Physics of Fluids ARTICLE pubs.aip.org/aip/pof

A simple hot wire temperature drift correction based on temperature sensitivity applied to a turbulent shear layer

Cite as: Phys. Fluids **36**, 105192 (2024); doi: 10.1063/5.0232138
Submitted: 5 August 2024 · Accepted: 27 September 2024 ·
Published Online: 25 October 2024

View Online Export Citation CrossMark

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ABSTRACT

A procedure is proposed to correct temperature drift for hot wire anemometry measurements in turbulent fields where the facility is not equipped with temperature control. The procedure consists of 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 correction can be applied to the instantaneous voltages by performing synced temperature measurements with constant current anemometry or constant voltage anemometry cold wire. The efficacy of the method is tested on a turbulent shear layer that develops on the side of an open jet wind tunnel not equipped with temperature control. The velocity statistics show a good match with respect to reference particle image velocimetry measurements, evidencing the self-similarity of the shear layer in contrast with the non-corrected data and the data corrected using the semi-empirical and analytical relation based on King's law modification. A correction based only on the temperature statistics shows indistinguishable results with respect to the instantaneous correction.

I. INTRODUCTION

Hot wire anemometry (hwa) is a robust and widely used experimental technique that allows us to obtain time series of a velocity field. This is particularly useful in turbulent fields where correctly capturing the velocity fluctuations is of primary interest. A thin metallic element with a diameter of the order of micrometers and length of the order of millimeters is heated for the Joule effect by an electric current and immersed in a flow field. A calibration curve links the velocity with the cooling of the heated probe (constant current anemometer) or the voltage necessary to keep the resistance constant through a Wheatstone bridge-based feedback loop (constant temperature anemometer).[1]

Errors in the calibration are, among all error sources in hot wire anemometry, the ones that mostly influence the overall accuracy of the velocity measurements. According to Ref. 1, the main source of calibration error is the temperature drift. Temperature drift usually describes the variation of the flow temperature during a certain measurement T_a with respect to the flow temperature during the calibration procedure. It means that a voltage dataset acquired at a certain temperature is calibrated using a calibration curve obtained at a different temperature. Temperature drifts can be classified as slow drift due to the electrical heat generated by a motor in a wind tunnel or fast drift due to the temperature fluctuations in a turbulent field.[2]

A practical example where both drifts are present is when performing measurements in large-scale industrial open jet wind tunnels, as the ones used in aeronautical or automotive contexts, where the size, and/or the motor power involved, prevents active control of the temperature. For such setups, the core of the jet is at a higher temperature with respect to the ambient condition of the quiescent region, leading to a non-negligible temperature gradient; the temperature in the core of the jet is itself function of the test velocity and of the ambient condition. In such setups, in addition, when performing measurements in a turbulent field, the effect of the instantaneous temperature fluctuations cannot be neglected.

In Fig. 1, we report the measurements acquired in the anechoic open jet wind tunnel of the Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA) at the École Centrale de Lyon. Three sets of measurements are shown: two calibrations curves obtained in the core of a jet (performed with a week of separation) and a set of measurements across the turbulent shear layer that develops on the sides of the open jet. The measurements are performed with two probes: one for

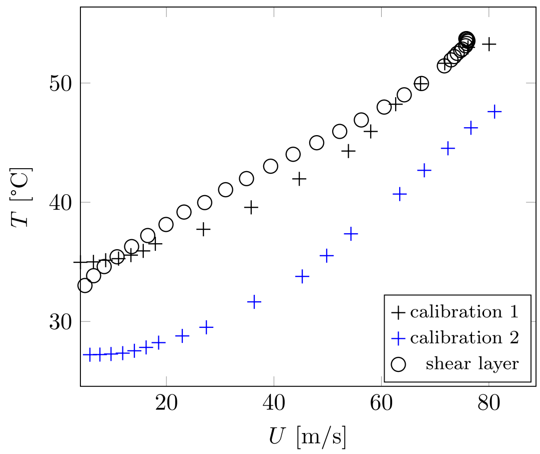

FIG. 1. Temperature variation as a function of the streamwise velocity during two calibrations and across the shear layer.

temperature and the other for velocity measurements. The probes are synced, so it is possible to plot the temperature variation as a function of the local velocity. The maximum speed achievable in the current setup is about 80 m/s, not dissimilar to most of the large-scale automotive and aeronautical facilities. Upon further inspection of the figure, we can clearly notice how a temperature variation is present for each point of the calibration (namely for each velocity); in other words, each point of the calibration curve is drifted. It is important to keep in mind that the velocity-temperature relation is not unambiguous as it strongly depends on the velocity at a particular measurement point and on the ambient condition that might vary from one day to another. In other words, it means that each mean velocity is not necessarily associated with one specific temperature; this explains the differences between two calibrations obtained within one week of measurements. What can be underlined is that the relation velocity-temperature curve changes completely when a measurement through the turbulent shear layer is performed. This is due to the different cooling behaviors that take place in the presence (shear layer) or in the absence (potential core) of a turbulent field. In the shear layer, temperature fluctuations generate an "instantaneous temperature drift" on the time series of output voltage of the hot wire that affects the velocity statistics evaluation.

Similar large temperature drifts are present in atmospheric boundary layer measurements, in heat transfer experiments, and in high Reynolds number facilities where the inadequate control of the ambient temperature can be an important issue.[3]

A first method to take into account temperature drift is automatic compensation in the Wheastone bridge, and the modification of the resistance in the circuit does not necessarily make a separate measurement of the ambient temperature T_a. The most common procedures, however, are analytical corrections.[4] These corrections rely on the acquisition of the ambient temperature T_a, during each velocity measurement. The corrections can be applied to the semi-empirical non-dimensional heat transfer relationship that links the convective heat transfer generated by the air flow with the heating of the hot-wire[5]

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

where Nu is the Nusselt number, Re is the Reynolds number, and A and B are calibration constants. However, the relation is derived for an infinitely long cylinder, namely a 2D section; thus, it is only applicable for long wires. In addition, the flow density, viscosity, and thermal diffusivity are functions of the temperature and are evaluated at an arbitrary defined "film temperature" $T_f = 1/2(T_w + T_a)$, where T_w is the wire temperature which can be obtained from the measured wire resistance.[2]

The corrections can be applied directly to the velocity and temperature calibration relation, leading to a King's law modification[2,6]

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

or, as proposed by Lienhard *et al.*[7]

$$E^2 = (AT_f^{0.84} + BU^{0.45})(T_w - T_a). \tag{3}$$

Bruun[2] (section 7.2.1) reported that the constants A, B, and n are themselves functions of the temperature T_a, and if this dependence is not taken into account, the uncertainty in the velocity measurement increases. Lemieux and Oosthuized[8] suggested to perform multiple calibrations at different T_a to obtain the constants $A(T_a)$ and $B(T_a)$ dependence on the temperature by performing a least-square fit. A linear dependence of the calibration constant with T_a was reported. However, finding the calibration constants dependent on the temperature requires multiple calibrations, each one obtained at a fixed temperature, and this is not applicable in facilities where the temperature is not controlled and varies for all the calibration points.

According to the procedure detailed in Refs. 9 and 10, 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 can be corrected with the formula

$$E_{\mathrm{corr}} = \left(\frac{T_w - T_0}{T_w - T_a}\right)^{0.5} \cdot E, \tag{4}$$

where T_0 is the ambient reference temperature related to the last overheat setup before calibration. This corrected voltage can be used as well in polynomial calibration curves.[11] Unfortunately, according to Ref. 10, this correction is only valid for moderate temperature variations, within 5 °C. As shown in Fig. 1, the temperature gradient during both calibration and measurements in the shear layer at high speed reaches values well above 20 °C suggesting that the correction proposed by Jørgensen[10] might lead to erroneous results.

Another widely used correction method relies on multiple calibration curves taken at different temperatures; the use of interpolation schemes allows us to cover the intermediate temperatures obtained during an actual measurement. Talluru *et al.*[12] proposed a method to account for multiple calibration drifts using what they called "intermediate single point recalibration." The method is based on an accurate traversing system, able to relocate the probe to the measurement position after the acquisition of a single point for the recalibration. However, the method could be difficult to implement where the measurement location is far from the position adopted for the calibration. This would require further complications in the setup and traversing system that makes the method 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.

To avoid multiple calibrations at several temperatures, Hultmark and Smits[3] proposed a calibration law in the form of

$$\frac{U}{\nu} = f\left(\frac{E^2}{k\Delta t}\right), \tag{5}$$

which allows us to compute the true velocity as a function of the voltage, viscosity, and thermal conductivity of air that have to be known as a function of the temperature and evaluated at the film temperature.

Blair and Bennett[13] investigated a multi-element constant temperature hot wire method that allows us to measure the temperature and velocity fluctuations simultaneously. The hot wires are closely spaced and conditioned with different over heat ratios. Lienhard and Helland[7] highlighted the complexity of the calibrations of the method proposed by Blair and Bennett[13] and the limitations of the multi-element probe method. Indeed, the method is applicable only for moderate mean temperature and velocity gradients and for moderate temperature fluctuations.

In this paper, we propose an instantaneous correction based on the sensitivity of the wire to the temperature. Coupling hot wire anemometry measurements and temperature measurements, calibration points as well as each actual measurement point can be corrected by taking into account the local temperature variation. A similar procedure is briefly mentioned by Ferchichi and Tavoularis,[14] but, to the author's knowledge, a rigorous description of the sensitivity method is not present in the literature. We will test the application of the sensitivity correction to the simple case of a turbulent shear layer that develops along the sides of an open jet wind tunnel. The self-similar development of the shear layer will be used as benchmark of the correction technique. The results will be compared with the common correction techniques proposed in Refs. 2 and 10. However, the current technique has been already successfully employed in more sophisticated contexts for turbulent flow measurements (http://lmfa.ec-lyon.fr/spip.php?article2421&lang=fr). We will first report the correction when the hot wire measurements are synced with time-resolved temperature measurements. Then, we will make a detailed correction based only on the statistics of the temperature field.

II. EXPERIMENTAL SETUP

The experiments are conducted in the anechoic open jet wind tunnel of the Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA) at the École Centrale de Lyon. A centrifugal fan powered by an 800 kW motor generates a flow having a maximum mass flow rate of about 20 kg/s. The jet is equipped with an inlet with a contraction ratio of 1.25, ending with a square exit section that measures 0.5 m in size. The maximum speed achievable with the current setup is around 80 m/s. The sensitivity correction is tested on the turbulent shear layer that develops on the side of the exit section.

As depicted in Fig. 2, the measurement setup consists of two probes, a constant temperature hot wire anemometer (CTA) and a cold wire anemometer that is either a constant current anemometer (CCA) or a constant voltage anemometer (CVA). The acquisitions of the hot and cold wires are synced. The distance between the two wires is about 2 mm, so it can be considered that the temperature measurements are obtained at the same location with respect to the velocity measurements. After performing additional measurements with

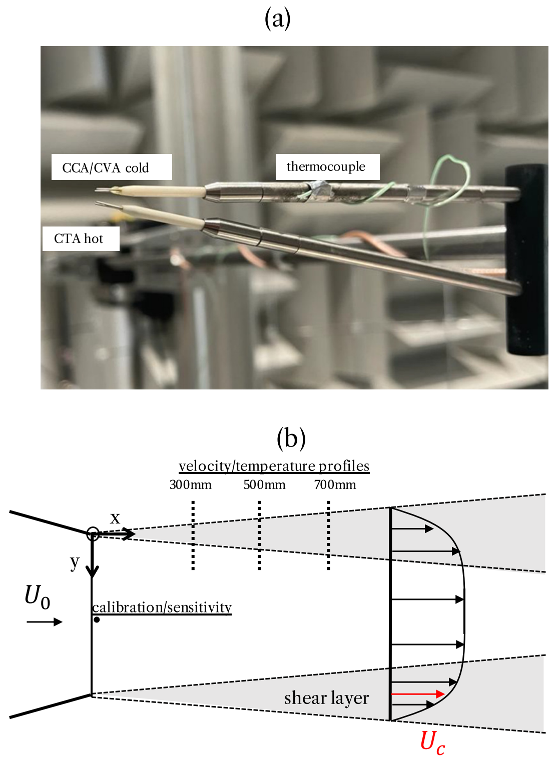

FIG. 2. Experimental setup. (a) Photo of the two probe arrangement. (b) Sketch of the setup and the measurement locations.

isolated probes, aerodynamics and heat interferences between the two wires can be considered as negligible. Fixed to the cold wire support, a thermocouple is installed. The thermocouple gives a further reference for the mean temperature, and it allows us to obtain the mean temperature when the CVA cold wire is installed, as the CVA allows us to measure only the temperature fluctuations.

The shear layer is surveyed at 55 m/s at three streamwise locations: 300, 500, and 700 mm downstream the exit section as depicted in Fig. 2(b). The two probes (cold and hot wires) are traversed through the shear layer Y direction, with the minimum displacement being 0.01 mm. To evaluate the self-similarity of the shear layer with respect to the variation of the free-stream velocity, profiles at 35 and 75 m/s are acquired at a streamwise coordinate $x = 500$ mm. As highlighted in Fig. 2, the hot wire calibration and the sensitivity evaluation are performed right downstream of the exit section in the core of the jet.

Signals both for the hot and the cold wires are acquired by a National Instruments PXI-4472 acquisition system. The sampling frequency is 104 kHz, the sampling time for each y-position is equal to 20 and 90 s for the spectra (maximum sampling rate of the DAQ card).

A. Hot wire: Constant temperature anemometer (CTA)

A Dantec gold-plated hot wire 55P01 (1.25 mm length and 5 μm diameter) straight probe is used to perform the velocity surveys in the shear layer. The wire is conditioned and operated using a Dantec Streamline Pro CTA Module 90C10 after the resistances are measured. An overheat ratio of 0.8 is imposed. The wire temperature after the conditioning is obtained by measuring the resistance of the wire and is found to be $T_w = 238\,^\circ$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 fourth-order polynomial fit following.[11]

B. Cold wire: Constant current anemometer (CCA) and constant voltage anemometer (CVA)

A cold wire is a fine-wire sensor operated at a very low overheat ratio that acts as a thermometer.[15] Due to the low currents/voltages and low overheat ratios involved, the wire is just sensitive to temperature variations and not to velocity variation. The cold wire allows us to perform time-varying temperature measurements; for this reason, it has to be preferred with respect to the thermocouples for measurements in turbulent fields: the size and the electronics allow indeed for a better frequency response. Cold wires can be operated by constant current anemometers (CCAs) or constant voltage anemometers (CVAs). The latter system allows for thermal inertia compensation through hardware corrections, leading to a better frequency response. For the constant voltage cold wire anemometer, the circuit allows us to calculate only the temperature fluctuations, so the instrument needs to be associated with a thermocouple type K [see Fig. 2(a)] to obtain the mean and the fluctuating component.[16] For further details about the CCA and CVA systems the reader should refer to Ref. 6.

In the current setup, the cold wire is an in-house modified Dantec 55P11 and operates as CCA or CVA, depending on the case. It has a 1.25 mm length and 2.5 μ m diameter, and it is made of tungsten. Additional measurements are reported in Fig. 4 with a CCA of 1 μm diameter. The CCA operates at a current of 0.1 mA through a Dantec Streamline temperature module 90C20, while the CVA works with a Tao Systems - CVA model 5003 with an input voltage of the wire circuit equal to 8.03 mV. The current and the voltage are tuned and checked with a multimeter prior to the measurements. The calibration for the CCA was performed against a thermocouple (type K) in a separate calibration oven at zero free-stream velocity, where the temperature is varied within the range of interest of the current investigation. The calibration curve for the CCA cold wire is depicted in Fig. 3 and

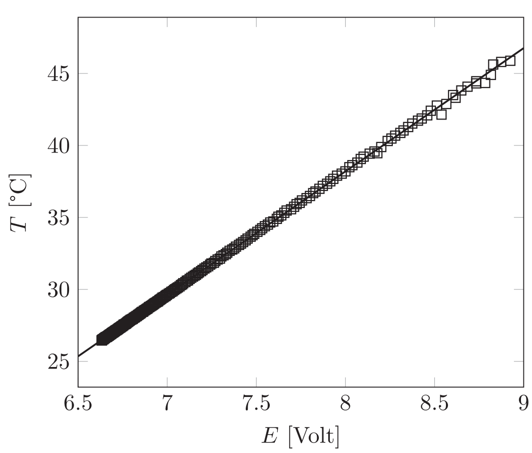

FIG. 3. Constant current anemometer cold wire calibration curve.

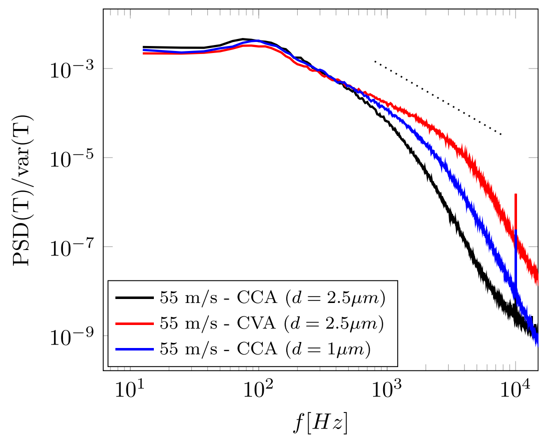

FIG. 4. Temperature spectra in the shear layer, $x = 0.5$ m and $U_0 = 55$ m/s, comparison between CCA and CVA and sensor diameter.

allows us to link directly the output voltage with the flow temperature. For the CVA, the procedure proposed in Refs. 17 and 18 is used to obtain the temperature fluctuations, automatically compensating for thermal inertia.

The different frequency responses of the two cold wire setups can be evidenced by reporting the temperature spectra obtained at the peak of the temperature standard deviation profile, shown in Fig. 4. The cutoff frequency of the CCA is in fact approximately equal to 900 Hz, while it increases to 3000 Hz for the CVA. In the figure, the effect of the wire diameter on the cutoff frequency is reported. The CCA wire with a diameter of 1 μm over-performs the CCA with a larger diameter (2.5μm). The latter is used in the current investigation for the sensitivity correction due to its larger robustness.

The temperature measuring devices employed in this investigation have been validated and compared with other techniques such as the Rayleigh scattering, further details can be found in Ref. 18.

C. Velocity measurement devices used as reference

Additional measurements are performed to be used as a reference against the hot wire measurements corrected with the sensitivity. Velocity profiles are obtained with a pitot tube at 55 m/s to better characterize the evolution of the turbulent shear layer thickness and to be used as a reference for the mean velocity profile.

Planar PIV measurements at 55 m/s, acquired during a separate experimental campaign, are reported as a reference for the streamwise mean and standard deviation profiles. The measurement plane is horizontal (xy), and the PIV plane is centered with a streamwise location of 500 mm. Two smoke generators are employed: one to seed the core of the jet and the other to seed the anechoic chamber to have sufficient particle density through the shear layer region. To keep the particle image size between 2 and 4 pixels and reduce peak-locking effects, the particle images are slightly defocused.[19] 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 an imaging tool. Lavision DAVIS 10.2 is used for calibration, synchronization, laser control, and image acquisition. Each run consists of 4900 image pairs for a duration of 0.98 s. Almost 20 runs are acquired to have a sufficient convergence of the statistics, allowing us 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 pixels to 8×8 with an overlap of 50%; this leads to a vector spacing of $\Delta x = \Delta y = 0.665$ mm and 34 200 vectors. The field of view (FOV) is 158×212 mm ($2.2\delta_\omega \times 1.6\delta_\omega$, where δ_ω is the vorticity thickness).

III. HOT WIRE TEMPERATURE SENSITIVITY

The evaluation of the temperature sensitivity of the wire, s, and its application to correct the output voltages are detailed in this section. The method relies 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 and the temperature variation for a fixed freestream velocity. The hot wire measurement has to be synced with a temperature measuring device. The temperature measuring device has to be ideally located close to the hot wire to assume that the temperature measured is the same as the one of the hot wire position. In the current setup, a thermocouple is fixed on the wire support and a CCA cold wire is located right above the hot wire as depicted in Fig. 2(a). If the wind tunnel has no temperature control, the procedure can be performed by placing the wire in a region of low turbulence level, for example, in the core region of the jet, as done in the current investigation, to have an almost uniform temperature and velocity and neglect the differences due to the different position between the wire and the temperature measuring device. Assuming no deterioration of the wire, it is believed that the procedure has to be conducted only once after the wire has been conditioned.

A. Sensitivity evaluation

During the sensitivity evaluation, it is important to keep the free-stream velocity fixed to make sure that the voltage variation is only due to the temperature variation in the flow. To do so, 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 to compensate for the changes in temperature and, as a consequence, in air 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 RPM to keep the free-stream velocity constant.

As depicted in Fig. 5(a), for a fixed free-stream velocity, the temperature in the core region increases with time before reaching some sort of plateau. During the temperature variation, the hot wire voltage and the temperature are acquired. A temperature-voltage curve for fixed free-stream velocities is built as illustrated in Fig. 5(b). The results show that the temperature dependence of the voltage, if isolated from the velocity dependence, is linear. A linear fit through the data allows us to calculate the temperature sensitivity parameter s as the slope of the straight line. In the current investigation, a value of $s = -0.029$ V/°C is found. In the current setup, to obtain a non-negligible temperature variation, the procedure has been carried out at moderate to higher velocities (around 50 and 70 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 devices or between one campaign and another. The voltage trend with the temperature on a wider range of temperatures, obtained in a different facility, is depicted in Fig. 6; the sensitivity is evaluated for a range of $\Delta T \cong 25^\circ$ C, the temperature range is similar to the one reported in the current shear layer setup (see Fig. 1). This further confirms the linear evolution of the voltage with respect to the temperature when fixing the velocity. All the results reported show a difference in sensitivity from one test case to another within the 3%. The limit for the linear relationship that links the voltage to the temperature through the sensitivity has not been found in the current investigation. This suggests a wide range of applicability of the current correction technique, at least for automotive/aeronautical facilities where the temperature variations are similar to the ones reported herein.

Tests at a lower over-heat ratio (0.6, reported in red in Fig. 6) evidence a decrease in the value of s from -0.029 to -0.036, suggesting that, if for a certain reason the over-heat is changed, the sensitivity needs to be recalculated. Finally, tests have been performed to evaluate the sensitivity at different locations in the shear layer, not only in the potential region of the jet. Of particular interest is the location where the maximum temperature fluctuations occur, which is approximately located in correspondence with the peak of the velocity fluctuations. The results reported in Fig. 6 (red curve) evidence an increase in the sensitivity of about 10%, where the temperature fluctuations are the highest. This suggests that, when correcting the temperature drift with the current approach in a high turbulent region, a larger uncertainty is expected if the sensitivity measured in the potential region is applied.

B. Voltage correction

Once the sensitivity has been evaluated, during each hot wire anemometry measurement (actual measurement or calibration points), the temperature from a temperature measuring device T_{meas} has to be acquired. The raw output voltage of the hot wire E associated with a specific T_{meas} has to be corrected to compensate for the temperature drift; this is done by shifting the voltage for each measurement point to an absolute reference temperature value T_{ref}

$$E_{corr} = E - (T_{meas} - T_{ref}) \cdot s. \tag{6}$$

The corrected values of the voltage are then the values as if they were acquired at a constant temperature equal to T_{ref} through all the measurements. This formula is valid in general for the mean voltage value and for the instantaneous voltage, for example, when measuring in a turbulent field. In the second case, the measured temperature needs to be a function of time to instantaneously correct the voltage value

$$E'_{corr}(t) = E(t)' - (T'_{meas}(t) - T_{ref}) \cdot s, \tag{7}$$

where in general superscript $'$ indicates the instantaneous value and the symbol or the over-line indicate the mean quantity. For the temperature, in particular, we can write the following:

$$T' = T + \theta, \tag{8}$$

where θ is the temperature fluctuation. Instantaneous correction then requires a temperature measurement to be decently resolved in time, so it is not applicable when using a standard thermocouple.

Shifting both the voltages of the calibration points and the actual measurements to a reference temperature leads to have the calibration

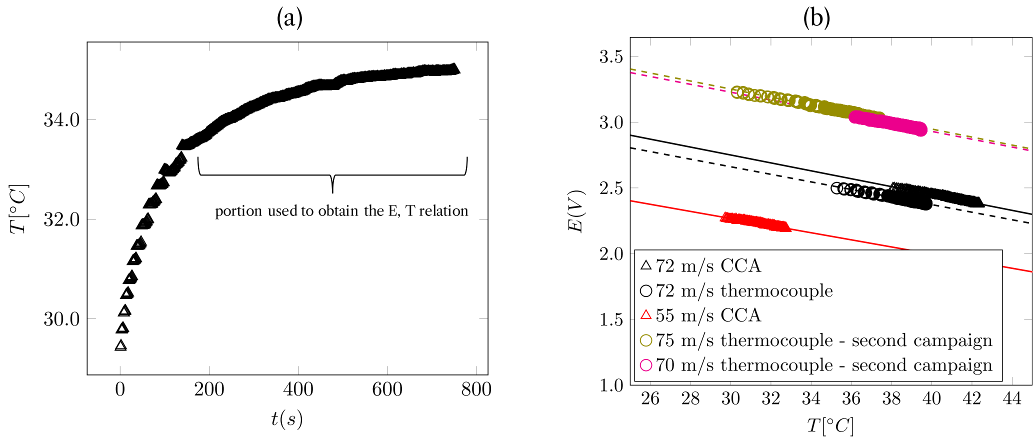

FIG. 5. (a) Temperature evolution with time in the potential region of the jet at fixed free-stream velocity. (b) Temperature sensitivity evaluation for several velocities using CCA and thermocouple in two different experimental campaigns.

constants not dependent on the temperature because all the voltages are shifted as both measurement and calibration were obtained at a reference temperature. It is worth underlining that it is crucial to use the same reference temperature, as well as the same temperature measuring device, for the sensitivity, calibration, and actual measurements to be consistent with the voltage shift.

In the current investigation, a polynomial calibration curve is chosen according to Ref. 11. In Fig. 7, the fourth-order polynomial calibration curves are depicted for the non-corrected voltages and after the application of the sensitivity correction. As depicted in the figure, changing the reference temperature shifts the calibration curves; however, the reference temperature can be chosen arbitrary and does not affect the final results for the velocity statistics calculation. The effect of changing the reference temperature is reported in Fig. 15 in the Appendix.

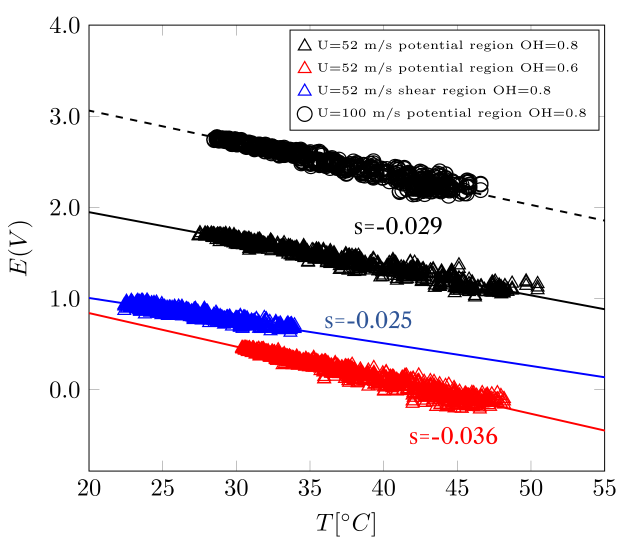

FIG. 6. Temperature sensitivity evaluation in a different facility obtained with a thermocouple, wider range of temperature, effect of over-heat and measurement location.

IV. TURBULENT SHEAR LAYER RESULTS FOR THE INSTANTANEOUS CORRECTION

In this section, we will report the results of the velocity statistics of the shear layer after the application of the sensitivity correction to the voltages. The correction is performed instantaneously on the signal thanks to the synced measurements of the CTA hot wire and the CCA/CVA cold wire, following Eq. (7). Despite the digital sampling rate of hot and cold wires being equal, it has to be underlined that the cold and hot wires have different frequency responses (see Figs. 4 and 13 for comparison where a different cutoff frequency can be noted in the temperature and velocity spectra). The temperature fluctuations having a frequency higher than the cutoff frequency of the cold wire are filtered out, and they do not contribute to the sensitivity correction for the high frequency velocity fluctuations. In other words, the temperature variation measured in one physical time step by the cold wire is used to correct multiple time steps in the velocity variation. The instantaneous correction will then be performed at a frequency that

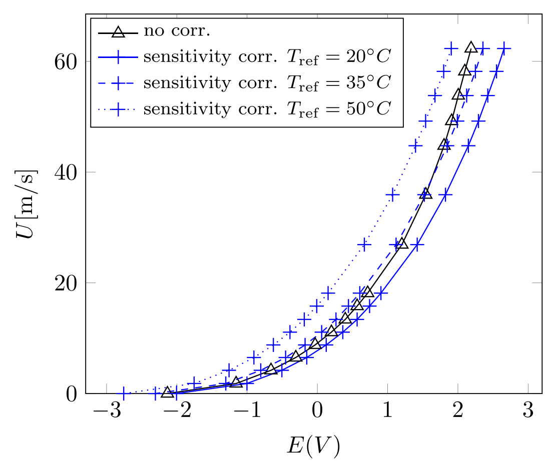

FIG. 7. Calibration curve modification due to the sensitivity factor for different T_{ref}.

corresponds to the frequency response of the cold wire used to measure the temperature.

The efficacy of the correction will be evaluated against the correction proposed in Refs. 2 and 10 and the results without correction and it will be based on the evaluation of the actual values of the velocity statistics as well as the self-similar evolution of the shear layer.

A turbulent free shear layer that develops when two initially separated uniform velocities interact evolves self-similarly downstream a certain streamwise coordinate. The two velocities are equal to U_0 and 0 in the current setup, leading to the definition of the convective velocity $U_c = U_0/2$. The three conditions to achieve a self-similar state are as follows: linear growth of the shear layer vorticity thickness

$$\delta_\omega(x) = \frac{U_0}{\left(\dfrac{\partial U(x)}{\partial y}\right)_{\max}}, \tag{9}$$

the collapse of the profile of the statistics when plotted using reduced coordinates, and the peaks of the statistics that decrease in the streamwise direction x reaching a plateau condition.[20]

As it can be seen in Fig. 8, the non-dimensional mean velocity profiles at 55 m/s follow the theoretical error function proposed by Gortler[21]

$$\frac{U(\eta)}{U_0} = \frac{1}{2}[1 + \mathrm{erf}(\eta + \eta_0)], \tag{10}$$

where erf() is the Gauss error function and the reduced spanwise coordinate is defined as

$$\eta = \sigma \frac{y}{x}, \tag{11}$$

where σ is the spreading parameter and it is equal to 11, and η_0 is the expansion of the potential core, and it is found to be equal to 0.4 in the current shear layer. The values are not dissimilar to the ones reported in the literature.[21,22]

To make non-dimensional the mean velocity, as well as all the other statistics reported in this and in the following sections, a reference value of U_0 is used. This value is checked for each measurement with a pitot tube immersed in the core region of the jet and is independent of the correction method used. The accuracy of this value is checked in a separate experiment with PIV measurements. The use of a separate reference value for the free-stream velocity allows us to highlight the absolute differences in the evaluation of the statistics. Upon further inspection of Fig. 8, one can highlight that, while for the sensitivity correction, the non-dimensional value of the mean velocity in the core of the shear layer is equal to unity, meaning that the actual value of the free-stream velocity is correctly obtained, applying Eq. (2) leads to a slight underestimation of the free-stream velocity and for the two other cases the non-dimensional value is underestimated leading to an error of approximately 5% on the evaluation of the free-stream velocity. This means that the other methods are not capable of obtaining a value of the free-stream velocity, U_0, as accurate as the sensitivity correction. In addition, this leads to erroneous scaling of the non-dimensional statistics. We can highlight that all the methods outperform the pitot profile for the lowest velocities due to the lower pitot accuracy when measuring very small pressure differences. However, all the methods show a velocity that is not exactly equal to zero in the quiescent part of the shear layer; this, according to Ref. 4, is attributed to natural convection in the low speed part of the shear layer.

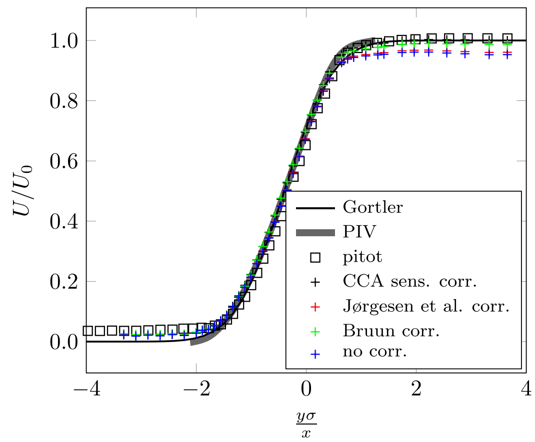

FIG. 8. Mean velocity profile in reduced coordinate at $U_0 = 55$ m/s, $x = 0.5$ m, comparison between theoretical profile by Gortler[21] [Eq. (10)], PIV, pitot and hwa data.

The streamwise evolution of the vorticity thickness for the different correction methods is reported in Fig. 9 together with semi-empirical relation reported by Candel *et al.*[23] PIV measurements and additional pitot surveys obtained in a previous experimental campaign are reported to cover a larger portion of the shear layer evolution. As highlighted in the figure, the correction method does not affect the vorticity thickness calculation, which is always obtained with a negligible error with respect to the theoretical growth, pitot, and PIV reference values.

The self-similarity of the streamwise velocity mean, standard deviation σ_U, and skewness s_U, at $x = 500$ mm when changing the free-stream velocity U_0 is reported in Fig. 10. Regarding the mean velocity profiles, the self-similarity for the no-correction as well as for the corrections by Bruun[2] and Jørgensen[10] is decent except for the region close to the potential region of the jet, where the temperature differences becomes increasingly important and the free-stream velocity value is not educed correctly. Regarding the standard deviation, for the not corrected data and the correction in Ref. 10, the profiles do not collapse, especially at the center of the shear layer, the peak in σ_U increases when increasing the free-stream velocity, suggesting a clear trend with the temperature increase. The correction method by Bruun[2] seems to outperform the method by Jørgensen[10] for the skewness and standard deviation, excluding the 35 m/s condition and the mean profiles. The skewness profiles for non-corrected results and for the correction in Ref. 10 at 75 m/s do not collapse across the shear layer, showing at the same time a marked deviation with respect to the PIV results. Conversely, it is possible to highlight that the hot wire results corrected with the sensitivity technique evidence a perfect self-similarity of the skewness profiles that, in addition, match well the PIV results; we can notice only a small deviation with respect to the PIV results in the positive peak of the skewness which corresponds to the low-velocity region of the shear layer. It is interesting to notice that the sensitivity correction outperforms the correction by Bruun[2] that overestimates the positive peak in the skewness profile despite showing a collapse of the profiles when changing the free-stream velocity.

However, even the results corrected with the temperature sensitivity do not show a collapse of standard deviation with respect to the PIV data. A peak value 6% below the PIV results is found. The PIV results are in good agreement with the results by Bell and Mehta[20] and Rogers and Moser,[24] namely a non-dimensional value of the σ_U peak around 0.15. The discrepancy with respect to the PIV results at the peak of the σ_U can be attributed to the aforementioned different values of the sensitivity s in correspondence with the region where the temperature and velocity fluctuations are the highest. This leads to higher uncertainty in the evaluation of the instantaneous velocity. A second plausible explanation is due to the spatial resolution of the hot wire that filters out the scales smaller than its length,[25] scales which are predominant in that portion of the turbulent shear layer. Similarly, the predominance of small scales in that portion of the turbulent shear layer can lead to an increased contribution of the error due to the offset between the hot and the cold wire, namely the hypothesis that the temperature fluctuations correspond to the hot wire location is, in a certain extent, less valid. Another possible reason is that the correction cannot be considered fully instantaneous, but it is restricted by the frequency response of the cold wire. The high frequency velocity fluctuations, which are due to small turbulent scales, are not fully corrected. The smallest turbulent scales are predominant in correspondence with the center of the turbulent shear layer, namely where the peak in σ_U is located. To partially confirm this hypothesis, the peak obtained with the correction based on the CVA cold wire, reported in Figs. 11 and 12, is slightly higher with respect to the one obtained with the CCA, while the profiles collapse in the other regions of the shear layer. This might be attributed to the larger cutoff frequency of the CVA with respect to the CCA (see Fig. 4).

For $U_0 = 55$ m/s, the streamwise development of the σ_U peak is reported in Fig. 12. For the sensitivity correction, the slight decreasing trend with the CVA and the almost constant value using the CCA can be considered a further confirmation that the self-similarity is correctly retrieved. On the contrary, without correction and using the correction by Jørgensen,[10] a non-monotonic behavior can be highlighted with the peak value that increases at $x = 500$ mm and decreases at $x = 700$ mm. For the correction proposed by Bruun,[2] the peak value at 55 m/s is larger for all the streamwise coordinates and evidence a plateau behavior.

The normalized velocity spectra in correspondence with the σ_U peak are presented in Fig. 13. The spectra for the different correction methods show the energy containing region, the inertia region, and the dissipation region. Despite the overall collapse of the spectra for the different methods, it is worth underlying that the inertial range is better described when the sensitivity correction is applied; the slope, in fact, is more close-fitting to the canonical $-5/3$.

V. TURBULENT SHEAR LAYER RESULTS FOR THE STATISTICAL CORRECTION

We reported the results obtained by correcting "instantaneously" the output voltage from the CTA hot wire using the sensitivity equation (7), in which the temperature is resolved in time and obtained with a CCA or CVA cold wire. Equation (6) uses the mean voltage and the mean temperature, $\bar{T}$, for each measurement point allowing us to compute the mean velocity. In Fig. 14(a), the comparison between the mean velocity profile obtained using the instantaneous temperature correction and the mean temperature correction is reported; the results shown are both obtained with the CCA cold wire. As can be seen, the

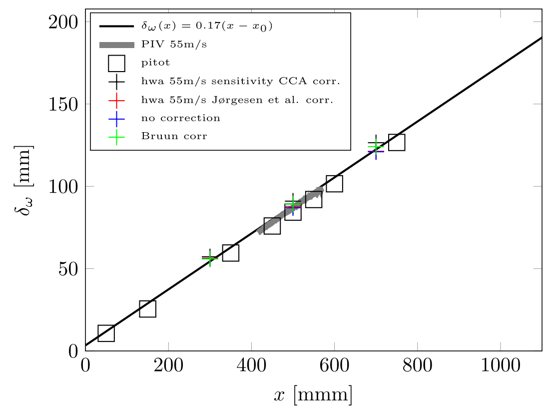

FIG. 9. Streamwise evolution of the vorticity thickness, comparison between different corrections methods.

mean velocity profiles are indistinguishable. It is worth noticing that the mean correction works well using a less sophisticated probe as temperature reference, such as the thermocouple, installed on the cold wire support. This probe, in fact, acquires data that are not resolved in time (0.3 Hz acquisition frequency) but allows a good evaluation of the mean temperature profile along the shear layer. However, as there might be some systematic error or offset between the CCA and the thermocouple, it is imperative to use one instrument for the sensitivity evaluation, calibration correction, and actual measurement correction.

As shown in Fig. 14(b), using the mean temperature to correct the time-resolved voltages leads to a further underestimation of the peak of the streamwise velocity standard deviation (blue triangle symbol). In this way, a voltage that evolves in time (and needs to be corrected instantaneously according to the instant temperature) is corrected with the average temperature. In other words, we are accounting for the mean temperature gradient but not for the temperature fluctuations due to the turbulent field. To take into account the temperature fluctuations, without relying on instantaneous temperature data, we can express the standard deviation of the corrected voltage $\sigma_{E_{corr}}$, 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 $\sigma_{T_{meas}}$

$$\sigma_{E_{corr}} = \sqrt{\sigma_E^2 + s^2\sigma_{T_{meas}}^2}. \tag{12}$$

Then, relying on the fourth order polynomial calibration equation to obtain the velocity as a function of the voltage[11]

$$U = C_1 + C_2E_{corr} + C_3E_{corr}^2 + C_4E_{corr}^3 \tag{13}$$

we can finally express the standard deviation of the velocity σ_U as a function of the standard deviation of the corrected voltage using the sensitivity

$$\sigma_U = \sqrt{\left(C_2 + 2C_3E_{corr} + 3C_4E_{corr}^2\right)^2 \cdot \sigma_{E_{corr}}^2}. \tag{14}$$

As depicted in Fig. 14(b), the results using what we can call "statistical correction," namely 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.

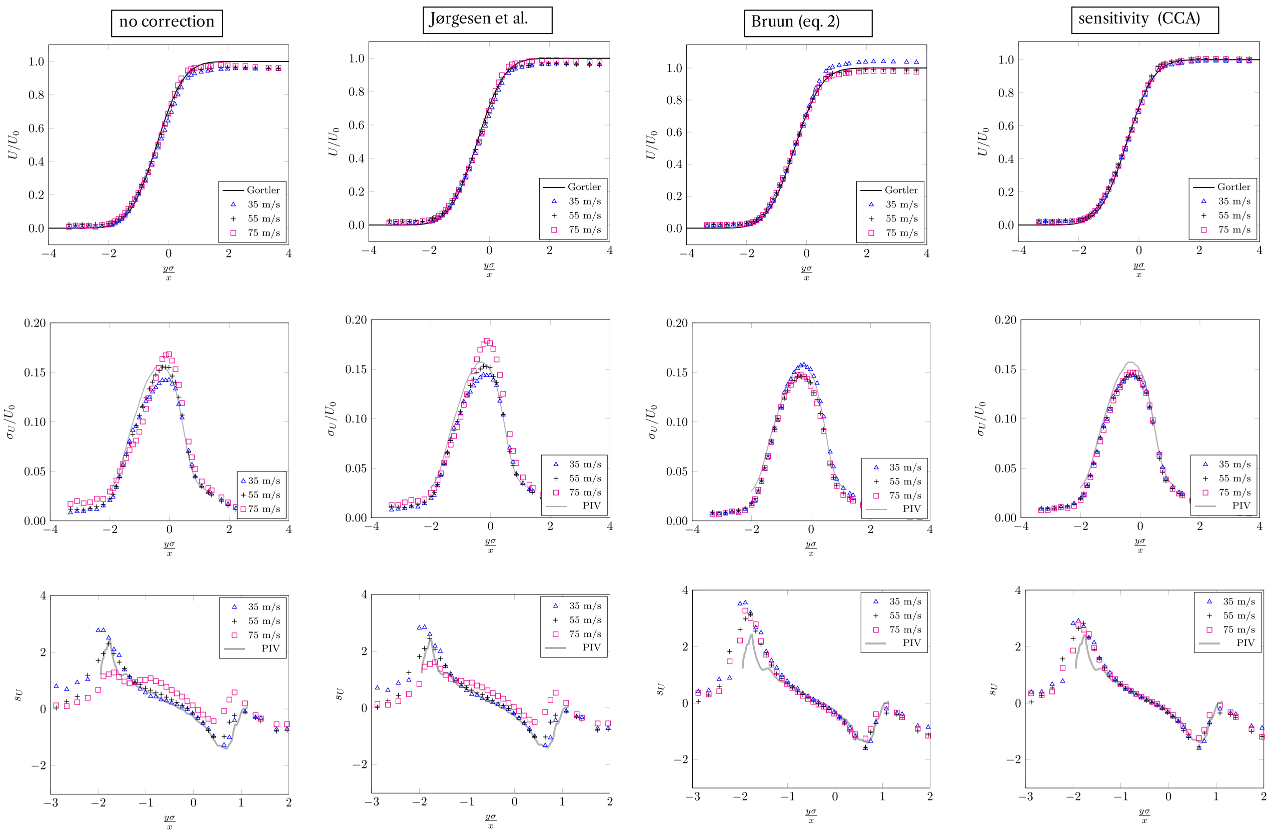

FIG. 10. Non-dimensional mean velocity U/U_0, standard deviation σ_U/U_0, and skewness profiles. Effect of the free-stream condition U_0. Reference value of U_0 is used to normalize the profiles.

VI. SUMMARY AND CONCLUDING REMARKS

We proposed a method to correct the hot wire temperature slow and fast drift for turbulence measurements with moderate to large temperature gradients, where the temperature varies as a function of the velocity and turbulent field. The method is based on the sensitivity of the hot wire to the temperature, which can be decoupled from the effect of the velocity and easily measured in the same facility of the experiment. The method is tested on a turbulent shear layer where the temperature gradient can reach values higher than 20 ° C. The sensitivity correction is applied instantaneously on the hot wire voltage by relying

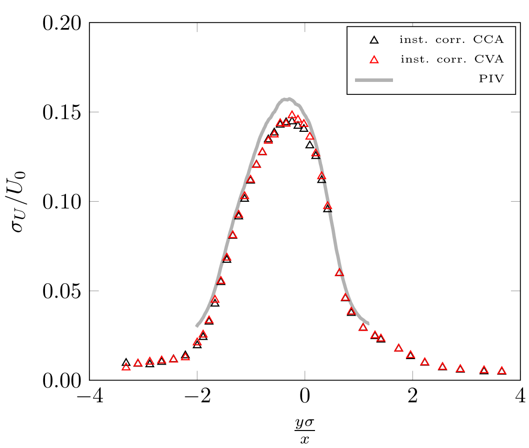

FIG. 11. Standard deviation of the streamwise velocity, comparison between CVA and CCA and PIV results as reference, $x = 0.5$ m and $U_0 = 55$ m/s.

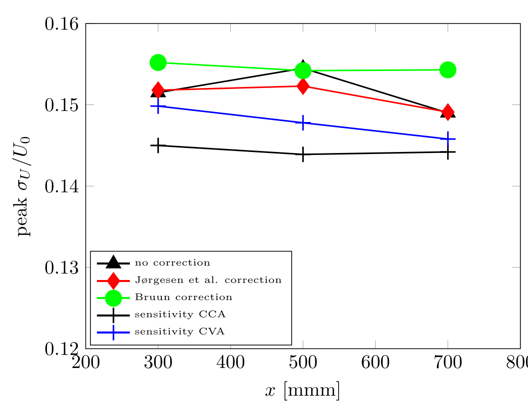

FIG. 12. Streamwise evolution of the peak of σ_U/U_0 at 55 m/s, different corrections methods.

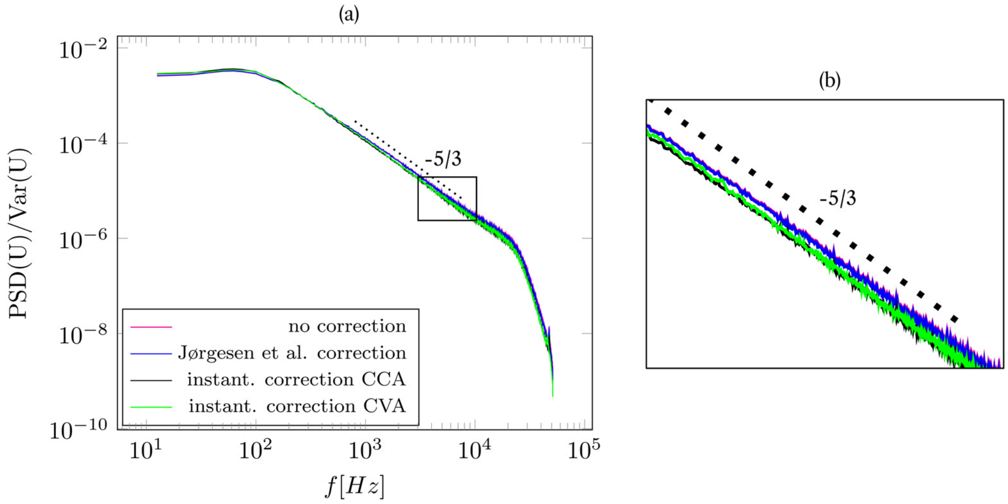

FIG. 13. (a) Velocity spectra at 55 m/s taken in correspondence with the σ_U peak, effect of the sensitivity correction, (b) focus on the inertial range.

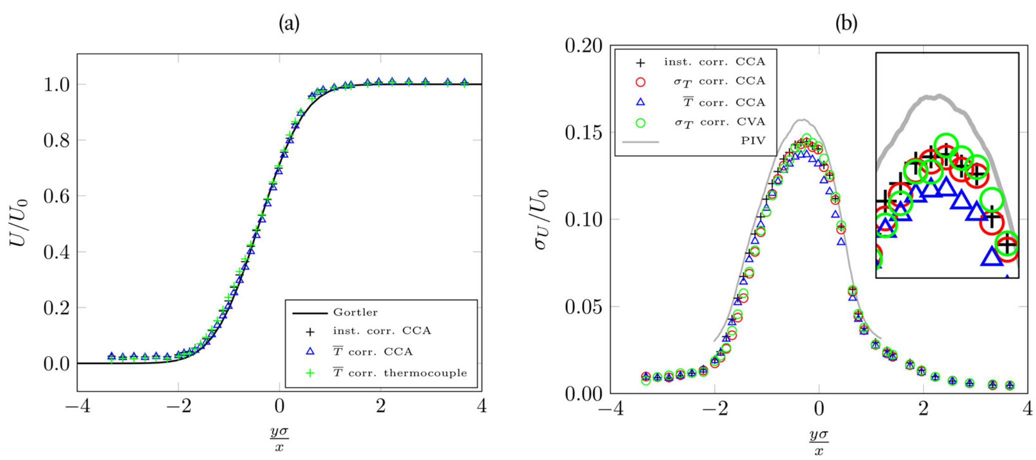

FIG. 14. (a) Mean and (b) standard deviation streamwise velocity profiles, comparison between instantaneous correction and correction using the statistics of temperature profiles.

on synchronized measurements with CVA and CCA cold wires. The results obtained by applying the sensitivity correction appear to slightly improve the evaluation of the mean velocity with respect to the method proposed by Bruun[2] and outperform the correction method by Jørgensen,[10] and the results without correction show an excellent evaluation of the streamwise velocity statistics and self-similarity of the shear layer. The results without the sensitivity correction 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 up to the third order can be evidenced with a close match with the PIV reference results.

A correction based on just the first and second order statistics of the temperature field is proposed and it is shown to correct as accurate as the instantaneous correction the mean and standard deviation of the velocity field.

Further work should be conducted on the development of a formulation to link the higher order velocity statistics to the high order temperature statistics. In addition, a similar derivation should be validated for more complex cases as cross-wires, which are better suited to survey turbulent shear layer as they provide two velocity components.[14] Finally, focus should be given to testing the sensitivity method formalized in this paper on other canonical setups as turbulent boundary layer and on a heated turbulent boundary layer.

ACKNOWLEDGMENTS

The present study is part of the program MAMBO "Méthodes avancées pour la modélisation du bruit moteur et avion" (Advanced methods for engine and aicraft noise modeling), coordinated by

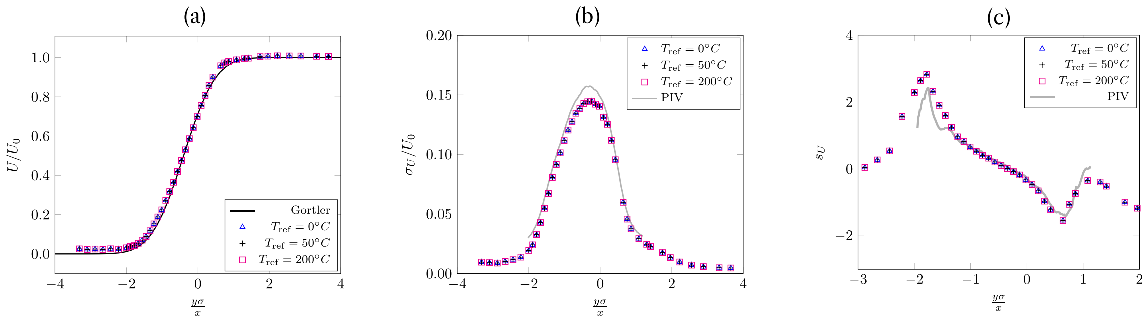

FIG. 15. Non-dimensional mean velocity U/U_0 (a), standard deviation σ_U/U_0 (b), and skewness (c) profiles. Effect of the reference temperature T_{ref}, profiles taken at $x = 0.5$ m, $U_0 = 55$ m/s.

Airbus SAS. This work was supported by the Direction Générale de l'Aviation Civile (DGAC) (Grant No. 2021-50). This work was performed within the framework of the Labex CeLyA of the Université de Lyon, within the program Investissements d'Avenir (ANR-10-LABX-0060/ANR-16-IDEX-0005) operated by the French National Research Agency.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Francesco Scarano: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Validation (equal); Writing – original draft (lead); Writing – review & editing (lead). **Emmanuel Jondeau:** Conceptualization (supporting); Data curation (supporting); Formal analysis (supporting); Validation (supporting); Visualization (supporting). **Edouard Salze:** Funding acquisition (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

APPENDIX

Effect of the reference temperature, T_{ref} on the non dimensional mean velocity U/U_0 (a), standard deviation σ_U/U_0 (b), and skewness (c) profiles.

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