EXPERIMENTAL MEASUREMENTS OF TURBULENT PROPERTIES IN A BOUNDARY LAYER WITH BLOWING

Françoise Bataille, Jean-Claude Rodet, André Lallemand
Centre de Thermique de Lyon, INSA,
20, avenue Albert Einstein, 69621 Villeurbanne Cedex, France

ABSTRACT

Simultaneous measurements of temperature and velocity in a bi-dimensional turbulent boundary layer of a hot flow above a porous plate, and submitted to blowing, are performed. Two different probes, a hot wire X-array and a cold wire are used. A new combined velocity and temperature calibration process, for the hot wire probe, has been developed and validated. The mean part and the fluctuating part of the two velocity components and of the temperature are determined when they are submitted to blowing.

NOMENCLATURE

a	overheating ratio
c	specific heat at constant pressure
d	diameter
E	voltage
F	injection rate $F = \frac{(\rho V)_{inj}}{(\rho U)_e}$
k	thermal conductivity
Nu	Nusselt number

$S_x = \left(\overline{u^2}\right)^{1/2}$

$S_y = \left(\overline{v^2}\right)^{1/2}$

$S_t = \left(\overline{t^2}\right)^{1/2}$

T	temperature
t	temperature fluctuation
U	longitudinal mean velocity
u	longitudinal fluctuation velocity
V	vertical mean velocity
v	vertical fluctuation velocity
α	temperature coefficient
ρ	density
τ	cold wire time constant

Subscripts:

e	main potential flow
f	fluid
N	normal to the wire direction
u	hot wire bridge output
θ	cold wire bridge output
w	wire
inj	injected or secondary flow

INTRODUCTION

The blowing is used to protect a solid wall from the detrimental effect of a hot fluid, usually a hot gas (main flow). The wall consists of a porous material and a coolant (secondary flow) is moving through the pores creating a cool layer on the hot gas side of the wall, protecting it.

A review of literature shows many experimental investigations (Jeromin, 1970; Moffat and Kays, 1984). Many of these studied the effect of blowing on the friction factor and on the heat transfer. Some of them focus on the influence of the main flow velocity (Moffat and Kays, 1968) and of the main flow turbulence level (Mironov et al, 1985). Baskarev et al (1977) investigated the influence of the injection rate on the heat transfer within a transition boundary layer over a porous wall. Excepting Romanenko and Kharchenko (1963), all these experimental studies have been performed with a weakly heated main flow (several tens degrees of difference between the two flows).

Despite these experimental investigations, no universal model does already exist to predict the interaction between a boundary layer over a porous wall and a secondary flow blowing off this latter. Theoretical and numerical studies have been performed to understand the behavior of the boundary layer particularly by Campolina et al (1998) and Bellettre et al (1998) and a suitable turbulence model within the blowing area would now be necessary. The experimental determination of the turbulent fluctuations of the temperature and velocity fields, and of their correlations, is useful at this stage of research.

The most commonly used technique for such a study is the multi-sensor probe, built with a cold wire located upstream of an X-configured hot wire probe (Chen and Blackwelder, 1978; Subremanian and Antonia, 1981). Blair and Bennett (1987) only used hot-wires at different overheat ratios to resolve both temperature and velocity. Because of its two main disadvantages (interference effects between the sensors and need of a temperature correction for the hot wire data), an other technique using a two-component laser Doppler anemometer (LDA) and a cold wire thermometer, has particularly been developed for measurements in a slightly heated turbulent boundary layer by Thole and Bogard (1994). This technique reveals one major inconvenient : the response of the cold wire deteriorates rather quickly because of the seeding particles which stick to the wire. Moreover, velocity measurements with the LDA become difficult even impossible, in the boundary layer, when strong blowing occurs (F > 2%) or when the main flow temperature T_e is higher than 100°C (Rodet et al 1998). Consequently, we decided to choose hot wire anemometry (HWA) for our study instead of LDA.

EXPERIMENTAL SET-UP

The measurements take place in the vicinity of a porous plate, within the test section of a heated wind tunnel, especially developed for blowing and transpiration cooling studies (figure 1). The aerodynamic and thermal features of the bi-dimensional turbulent boundary layer which is developed on the horizontal floor of this test section, in isothermal or non-isothermal conditions, with or without injection and for a given main air flow velocity (10 $m.s^{-1}$), have been determined in a previous study by Rodet et al (1998). The same configuration will be used in the present study.

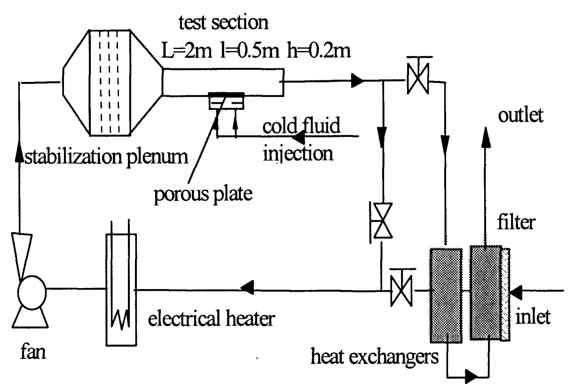

Figure 1. Experimental set-up

The test section consists of fixed pyrex side walls, and modular duralumin roof and floor. The 500 x 200 x 3 mm^3 porous plate, made of sintered-stainless-steel, 30% porosity and 30 μm average pore diameter, is flush mounted in the floor. The blowing system delivers fresh air through a 150 mm high plenum fitted under the porous plate and designed to provide an uniform blowing into it.

INSTRUMENTATION

A Pitot tube and a thermocouple movable in the test section are used to measure the mean velocity and the mean temperature in the main flow. The longitudinal and vertical instantaneous velocity components are measured in the vicinity of the porous plate, by using a hot wire anemometer equipped with a X-array probe. This probe is able to withstand temperatures as high as 300°C and has two perpendicular sensors which are made of platinum and rhodium 2.2 mm long and 10 μm thick wires. These ones are heated and kept to a constant temperature T_w, equal to 500°C, so that the overheat ratio a, given by the relationship (1) :

$$a_w = \frac{R_w - R_f}{R_f} = \alpha(T_w - T_f) \quad (1)$$

with : $\alpha = 0.0016\ K^{-1}$

is variable, according to the probe location in the boundary layer, to the potential main flow temperature T_e and to the injection rate F; for example for T_e = 250°C and F = 2% , a roughly varies within the range [0.40 ; 0.64]. The overheating and consequently the sensitivity to velocity are greater near the plate where the velocity magnitude is lower.

The instantaneous temperature is measured by a cold wire thermometer located beside the X-probe (the spacing between the two probes is approximately 30 mm) at the same longitudinal abscissa (figure 2).

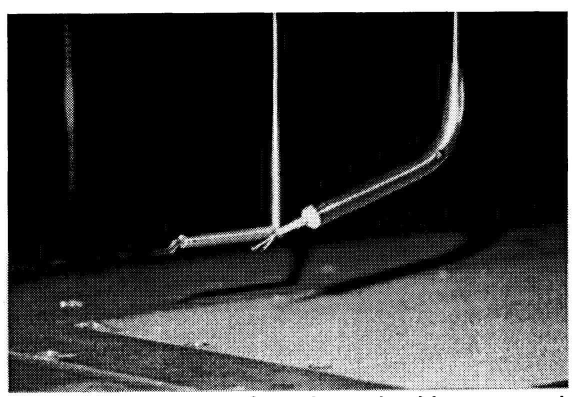

Figure 2: Picture of the hot wire X-array and cold wire probes above the porous plate

The sensor, made of a platinum-rhodium 5 mm long and 5 μm diameter wire, coated with a silver jacket is soldered to the prongs with special tin withstanding temperatures as high as 300 °C. This coating is then locally removed in the middle of the wire with nitric acid; the bare part of the wire is approximately 1 mm long. The cold wire probe resistance is about 10 Ω at ambient temperature and the constant current intensity through the wire is a little less than 1 mA. Its time constant, given by the relation (2):

$$\tau = \frac{\rho_w c_w d^2}{4 k_f Nu} \quad (2)$$

is in the range of 200-500 μs according to the main flow velocity and temperature (τ is all the higher as the flow velocity is lower and its temperature higher), so that its cut-off frequency is between 300 and 800 Hz.

PROBES CALIBRATION

The two probes are simultaneously calibrated within the test section potential flow. Because of high temperature gradients in the turbulent boundary layer and because of high sensitivity of the hot wires response with temperature, a combined velocity and temperature calibration of the X-probe over the anticipated ranges of 3-12 m/s and 25-250°C respectively, must be performed. Several velocity calibrations are carried out for both wires at a number of different fluid temperatures, and a fitting is then achieved for each wire, based on the following heat transfer relationship (3):

$$E_u^2 = A(T) + B(T)\, U_N^n \quad (3)$$

The coefficients A(T) and B(T), chosen as polynomial functions, reveal themselves to be linear functions of temperature:

A(T) = a+bT B(T) = c+dT

The non-linear fitting, achieved under the Mathematica software, uses around 35 measurement points (7 velocity points time 5 temperature points) and determines the coefficients a, b, c, d and the exponent n.

The fitting has been validated by the calculation for 63 measurement points (7 velocities points time 9 temperature points), of the residual velocity errors which are the relative error between the velocities obtained by the fitting and the actual velocities measured by the Pitot tube; these residual errors plotted on the graph of figure 3 against velocity and temperature are in the range [-3, +3 %], which is roughly equivalent to the velocity measurement accuracy by the Pitot tube.

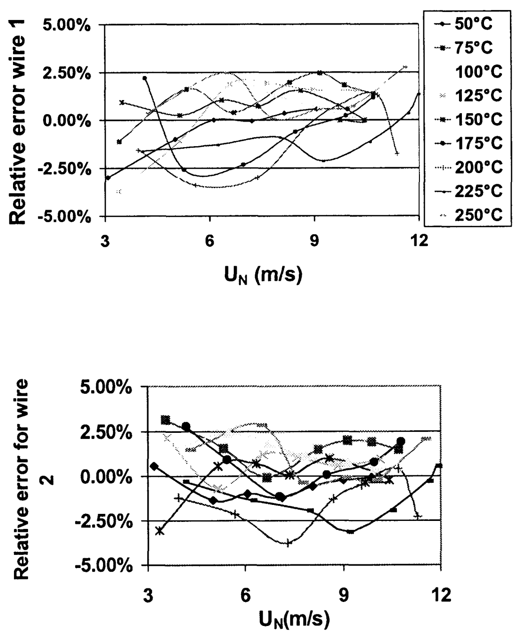

Figure 3: Residuals errors for the hot wire probe

The cold wire thermometer response, $E_\theta(T)$, in the range of 25-125°C, is a linear function of the fluid temperature; velocity contamination of the temperature signal was found to be minimal and hence no correction was made. Beyond 125°C, the response is not only no more linear, but reveals quite rapid variations; this phenomenon could be explained by the diffusion, at these temperatures, of traces of silver into the platinum wire, changing its resistivity. Therefore, only results obtained below this temperature are presented in this paper.

PROFILES MEASUREMENTS

Profiles obtained at the middle of the porous plate are presented for a main flow temperature of 75 °C and for two injection rates equal to 0.5 and 1 %. The longitudinal mean velocity profiles, the velocity fluctuations rms values, and the velocity fluctuations correlation for F=0 and F=1%, are compared with results obtained by Rodet et al (1998) using LDA. The mean velocity profiles (figure 4) match quite well but we can notice differences in figures 5, 6 and 7 for the fluctuations especially for the correlations. On the figure 4, the influence of the injection rate on the longitudinal mean velocity profile is shown. We can notice that the logarithmic law becomes little by little linear when the blowing increases and the boundary layer thickens.

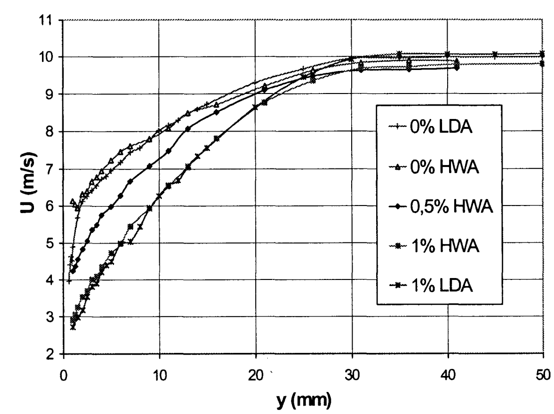

Figure 4: Longitudinal mean velocity profiles

On the figures 5, 6 and 7, it can be observed that the maximum of the fluctuations increases with the injection rate and is shifted in the opposite direction of the porous wall. Hence, the blowing increases the turbulence and moves the turbulent peak in the boundary layer. The gap between LDA and HWA measurements could be explained by the fact that the hot wire probe has a much smaller spatial resolution than this of the LDA (1.55 x 1.55 x 1 mm^3 instead of 1 x 0.1 x 0.1 mm^3); therefore, due to the mean flow gradients, an important temperature discrepancy between its prongs 1.55 mm vertically spaced, can exist, and introduce errors. The use of wires with a short active length in their middle, far away from the prongs tips, would be quite better for these measurements.

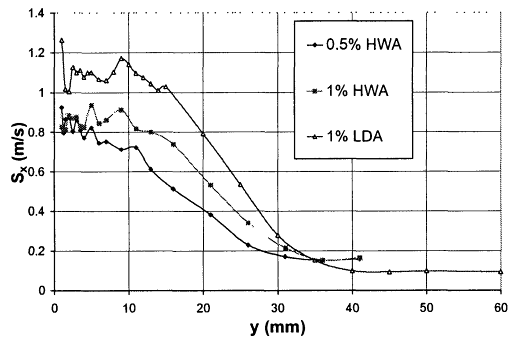

Figure 5: Longitudinal velocity fluctuations rms profiles

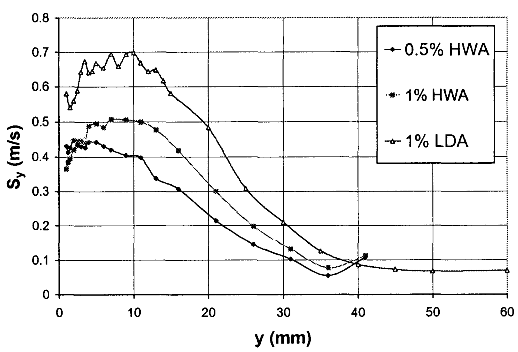

Figure 6: Vertical velocity fluctuations rms profiles

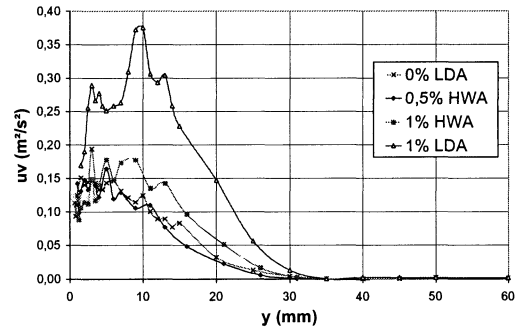

Figure 7: Velocity fluctuations correlation profiles

Figure 8 presents the mean and the temperature fluctuations rms profiles. The same trend as for the mean longitudinal velocity can be noticed for the mean temperature. There is an important decrease of the temperature near the wall with injection, especially when the injection rate increases. Furthermore, we can observe that the fluctuations of temperature are more important with blowing. We did not observe a shift of the temperature fluctuations as it was the case for the velocity fluctuations. Consequently, the blowing seems to act differently on the temperature and velocity fluctuations.

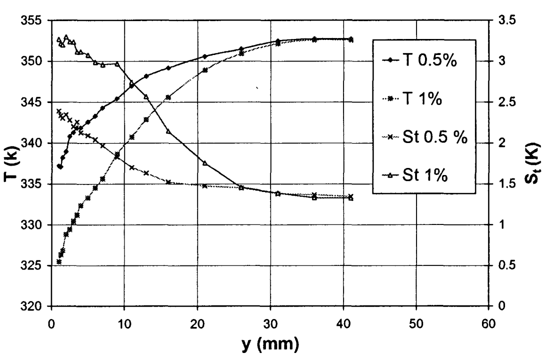

Figure 8: Mean and fluctuations rms temperature profiles

Conclusion

A new method for the calibration of a hot wire probe, associated with a cold wire, enables the measurements of velocity and temperature profiles in a non-isothermal boundary layer. The velocity profiles have been compared with these obtained in the same configuration by LDA. We noticed a decrease of the mean velocity and of the mean temperature in the boundary layer submitted to blowing and we observed that the injection modifies the velocity and temperature fluctuations.

The use of a special three wire probe (two hot wires and one cold), should improve these measurements and permit to obtain the turbulent heat fluxes and other turbulent properties.

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