Transient velocity-temperature correlation in the near-wall region of lazy plume over horizontal surface

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Abstract: The subject of this work is to investigate the thermal and the momentum boundary layer in the near-wall region of plumes above horizontal surfaces by measurements. The problem is to get the information of the temperature and the velocity field simultaneously with identical spatial resolution and at the same time steps. A solution is presented employing a background-orientated-schlieren-method (BOS) and particle-image-velocimetry (PIV). Using BOS-method leads to gradient field of the refractive index regarding to the temperature gradient field. In this article different methods for calculating the scalar field of the temperature as well as the measurement method in combination with PIV are presented. As an example the boundary layer around a single hot wire with a temperature 5 to 10 K above the surrounding is investigated.

1. Introduction

The subject of this work is to investigate the thermal and the momentum boundary layer in the near-wall region of plumes above horizontal surfaces. The problem is to get the information of the temperature and the velocity field simultaneously with identical spatial resolution. A solution is presented employing a background-orientated-schlieren-method (BOS) and particle-image-velocimetry (PIV). The temperature of the hot-wire ranges between 5 K and 10 K above the environment.

The velocity information is taken by a 2d2c-PIV-system with a temporal resolution of 10 Hz. This is sufficient for a transient measurement in convective problems as frequencies of the plume are below 1 Hz. For temperature measurement the background-orientated-schlieren-method is established. The main principle of this method is a line-sight-sight technique. All temperature gradients between camera and a choosen background affect the results. This technique was introduced by Meier (2002). The temperature calculation can be done by resolving the measured displacement of the background.

Two different approaches are presented:
a. Using path integrals

2. Experimental Setup

Figure 1 shows the schematically drawing of the choosen experimental setup. Velocity and temperature are observed by two different cameras. Camera 1 is focused on an appropriate background. The background contains a stochastic pattern fitting the needs of the spatial resolution.

Camera 2 is focused on a light sheet provided by a laser with 532 nm wave length. The light sheet is positioned above the hot wire. The field depths of both cameras and their optical equipment allow the acquisition of the signals separately. Advantageously the light sheet is taken for the illumination of the background for temperature measurements by a diffuse mirror. For a better determination of the stochastic background the wave length of background necessarily differs from 532 nm for the velocity measurement. To achieve this difference in the wave lengths a fluorescence technique is utilized. The fluorescent background shifts the wave length from 532 nm to 590 nm for example.

Applying different optical filters the signals are separated from each other, calculated and afterwards combined for comparison of both information.
By using this method the temporal correlation between the temperature field and the velocity field is shown. The experimental setup can be seen in figure 1.

For observing the same field with both cameras, a beam splitter is used to bring both optical axes in coincidence. The alignment of these cameras is shown in figure 2 a.). Both cameras have a spatial resolution of 1600 x 1200 px. The observed area has a dimension of 45 mm x 34 mm. The temporal resolution is 10 Hz.

In figure 2 b.) the used hot wire is presented. The hot wire is fixed between two isolated clampings at a distance of 400 mm and 70 mm above the horizontal surface at the bottom. The hot wire (0.6 mm stainless steel) is driven by a constant DC-Voltage. This setup provides a constant heat transfer of 8 W from the hot wire to the surrounding resulting in convection as shown in figure 3 b.).
3. Temperature calculation - Scalar field from gradient field

As the measurement of the velocity field is done with a commercial system provided by DantecDynamics (DynamicStudio). The temperature measurement and calculation afterwards shall be described more in detail.

The determination of the temperature is done with a background schlieren method (BOS). Figure 4 shows the change of the optical axis, when a medium with a gradient of the refractive index is in the optical axis.

\[
\varepsilon_x = \int \frac{1}{n} \frac{\partial n}{\partial x} \, dz
\]

The displacement of the background and the change of the refractive index \( n \) in the medium according to Pedrotti et al. 1996 and Raffel et al. 2007 have following formal context.

A gradient in the x direction results in a distortion of the background in the x-direction. The same applies for the gradient in the y-direction. Gradients in the optical axis \( z \) have no influence on a distortion.
The shift of the background can be determined photometrically. As it can be seen from the equation (1) further, the integration of all gradients normal to the viewing direction leads to the total displacement or distortion of the background. The detection of different indices of refraction in the z-direction is not possible with this method shown.

As it can be seen out of figure 4 the total displacement angle $\epsilon_x$ can be calculated point wise with the measured displacement using equation (2)

$$\epsilon_x = \tan \frac{\Delta P_x}{z_D} \approx \frac{\Delta P_x}{z_D}$$

The simplification for small angles is used for further calculations.

For the calculation of the displacement of background between the disturbed and undisturbed pattern the algorithm provided by DynamicStudio is used.

Combining (1) and (2) leads to (4) where $\frac{\partial n}{\partial x}$ is unknown. It is said that for small changes the refractive index is constant with $n_0$.

$$\frac{\Delta P_x}{z_D} = \int \frac{1}{n} \frac{\partial n}{\partial x} dz = \frac{1}{n_0} \frac{\partial n}{\partial x} z_N$$

$$\frac{\partial n}{\partial x} = \frac{n_0}{z_N z_D} \frac{\Delta P_x}{z_D}$$

As the condition of integrability (5) is fulfilled the scalar field of $n$ can be calculated with equation (6)

$$rot \ (grad \ n) = 0$$

$$n = div \ (grad \ n)$$

Using the relation of Gladstone-Dale (7) [Gladstone 2007] and the general gas equation (8) the Temperature can be calculated with equation (9).

$$n - 1 = K p$$

$$p V = m R T$$

$$T = \frac{K p}{n-1 R}$$

Due to the experimental process with measurement irritations the condition of integrability (5) cannot be fulfilled in every case. So there are different approaches to get the needed information.

a. Using path integrals

For method a. the change of temperature distribution is calculated point wise. Starting at a known point the neighboring point is the result of gradient to this point and the distance according to a linear equation.

Method b. is a Poison-Solver as suggested by Gobbert for the use in SciLab. This solver is run until a sufficient low value $rot(n)$ is reached.

4. Results

Different ways for calculating the temperature distribution from the background displacement are presented in the following figures. The measured background displacement is indicated in the figure 5. Here the magnitude of the displacement is indicated by a color ranging from red-grey-blue for a single shot of the
time depending flow field. The velocity is shown as stream line indicated by a colorbar on the right side of the picture. For further examination this flow field is shown as a vector with respect to a better indication of the temperature field.

Fig. 5 Calculated background distortion and stream lines. The background distortion is shown in colors from blue to red by the magnitude of the distortion.

In figure 6 the result using a line path integral method is shown. This method calculates the first column (x=1) and starting from this, every row is calculated from left to right. On the right side the results of two cut-troughs in different height (150 px and 300 px) are shown.

Fig. 6 Calculated temperature field and velocity vectors with line integral methods. The diagram in the right shows the cuts for the height of 150 px and 300 px (indicated by crossmarks)

Using a Poisson-Solver as described in Gobbert et al (2005) has advantages in preventing errors and calculation speed. Figure 7 shows the result of such an algorithm. For this algorithm a Dirichlet-boundary condition has been choosen.
In relation to the line-integral method it can clearly be seen that the calculation noise can successfully be reduced. On the opposite side the results are strongly influenced by the boundary condition. Especially at the starting point of the convection plume both calculated temperature fields are different.

By taking method A noisy values are leading to noisy results in the direction of line-integral. In method B the selected boundary condition leads to errors in the temperature field because of forced smooth changes just right to the boundary itself.

5. Summary and Conclusions
In this article a method has been presented to get the temperature field and the velocity field of a boundary around a hot wire. Two different methods have been used. The measurement of the velocity is done by Particle-Image-Velocity (PIV). For temperature detection the Background-Oriented-Schlieren-Method (BOS) has been used. Both information (velocity and temperature) are measured at the same time and the same spatial resolution. For the reduction of the mutually influencing of both signals a frequency shifting method using fluorescence has been successfully used.

As the velocity calculation has been done using a commercial code the calculation of the temperature field has been examined more in detail. A method using line path integrals shows the strong dependency of the result from very noise-less signals.

The application of methods using Poison-Solvers allows the reduction of noise by simple algorithms and has a short calculation time. Nevertheless, the result of this method is strongly depending on the selected boundary conditions for the calculation.

4. References


