Coupled temperature and velocity measurements in turbulent natural convection flows.

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Abstract. The goal of this paper is to develop simultaneous measurements of the temperature and velocity in order to contribute to the development of models adapted to natural convection flows and better apprehend their turbulent characteristics. The experimental setup consists in a vertical open channel whose sidewalls are kept at ambient temperature. A heated square bar is placed into the lower part of this channel close from one of its wall. It drives air in the whole channel. The temperature of the bar is chosen to obtain a turbulent air flow. This study focuses on the measurement technique developed to realize synchronized temperature and velocity measurements in a turbulent natural convection flow. This technique permit to measure turbulent heat fluxes (<u'T'> or <v'T'>). Measurement strategies will be presented and discussed in the paper. Some experimental care is needed to avoid disturbing the airflow. The challenge is to choose two complementary measurement techniques which have to be synchronized but which cannot be carried out at the same location when a laser is used. In this study, the velocity and the temperature measurements are respectively carried out using PIV technique and a specific K type micro-thermocouple (12.7 µm in diameter). The location of the thermocouple with respect to the laser sheet has been investigated as well as the influence of the laser on the temperature measurements. The criterion used for finding the best location is the correlation coefficient between the temperature and the velocity data. Some preliminary results of coupled velocity-temperature measurements are provided showing the feasibility of this kind of measurements.

1. Introduction

Natural convection flow plays an important role in processes occurring in our environment, in industrial and safety applications, and in many other areas. Such flows are mainly turbulent, and turbulence significantly contributes to the transport of momentum and heat. Patterns are linked to the inherent coupling between the velocity and temperature fields. This coupling appears in the transport equations by means of additional turbulent heat flux (<u'T'> or <v'T'>). To measure such quantities, we developed a measurement technique that allows completing simultaneous measures of temperature and velocity in a specific location. Simultaneous measurements of temperature and velocity are quite difficult, especially in turbulent natural convection due to its sensibility to perturbations.

Only a few studies have been focused on this topic and mainly for periodic turbulent forced flows where simultaneous measurements are not necessary [1]. In 1994, Tholet and Bogard [2] considered the simultaneous temperature and velocity measurements in order to determine turbulent heat fluxes.
and temperature-velocity correlation coefficients. Their method used a two components Laser Doppler Velocimetry (LDV) system for the velocity measurement and a 0.64 µm cold-wire for the temperature measurements. They positioned the cold wire 0.3mm away from the LDV volume probe, in the heated turbulent boundary layers with a free stream velocity of 8 m.s\(^{-1}\). Wardana [3] investigates in 1995 the velocity-temperature correlation in a strongly heated channel flow using the LDV technique and a resistance thermometer. Later, in 1999, Pietri [4] performed simultaneous measurements of two velocity components and temperature in a slightly heated jet, combining a 0.63 µm cold wire and Laser Doppler Anemometer (LDA) technique. More recently, Felis [5] performed simultaneous temperature and velocity measurements, using the LDA technique and a K type thermocouple having a diameter of 25 µm. They used this technique in a double stream-jet air curtain for heat confinement in case of tunnel fire. Hu [6] tried to develop simultaneous velocity and temperature measurements in the wake of a heated cylinder using a novel optical diagnostic technique, namely the Molecular Tagging Velocimetry and Thermometry (MTV&T). Nevertheless, their experiment was conducted in a water channel. For turbulent natural convection flows, no such measurements have been found so far in literature.

The metrology chosen in this study is based on both the PIV and micro-thermocouple thermometry. Velocity measurement by PIV has been chosen for its constant and imposed data rate. Measurements are carried out in a vertical channel where a solid bar is heated, inducing a turbulent natural convection flow in this channel. The experimental setup, the methodology as well as the first results obtained in such a configuration are presented thereafter.

2. Experimental setup and methodology

2.1. Experimental setup overview

The bench system used in this study is a vertical open channel of 60 cm in height (H), 12 cm in width (d) and 30.5 cm in depth (l). The lateral channel walls are 5mm-thick iron plates and are considered as isothermal and at ambient temperature. The front and rear walls are made of Plexiglas® to allow PIV measurement. A horizontal square bar made of aluminum is located on the lower part of the channel. This heated square bar has a square section of 4 cm. The center of this bar is located at 13 cm from the inlet in the vertical direction and 3 cm from the wall in the horizontal direction. It is maintained at imposed temperature using a cartridge heater. The working fluid is the air. Two vertical slots (5 mm in width) made of Plexiglas® at mid-depth of the channel allow the laser sheet passage. Figure 1 shows a schematic diagram of the experimental setup as well as the location of the bar and the coordinate system used in this study.

![Figure 1. Working bench system: (a) full design (b) schematic diagram](image-url)
To avoid environmental perturbations, the channel is located in a dedicated room having two vertical walls of glass.

2.2. **Metrology used**

The temperature of the square heated bar and of the channel wall were measured with 50 µm K-type thermocouples connected to an Agilent 34972A data acquisition switch unit with integrated cold junction (±1°C accuracy). The ambient temperature was measured on the same acquisition unit by a 100 µm T-type thermocouple. The heating process of the solid bar was controlled with an EA-PS 8360-15 power supply. Due to high conductivity of aluminum, the bar remains isothermal.

The air temperature in the channel was measured by a thermocouple especially designed and mounted on a 3D traverse system computer-controlled. The cold junction was maintained at known reference temperature into a thermo regulated bath and an additional 4-wire PT100 probe measures temperature of the bath. The geometry and the dimensions of the, micro-thermocouple were chosen not to disturb the flow and to respond accurately to the temperature signals. This probe (Figure 2.a) is constituted by a 12.7 µm type K thermocouple connected at two 20 mm long pins (one in alumel and the other one in chromel). These pins are 100 µm in diameter. Moreover, to minimize the decrease in sensitivity and frequency response due to heat conduction along the wire, the length-to-diameter ratio of the sensor has to be set above 200 [7]. The thermocouple probe described here was used to measure the air temperature in turbulent natural flow that has a maximum velocity of about 35 cm/s. In agreement with the dimensions of the thermocouple, it implies (from [7]) a sensor time constant of about 1.6 ms and an attenuation factor equal to 7% for measurements at 25 Hz. This probe was used for averaged measurements over an integration time of 0.1 NPLC (Number of Power Line Cycles) meaning 2 ms; its frequency response is well adapted to the required application. For the air temperature, the previously described micro-thermocouple is connected to a NI 4071 DMM mounted on a NI PXI 1031 real time chassis. The acquisition is made with the ±100 mV range allowing 6-½ digits resolution measurements up to 100 Hz. Thus, it implies a temperature resolution of 0.025°C±0.01°C.

![Thermocouple probe](image1.png)

**Figure 2.** Thermocouple probe (a) and experimental setup under PIV measurements (b).

Velocity measurements were performed with the PIV technique using a 100Hz double-pulsed laser (Nd-YAG). The laser sheet passes through the 5mm-thick glass window at mid-depth of the lateral walls (see Figure 2 (b) ) and generates a light sheet of about 1.5 mm in thickness. The air is seeded with 1-5 µm oil particles produced by a Laskin generator at ambient temperature using Shell Ondina Oil. The PIV measurements are carried out at 25 Hz using a Dantec SpeedSense 9040 CCD video camera with a dynamic resolution of 8 bits/pix. The CCD camera was placed perpendicularly to the laser sheet and is equipped with a Nikkor lens having a 60 mm focal length and a 2.8 maximum aperture. The images are recorded with a 1632x1200 pixels resolution. The local particle-image
displacement was determined using an algorithm based on cross correlation with a 32×32 pixels interrogation window. The field of view is adjusted in order to make the time interval between the two lasers pulses equal to integration time used in the temperature measurement (i.e. 2 ms). The real dimensions of the PIV images in the XY-plane are, in our case, 108.3×79.7 mm². Statistical analysis is finally performed by averaging 3197 fields of velocity vectors.

The temperature measurements of the heating bar, the ambient temperature and the channel wall are triggered by the first PIV acquisition. They are acquired by the Agilent 34972A unit during the whole duration of the PIV measurements with an acquisition rate of 1 Hz.

2.3. Measurements synchronization
To achieve simultaneous real time measurements, temperature and velocity measurements are synchronized using a BNC 575 pulse/delay generator. The pulse/delay generator is initially used to control the PIV signals via Dantec DynamicStudio software. An additional output is then programmed on the BNC 575 to synchronize and trigger the temperature measurements on the first laser pulse.

2.4. Experimental precautions
Due to the metrology employed, temperature and velocity measurements cannot be carried out at the same location since the laser sheet would disturb the measured temperature. The main query in using temperature and PIV measurements is how close the thermocouple and the PIV laser sheet could be placed. To ensure that the laser sheet does not heat the thermocouple, we have analysed the influence of the distance between the laser sheet and the thermocouple in the Z-axis temperature profile. The Figure 3 plots a dimensionless temperature profile when the square heated bar is not powered on. The 0-position corresponds to the point where the thermocouple reaches the maximum temperature elevation. In order to study the laser influence on the thermocouple response, the mean temperature profile along the Z-axis was carried out using 15000 temperature measurements at 500 Hz. This frequency was used in favour of extensive spectral analysis.

In Figure 3, it can be seen that in the region at mid-depth, corresponding to $Z^*=z/l \in [-0.005;0.005]$ (i.e. $z \in [-1.5 \text{ mm}, 1.5 \text{ mm}]$), around the PIV laser sheet, the temperature measured by the thermocouple increases (up to 1.4°C) because of the PIV laser sheet energy. The temperature measurements in this area cannot be carried out. So, for simultaneous temperature and PIV velocity measurements, the thermocouple is located at $Z^*=z/l= 0.003$ (i.e. $z \approx -0.9 \text{ mm}$) from the 0-position previously defined. This position is considered as the closest distance where the laser sheet does not disturb the temperature measurements. In addition, at this location, see figure 4, the intrusive temperature measurement does not disturb airflow in the channel (see for instance the streamlines in the close view of the thermocouple).

The second important point is the choice of the velocity vector to be used for evaluating the dimensionless turbulent heat fluxes ($<U'T'>*$ or $<V'T'>*$). Indeed, the PIV provides instantaneous velocities. This choice could be guided by the correlation coefficient between velocity and temperature signals. In our case, for each position of the thermocouple in the x-direction, 3197 synchronized velocity (i.e. 6394 images, maximum number of images allowed by the camera capacity storage) and temperature measurements have been carried out at 25 Hz. The measurement time for each location
was enough to obtain converged statistical quantities; for instance, in the plume, relative differences between mean and RMS quantities for a measurement time of 128s and 600s are lower than 3%.

For velocity calculations a cross-correlation analysis is used. In that case, the velocity vector with the maximum correlation coefficient related to the temperature measurements was searched in the area of the thermocouple welding. Results in terms of correlation coefficients or temporal signals (temperature and velocity) will be provided thereafter.

3. Dimensionless results and discussion
Results presented in this paper are obtained by coupled temperature and velocity measurements for a channel including a heated square bar maintained at about $T_b=87.6$ °C (Figure 4). The temperature measurements take place 220 mm upward from the bottom inlet of the channel (i.e. $Y*=y/d=1.83$, $d$ the channel width). The ambient temperature is about $T_{amb}=21.2$°C. It implies a Rayleigh number based on the height $H$ of the channel about $Ra_H = \frac{\rho_C \Delta T H^3}{\nu} = 1.15 \times 10^9$ and a reference velocity $V_{ref} = \frac{\alpha}{H} Ra_H^{1/2} = 1.54$ m/s. Note that other definitions of the reference Rayleigh number may be found in literature [8], but using one or the other has no impact on the conclusions of this paper. This channel is driven by a turbulent natural convective flow and measurements are carried once the heated bar achieves a steady regime, i.e. about 4h after it was powered on. Note that all the results presented thereafter are dimensionless: velocities are scaled using $V_{ref}$ and temperature by using $T_{amb}$ and $\Delta T=T_b - T_{amb}$.

\begin{align*}
Ra_H &= 1.15 \times 10^9, \quad V_{ref}=1.54 \text{ m/s} \\
T* &= \frac{T - T_{amb}}{\Delta T} \\
U* &= \frac{U}{V_{ref}} \\
V* &= \frac{V}{V_{ref}} \\
U_{rms}* &= \frac{U_{rms}}{V_{ref}} \\
V_{rms}* &= \frac{V_{rms}}{V_{ref}} \\
T_{rms}* &= \frac{T_{rms}}{\Delta T} \\
X* &= x/d \\
Y* &= y/d \\
Z* &= 0
\end{align*}

**Figure 4.** (a) Contour map and streamlines for the dimensionless vertical component ($V*$) of the mean velocity without thermocouple. Close view of the flow around the thermocouple (in the top right corner); (b) dimensionless mean profiles for the temperature ($T*$) and for horizontal ($U*$) and vertical ($V*$) velocity components (c) dimensionless temperature RMS fluctuations ($T_{rms}$), horizontal and vertical velocities RMS fluctuations ($U_{rms}$, $V_{rms}$). $Y*=1.83$ and $Z*=0$. ♦ coupled measurements, ■ non-coupled measurements.
Figure 4 (a) shows the dimensionless contour map of the vertical component (V*) of the velocity on the X,Y-plane and streamlines for the entire channel design with a zoom on the thermal probe zone. In figure 4 (a) it can be seen that the thermocouple does not perturb the fluid flow since the streamlines are not deviated around the thermocouple, excepted close to the pin where velocity cannot be correctly measured due to image saturation. Figure 4 (b) shows the distribution in the X-direction of the dimensionless profiles for the vertical (V*=<V>/V_{ref}) and horizontal (U*=<U>/V_{ref}) components of the velocity as well as the profiles of the dimensionless temperature (T* = (T_{air} - T_{amb})/ΔT) at Y* = y/d= 1.83. Figure 4 (b) shows that the mean temperature agrees closely with the distribution of the mean velocity. The mean temperature and the vertical mean velocity have always positive values: they both increase up to a maximum value located in the plume at X*=x/d≈0.15 and then they decrease until reaching a low value outside the plume. The horizontal mean velocity has always negative values. It decreases down to a minimum located in the plume at X*=0.15 and then grows to reach zero outside the plume. The position of the heating bar, close to the left side wall, induces an aspiration of the plume to the wall (Coanda effect between the plume and the wall). Note that, the RMS temperature profile presents a little perturbation close to the maximum at X*=0.15. Figure 4 (c) shows the profiles in the X-direction of the velocity and the temperature RMS fluctuation at Y* = y/d= 1.83. The same trend is also observed on the dimensionless RMS fluctuations of the horizontal velocity component U*_{RMS} but not on the dimensionless RMS fluctuations of the vertical velocity component V*_{RMS} (cf. Figure 4 (c)). This perturbation is due to the wake of the heated bar and cannot be attributed to a default in the coupled measurement method.

In the figure 4 (b) and (c), lines in mean and RMS velocity profile correspond to velocity profiles carried out without temperature probe. Notice, once again, that the probe does not disturb the airflow in the laser sheet plane.

| Table 1. Dimensionless mean and RMS temperature and velocity data at Y*=1.83 and their respective correlation coefficients. |
|---|---|---|---|---|---|---|
| X*=x/d | T* / T_{rms} | U* / U_{rms} | V* / V_{rms} | R_{TV} | R_{TU} | R_{UV} |
| 0.063 | 0.048 / 0.027 | -0.003 / 0.005 | 0.033 / 0.021 | 0.912 | -0.787 | -0.697 |
| 0.081 | 0.111 / 0.060 | -0.011 / 0.010 | 0.076 / 0.039 | 0.926 | -0.790 | -0.857 |
| 0.109 | 0.109 / 0.053 | -0.012 / 0.012 | 0.084 / 0.036 | 0.876 | -0.657 | -0.580 |
| 0.127 | 0.134 / 0.052 | -0.016 / 0.013 | 0.096 / 0.036 | 0.827 | -0.661 | -0.517 |
| 0.155 | 0.171 / 0.052 | -0.019 / 0.015 | 0.125 / 0.037 | 0.751 | -0.433 | -0.467 |
| 0.211 | 0.178 / 0.074 | -0.018 / 0.011 | 0.134 / 0.060 | 0.814 | -0.211 | -0.261 |
| 0.248 | 0.127 / 0.079 | -0.016 / 0.008 | 0.110 / 0.057 | 0.912 | 0.020 | -0.085 |
| 0.266 | 0.074 / 0.061 | -0.013 / 0.006 | 0.079 / 0.052 | 0.918 | -0.127 | -0.172 |
| 0.285 | 0.036 / 0.022 | -0.012 / 0.006 | 0.053 / 0.031 | 0.882 | 0.054 | 0.029 |
| 0.322 | 0.024 / 0.014 | -0.010 / 0.005 | 0.048 / 0.025 | 0.821 | 0.103 | 0.108 |
| 0.340 | 0.022 / 0.010 | -0.010 / 0.006 | 0.048 / 0.022 | 0.726 | 0.198 | 0.106 |
| 0.396 | 0.018 / 0.004 | -0.010 / 0.004 | 0.043 / 0.011 | 0.564 | 0.159 | 0.053 |
| 0.544 | 0.017 / 0.001 | -0.010 / 0.005 | 0.031 / 0.012 | -0.442 | -0.121 | 0.227 |
| 0.747 | 0.017 / 0.001 | -0.006 / 0.005 | 0.033 / 0.011 | -0.335 | -0.194 | 0.006 |

Table 1 gathers the mean and RMS dimensionless data of measured quantities at different locations as well as the corresponding correlation coefficients $R_{AB}$ ($R_{AB} = \frac{\sum(A-\overline{A})(B-\overline{B})}{(\sum(A-\overline{A})^2)^{1/2} \cdot (\sum(B-\overline{B})^2)^{1/2}}$) that define the degree of similarity between two the signals A and B.
The temperature–vertical velocity coefficients, $R_{TV}$, reach high values in the plume (up to 0.926) where natural convection effects are important implying a strong coupling between temperature and velocity. Outside of the plume where the velocity is close to zero, this correlation coefficients decrease since this area is less affected by natural convection: the coupling between temperature and velocity is weaker, the mean values are almost null and the measurements are more sensitive to noise (see RMS values in table 1) and external perturbations what explains this decrease in term of correlation coefficient.

To illustrate the similarity between the temperature and velocity profile, Figure 5 plots instantaneous values of temperature and vertical velocity at $X^*=x/d=0.266$. The correlation coefficient between these two signals for the whole acquired signals (i.e. 127.88 s) is in this case $R_{TV}=0.918$ (cf. table 1).

The synchronized temperature and velocity measurements lead to the estimation of the dimensionless Reynolds stress ($<U'V'^*>$) and dimensionless turbulent heat fluxes ($<U'T'^*>$, $<V'T'^*>$) at $Y^*=1.83$, plotted in Figure 6.

The vertical turbulent heat flux displays two relevant peaks. The largest one coincides with the maximum of mean velocity and the other one occurs between the left wall and the first peak. This is due to the wake of the heated bar which disturbs the flow upstream. As previously, the horizontal turbulent heat flux ($<U'T'^*>$), and the Reynolds stresses ($<U'V'^*>$) are only slightly influenced by the wake at the same location. It is not so surprising in this case that ($<U'V'^*>$) and ($<U'T'^*>$) were quite similar since $V$ and $T$ instantaneous profiles are almost identical. Thereafter, a turbulent Prandtl number can be estimated close to 1. Future works are envisaged to complete extensive study concerning this geometry and turbulent Prandtl number.
4. Conclusion
This paper presents the development of coupled simultaneous measurements of temperature and velocity in order to contribute to the development of turbulence models adapted to natural convection flows. The velocity measurements are carried out using PIV technique synchronized with the temperature measurements using a specific type K micro-thermocouple (12.7 µm in diameter). The coupled measurements are performed in an open vertical channel, with vertical walls maintained at constant temperature equal to the ambient temperature, and heated by a square bar placed into the channel. In the first step, the correct distance between the thermocouple and the laser sheet for PIV has been identified in order not to perturb the temperature measurements. Then, coupled temperature and velocity measurements have been carried out at Y*=1.83, slightly above the heated bar.

Experimental data reveal good correlation coefficients between the temperature and velocity fields. As expected, the maximum correlation is encountered within the plume above the heated bar. From these measurements, calculations of the dimensionless Reynolds stress (\(\langle U'V' \rangle\)) and of the turbulent heat flux (\(\langle U'T' \rangle, \langle V'T' \rangle\)) have been performed and are displayed in terms of profiles in the x direction for Y* = y/d = 1.83.

Other temperature and velocity coupled measurements are planned to investigate other elevations in channel. Then, this measurements technique will be applied to cavity flows in order to construct an experimental database required to validate more accurate turbulence models for natural convection flows.

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