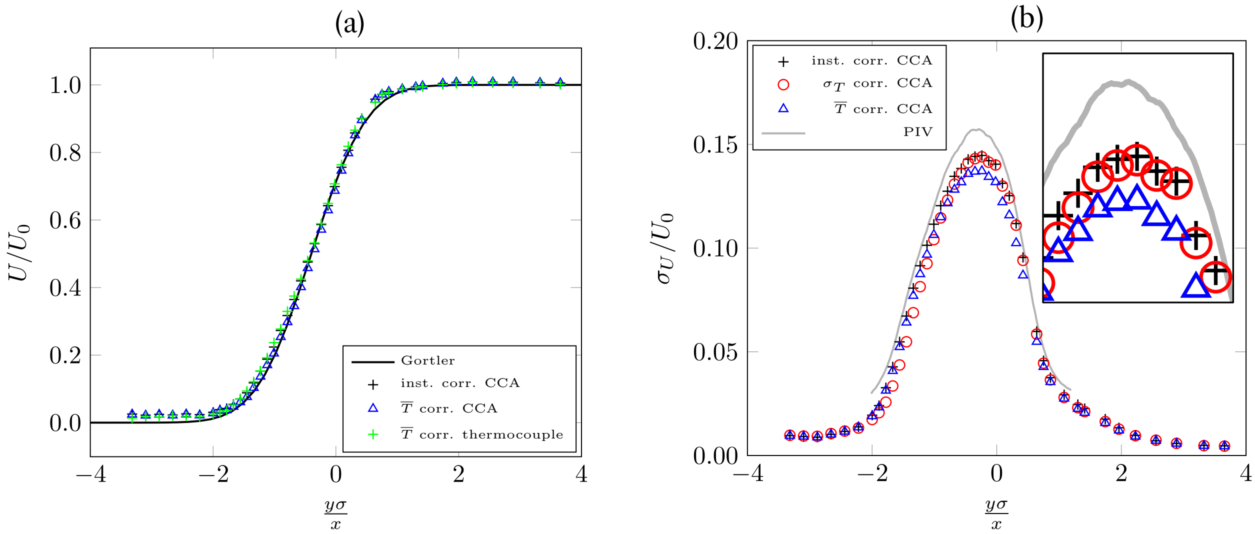

Figure 7. Mean (a) and standard deviation (b) streamwise velocity profiles, comparison between instantaneous correction and correction using the statistics of temperature profiles.

shear layer where the temperature gradient can reach values higher than 20°C. The correction is applied instantaneously on the hot wire voltage by relying on synchronised measurements with a CCA cold wire. The results obtained applying the sensitivity outperform the correction method proposed by Jørgensen (2002). An excellent evaluation of the streamwise velocity statistics and self-similarity of the shear layer is reported. A correction based on just the first and second order statistics of the temperature field is proposed and it is shown to correct the velocity statistics as accurate as the instantaneous correction. Further works should be conducted to extend the sensitivity correction to for more complex cases as cross-wires and on other canonical setups as turbulent boundary layers.

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