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# Reducing Hot/Cold Wire Anemometer Data on Low Reynolds Number Flows

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***Abstract.*** *This paper concerns the use of thermal anemometry for simultaneous measurements of velocity and temperature fields in wind tunnel simulated atmospheric flows. The experiments were carried out in facilities of the Laboratory of Turbulence Mechanics(PEM/COPPE/UFRJ), and a detailed description of the whole experimental apparatus and calibration procedures is given. This work is focused on the investigation of the most suitable calibration laws, among a set classical ones, for single and X-hot-wires as well as cold-wires for measurements in low Reynolds number and stratified flows. The advantages and limitations of the methods will be discussed. The results are shown in the form of tables, equations and calibration curves for temperature and velocity data, and for two components of velocity. A careful uncertainty analysis of the results is also given. Some measurements of simulated stratified atmospheric conditions are presented so as to illustrate the potencial of hot wire anemometry for extracting information on various aspects of the turbulent motion.*

***Keywords:*** *Turbulence, experimental methods, hot-wire anemometry, temperature measurements, calibration, stratified flows.*

## 1. Introduction

The atmospheric boundary layer has always aroused much interest and speculation from scientists. Because the boundary layer occupies the lowest 500-1000m of the earth's surface where turbulent motions are responsible for sharp gradients of momentum, heat and water vapour its behaviour must be well undestood if the effects of small scale phenomena on weather prediction and circulation models are to be accounted for. Despite the great importance and influence of atmospheric flows in human lives and activities, systematic scientific investigation of this region is confined to the latest 40 years. Almost all of that inquiry, however, has been devoted to simple situations, as boundary layer flow over flat, open land. With some isolated exceptions, the extension to more complex situations such as flat but heterogeneous surface, flow over hills and valleys has been pursued only during the last 15 years by a small growing group of researchers.

The reasons for the slow accumulation of understanding in this area are basically two: difficulties in measurements and difficulties in handling the mathematical description. The root cause of both is turbulence – the chaotic, essentially unpredictable variations in atmospheric properties. The development of knowledge in this area came only when fast-response measurement techniques started to be used.

In the past years, the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ has continuously increased its interest in geophysical flows, particularly in large scale atmospheric flows. Therefore, great effort has been dedicated to reproduce such fenomena in a laboratory environment. This has naturally led to comprehensive research and development of projects on measurement tecniques, acquisition and data treatment.

Normally, wind tunnels are asked to run at high velocities, as most of the experimental facilities around these days were built aimed at aeronautical applications. Instrumentation, therefore, including hardware and software, were normally developed for high speed flows. Wind tunnels for environmental applications, however, run at low speeds. As such, particular techniques have to be developed to handle this type of flow. In addition, environmental applications require almost as a role the analysis of flows subject to abrupt changes in temperature.

Investigations of the velocity field on turbulent, unheated, steady flows concerning hot wire anemometry have already received considerable attention. However, only a handful studies are available for unsteady, heated flows. Most of cold-wire anemometry literature is restricted to situations where only a slight compensation for ambient temperature deviations is need to correct the hot-wire signal. Bremhost(1985) reviewed difficulties and methods associated with correct velocity measurements in heated flows using hot-wire anemometers and proposed a method for automatic compensation to give a corrected, instantaneous velocity signal by use of a hot and cold-wire anemometers simultaneously. The method was limited to flows with a spectral content below the corner frequency response of the cold wire.

Nevertheless, in atmospheric flows, stratification conditions exert a great influence on the velocity field, requiring the simultaneous measurement of instantaneous velocity and temperature for a correct characterization of any phenomena under study. This work is concerned with an extension of resistance wires for the investigation on the influence of the temperature field in the properties of boundary layers, so as to obtain a better understanding of the mixing processes involved in such problems.

In general, one of the most important aspects of thermal anemometry is the accurate interpretation of the anemometer signal. The main purpose of any sensor calibration is to determine, as accurately as possible, the relationship between the anemometer output voltage and the physical property under consideration, in this case velocity or temperature. However, the direct output from all practical calibration procedures is raw calibration data which will contain measurements uncertainties. An additional complication is that the true calibration curve of the probe is not known, and furthermore it depends on particular characteristics of each experiment.

The objective of this work is then to investigate the appropriate method of curve fitting the data, for measurements on specific conditions of low velocity and temperature gradients. The work also intends to minimise any experimental error if a good accuracy is to be obtained. Those aspects were considered in both the velocity and temperature measurements, with the main purpose being to compare several curve fitting methods on a commom basis, by using the same input data, and to identify both accuracy and suitability for implementation on a microcomputer.

A detailed description of the procedures used to calibrate sensors for velocity and temperature measurements, and also the calibration process of X hot-wires for measurements of two components of the velocity vector is given. Results are shown in the form of tables, equations and calibration curves. Measurements of stratified boundary layers illustrates the accuracy of the method used. A discussion of uncertainty analysis is also done.

Despite the centered interest of the paper be the treatment of flows subject to changes in temperature, for the sake of completeness, data on constant temperature flows will also be presented.

## 2. The Experimental Facilities

### 2.1. Wind Tunnels

The Laboratory of Turbulence Mechanics has two open-circuit wind tunnels. One of the tunnels, aimed at environmental fluid mechanics, is the low-velocity stratified-flow wind tunnel, that has been described in Cataldi et al.(2001). The tunnel's main objective is to simulate stratified atmospheric boundary layers. Some improvements have been recently made in the tunnel to achieve a better representation of atmospheric flows and similarity conditions. The test section has now an overall length of 10m, with a cross section area of 0.67 m x 0.67 m. The position of the roof can be ajusted at will so as to produce different pressure gradients. In this case a special care is taken to set the pressure gradient near zero.The potencial velocity of the wind tunnel varies from zero to 3,5 m/s, and the free stream has a turbulence intensity of about 2%.

A stratification section consisting of 10 eletrical resistances is able to heat the flow differentially up to 100

$^oC$; each of the resistances can be controlled individually. Following the heating section, the floor temperature can also be raised by 100 $^oC$ over a 6m long surface, by a series of resistances with a controlled variation of $5^oC$. The total heating capacity of each panel is about 7 $kW/m^2$. The whole facility is capable of developing gradients of up $50^oC$ at uniform mean speeds in the range 1,5–2,5 $m/s$, so as to generate different levels of instability.

The second wind tunnel is a low-turbulence wind tunnel with turbulence intensity levels of the order of 0.2%. This wind tunnel can be set to run at velocities that can reach 13 m/s; the test section is 4m long, the cross section area is 0.30 x 0.30 m. This tunnel was adapted for the calibration of the cold-wire with the inclusion of a new heating section. The heating section was built with four electrical resistances in series, each one of them consisting of strings distributed transversally to the flow.

Both tunnels have honeycombs and screens to control the turbulence levels and to garantee a uniform flow. The computer-controlled traverse gears are two-dimensional and capable to position sensors with an accuracy of 0.1 mm. The experiments are conducted in a controlled environment, with the laboratory temperature set to 18,0 $^oC \pm 0.5$ $^oC$.

## 2.2. Instrumentation

In all experiments, simultaneous measurements of streamwise velocity and fluctuating temperature were obtained by using thermal anemometry. The measurements accounted for any large temperature variation in interpreting the sensor response. To perform the measurements a temperature-compensated Dantec probe, model 55P76, was used. This probe consists of two sensor elements: a hot-wire and a resistance-wire, usually called cold-wire, situaded 2 mm below and 5 mm downstream of the former. Both sensors are Pt-plated tungsten wires, 5 $\mu m$ in diameter, overall length of 3mm and sensitive wire length of 1,25 mm. They are copper and gold plated at the ends to approximately 30 $\mu m$. They were connected respectively to a constant temperature bridge, Dantec 55M10 and to a constant current brigde, Dantec 56C20.

For the measurement of both velocity components, $u$ and $v$, an X hot-wire Dantec probe, model 55P51, was used with the sensors set in a plane parallel to the probe axis. Such procedures are schematically represented in Figure 1.

Reference measurements for velocity was obtained from a Pitot tube connected to an inclined manometer; temperature reference data was obtained from previously calibrated microthermocouples.

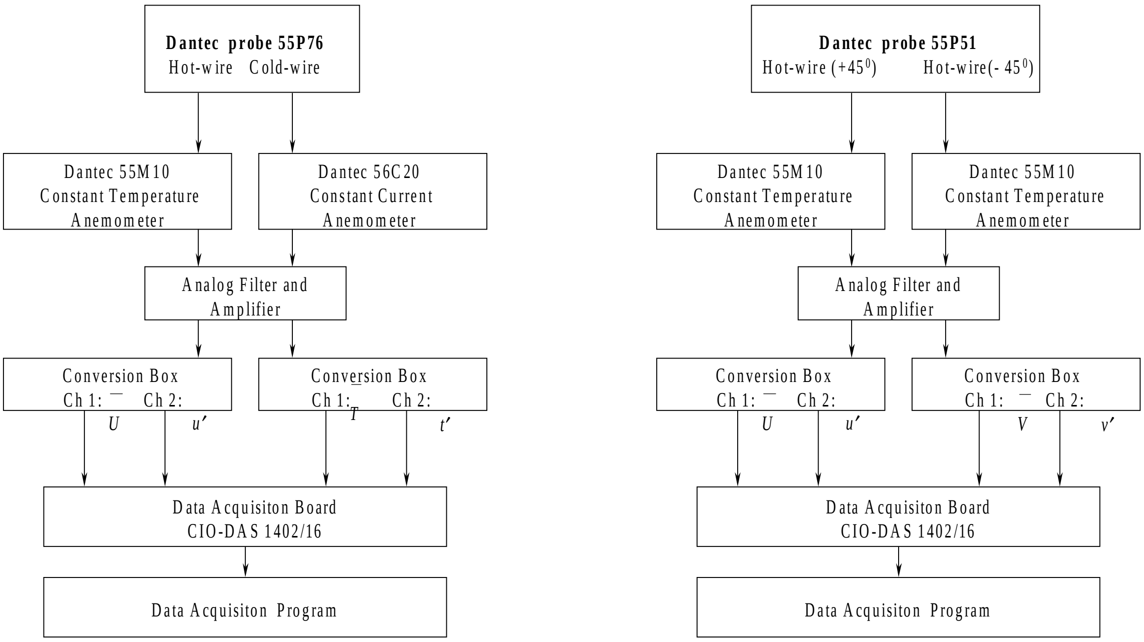

Figure 1. Scheme of data acquisition procedure for temperature and velocity measurements and two-channel velocity measurements.

## 3. Theoretical Analysis

Among the several possible methods that can be devised to characterize the velocity and temperature dependence of thermal anemometers signals, it is possible two classify them in three main categories (Freymuth, 1970):

1. The linear correction method where the heat transfer from the probe is assumed to be proportional to a product of the temperature difference $T_w - T_a$ and a function of the velocity, where $T_w$ is the temperature of the heated wire and $T_a$ is the ambient temperature. The output voltage, $E$, of a constant temperature hot-wire anemometer can hence be represented by:

$$E^2 = f(U)(T_w - T_a). \tag{1}$$

2. The convective heat transfer is expressed in a nondimensional form involving a relationship between the Nusselt number, $Nu$, the Reynolds number, $Re$, and the Prandtl number, $Pr$.
3. Direct calibration of the variation in the anemometer output voltage, $E$, with the velocity, $U$, and the fluid temperature, $T_a$, for a given hot resistance setting, $R_w$.

The third method is the most complex to implement but it is also the most accurate, and will be adopted in this work. The calibration data obtained by this method can reveal to what an extent the other methods can be used to evaluate the temperature and velocity sensitivity of a hot-wire probe operated in the CT mode.

### 3.1. Temperature Calibration for the Cold-Wires

Fluid temperature measurements are often performed with a hot-wire sensor operated in the constant-current mode at very low overheat ratio, in order to minimise Joule heating. Ideally, the wire sensor behaves like a resistance thermometer.

Temperature measurements with resistance wires require both low drift, low noise constant current anemometers and high quality amplifiers. If the resistance wire is heated by a current $I = 0.15mA$, then the “hot” resistance $R_w$ will only deviate from $R_a$ by $(R_w - R_a)/R_a \simeq 0.0004$, and the corresponding temperature difference $(T_w - T_a)$ will be less than $0.1\ ^oC$.

Thus, a common practice is to consider $R_w = R_a$, with

$$R_a = R_0 \left[1 + \alpha_0 (T_a - T_o)\right]. \tag{2}$$

For practical applications, it is recommended that a temperature calibration of the resistance-wire is used to determine the calibration constants in the relationship

$$R_a = A + B\, T_a. \tag{3}$$

### 3.2. Temperature and Velocity Calibration for Hot-Wires

The most accurate way of establishing the velocity and temperature sensitivity of a constant temperature hot-wire probe, operated at a fixed hot resistance, $R_w$, is to measure the anemometer output voltage, $E_w$, as a function of the velocity, $U$, and fluid temperature, $T_a$. This type of calibration is often carried out by performing a velocity calibration at a number of different fluid temperatures.

The functional form of the calibration data may be evaluated as

$$E = F(U, T_a)_{T_w = const}, \tag{4}$$

but, more commonly, the calibration data have been interpreted in the form

$$E = F(U, T_a - T_w)_{T_w = const}. \tag{5}$$

To evaluate $T_w$ it is necessary to measure the hot resistance, $R_w$, and this requires a knowledge of the probe and cable resistance. The mean wire temperature, $T_w$, corresponding to $R_w$ is normally determined by the equation:

$$R_w = R_0 \left[1 + \alpha_0 (T_w - T_0)\right], \tag{6}$$

where the temperature coefficient of resistance, $\alpha_0$, is a property that is usually given by the manufacturer of the probe.

For single normal probes, in this case the hot-wire probe, the classical convective heat transfer law, King´s law, can be written as

$$E^2 = A + BU^n, \tag{7}$$

where $A$, $B$ and $n$ are empirical constants.

Equation 7 is a very good approximation to the velocity calibration data, obtained at a constant value of $T_a$, provided the calibration constants are determined by a least-squares curve fit. This procedure has been applied by other authors to their velocity calibration data using the wire voltage relationship

$$\frac{E_w^2}{R_w\left(R_w - R_a\right)} = A + BU^n. \tag{8}$$

This curve-fitting procedure gave the most accurate results, but $A$, $B$, and $n$ were found to be functions of $T_a$. When a constant value of $n(= 0.45)$ was selected, $A$ and $B$ also became constants, and the increase in the uncertainty is insignificant for most hot wire anemometry aplications.

A similar approach was adopted by Lemieux and Oosthuizen(1984). They expressed their calibration relationship in the form

$$E^2 = A^* + B^*U^n, \tag{9}$$

and for each value of $T_a$ they determined the values of $A^*$, $B^*$ and $n$ by a least squares curve fitting procedure. In their subsequent signal analysis the optimum value for $n$ was selected as being the average value from their four calibration curves. The corresponding calibration coefficients $A^*$ and $B^*$ were found to vary linearly with $T_a$:

$$A^* = A_1 + A_2T_a, \tag{10}$$

$$B^* = B_1 + B_2T_a. \tag{11}$$

A linear variation of $E^2$ with $T_a$ has also been reported by other authors. In conclusion, most experimental investigations of this type, covering small or moderate variations in $T_a$, have demostrated that the output signal from a hot-wire probe operated in the constant temperature mode is directly proportional to a product of the temperature difference $(T_w - T_a)$ and a function of the velocity.

### 3.3. X Hot-wire Calibration

Two-component velocity measurements are commonly performed with a probe with two wires placed in an X-configuration. For signal analysis purpose, one normally assumes that the two wires are contained in the same plane. However, for practical purposes the two wires cannot be placed too close together or else the thermal wake from one wire will affect the output from the other wire. Jerome et al.(1971) have shown that if a wire spacing of about 1 mm is used, then, the hot-wake effect is negligible. Despite some operating difficulties such as prong-wake problems and aerodynamic disturbances effects, X-probes have become very popular over the years.

For calibration and evaluation purposes the standard procedure is to consider that velocity component perpendicular to the X-probe is small compared to the velocities in the two in-plane components ,$U$ and $V$, so that the response equations for the two-wires can be expressed as

$$E_1 = F_1(U,V) = F_3(\tilde{V},\theta,\alpha), \tag{12}$$

$$E_2 = F_2(U,V) = F_4(\tilde{V},-\theta,\alpha). \tag{13}$$

where $\tilde{V}$ denotes the magnitude of the flow vector, $\theta$ the flow angle and $\alpha$ the yaw angle of the wires.

A simplified calibration procedure and signal analysis can be developed by introducing the effective-velocity concept whereby we consider

$$\begin{aligned} V_e &= \tilde{V}f(\alpha) = \tilde{V}(\cos^2\alpha + k^2\sin^2\alpha)^{1/2}, & (14)\\ &= (U_N^2 + k^2U_T^2)^{1/2}. & (15)\end{aligned}$$

$$k = \frac{1}{\sin\alpha}\big[\big(\frac{E^2(\alpha) - A}{E^2(0) - A}\big)^{1/2} - \cos^2\alpha\big]^{1/2}. \tag{16}$$

Then, the response equation for the two wires can be written as

$$E_1^2 = A + BV_{e1}^n, \tag{17}$$

$$E_2^2 = A + BV_{e2}^n, \tag{18}$$

Thus for the complete velocity and flow-angle range the X-probe calibration relationship can be expressed as

$$E^2 = A(\theta) + B(\theta)V_e^{n(\theta)}. \tag{19}$$

The so called $V_e$-calibration method consider each wire in the X-probe independent, so that a standard calibration for a single inclined probe is used. The result is that a simple expression for $V_e$ can be cast as

$$V_e = f(\alpha)\,[U - g(\alpha)v], \tag{20}$$

where

$$f(\alpha) = (\cos^2\alpha + k^2\sin^2\alpha)^{1/2}, \tag{21}$$

$$g(\alpha) = \frac{(1-k^2)\cos^2}{(\cos^2\alpha + k^2\sin^2\alpha)}\tan\alpha. \tag{22}$$

The values of $U$ and $V$ can then be obtained by the modified sum-and-difference procedure, which yields

$$U = \frac{[V_{e1}/f_1(\alpha_1)]g_2(\alpha_2) + [V_{e2}/f_2(\alpha_2)]g_1(\alpha_1)}{g_1(\alpha_1) + g_2(\alpha_2)}, \tag{23}$$

$$V = \frac{[V_{e2}/f_2(\alpha_2)] + [V_{e1}/f_1(\alpha_1)]}{g_1(\alpha_1) + g_2(\alpha_2)}, \tag{24}$$

For flows subject to temperature variations, parameters $A$ and $B$ must be considered dependent not only on $\theta$ but also on $T$.

## 4. Results

### 4.1. Calibration

In the following we will describe the calibration procedure for both the hot-wire and the cold-wire; emphasis will be placed on the cold-wire procedure.

The calibration was performed in the low-turbulence wind tunnel sited in the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ.

- Circuit: open.
- Test section: 0.30 m high, 0.30 m wide and 2 m long.
- Wind speed: continuously variable from 0.5 to 16 m/s.
- Longitudinal pressure gradient: adjustable to zero by means of an adjustable ceiling.
- Turbulence intensity: below 0.2%.
- Incoming flow temperature: variable from 20 to $35^oC$.
- Number of resistences used to heat the incoming air: 4.
- Resistances capacity: 7 kW.

A general view of the low-turbulence wind tunnel is shown in Figures 2 and 3.

Figure 2. General view of the low-turbulence wind tunnel and the heating elements.

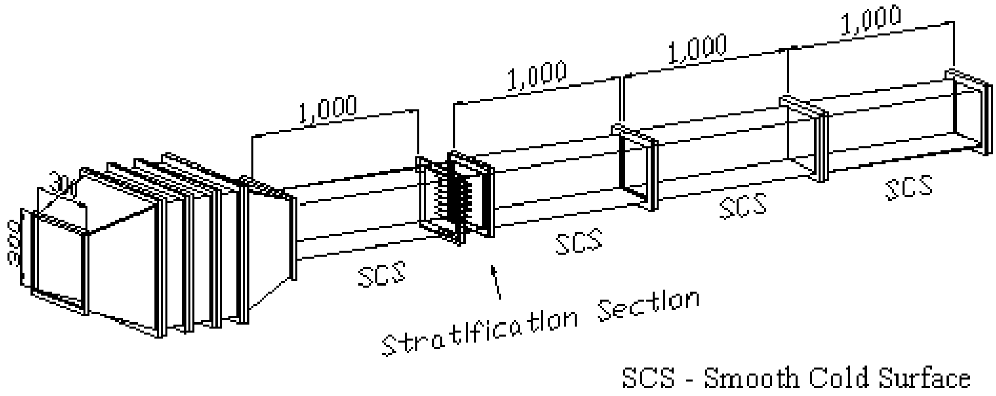

Figure 3. Schematic view of the low-turbulence wind tunnel and the heating elements.

For the present measurements, a DANTEC 55M01 main unit together with a 56C20 constant current bridge was used. The boundary layer probe was of the type 55P76. A Pitot tube, an electronic manometer, and a computer controlled traverse gear were also used. In getting the data, 10,000 samples were considered. The reference mean temperature profiles were obtained through a chromel-constantan micro-termocouple mounted on the same traverse gear system used for the hot-wire probe. An uncertainty analysis of the data was performed according to the procedure described in Kline[20]. Typically the uncertainty associated with the velocity and temperature measurements were: $U = 0.0391\ m/s$ precision, 0 bias (P=0.95); $T = 0.2\ ^oC$ precision, 0 bias (P=0.99).

To obtain accurate measurements, the mean and fluctuating components of the analogic signal given by the anemometer were treated separately. Two output channels of the anemometer were used. The mean velocity profiles were calculated directly from the untreated signal of channel one. The signal given by channel two was 150 KHz low-pass filtered leaving, therefore, only the fluctuating velocity. The latter signal was then amplified with a gain controlled between 1 and 500 and shifted by an offset so as to adjust the amplitude of the signal to the range of the A/N converter.

The typical calibration range for a cold-wire probe is shown in Table 1.

The dependence of the hot-wire voltages, $E_w$, on the air velocity, $U$, for different ambient temperatures is shown in Figure 4.

Table 1: Typical calibration range for a cold-wire anemometer.

| Author | Velocity Range (mm) | Temperature Range $^o$C |
|---|---|---|
| Pessoni and Chao(1974) | 6 to 0 | 22 to 60 |
| Koppius and Trines(1976) | 0.5 to 5 | 10 to 80 |
| Fiedler(1978) | 2 to 20 | 21 to 50 |
| Dekeyeser and Launder(1983) | 7.6 to 15.4 | 25 to 35 |
| Lemieux and Oosthuizer(184) | 0.5 to 4 | 25 to 55 |
| Bremhorst(1985) | 1.5 to 35 | 20 to 80 |
| COPPE/UFRJ | 0.5 to 3.0 | 20 to 35 |

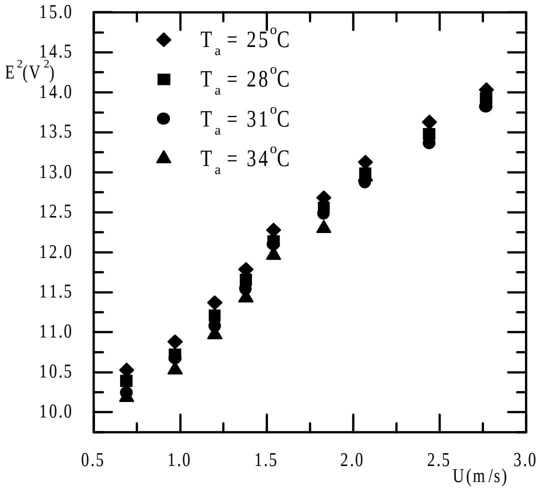

Figure 4. The dependence of hot-wire voltage on the air velocity for different ambient temperatures.

The calibration coefficients $A*$ and $B*$ corresponding to the curves in Figure 5 were found to vary linearly with $T_a$. A linear variation of $E^2$ with $T_a$ as been observed by Fulachier(1978), by Champagne(1978) and by Dekeyser and Launder(1983).

The present data were obtained with a 5 $\mu$m diameter tungsten wire with an overheat ratio of 1.8; this corresponds to a temperature difference $T_W$ - $T_a$ of about 220 $^o$C.

In conclusion, and after other authors, we have found that the signal from a hot-wire probe operated in the constant temperature mode is directly proportional to a product of the temperature difference and a function of the velocity.

Figure 5 shows the variation of the calibration parameters $A*$ and $B*$ with the fluid temperature.

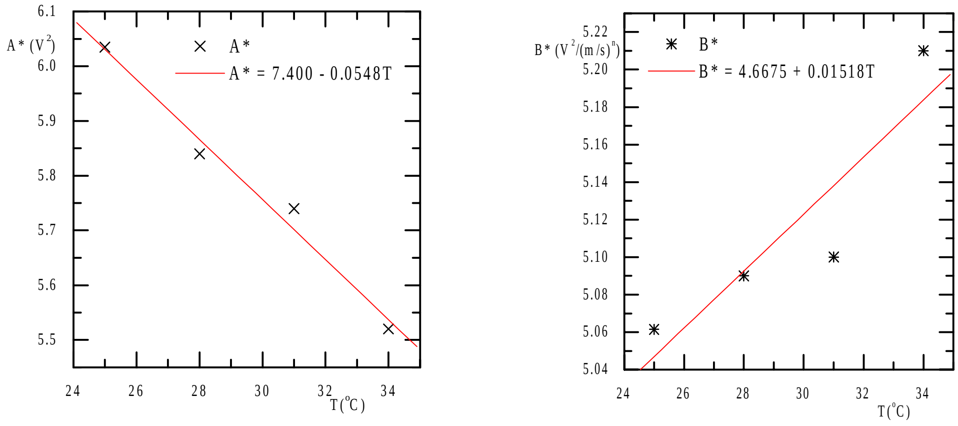

Figure 5. Variation of the calibration parameters $A*$ and $B*$ with the fluid temperature.

The X-probe was calibrated through the $V_e$-calibration method whereby each wire in the probe is calibrated independently, and the calibration procedure for the inclined probe is used. The calibration of both wires was performed simultaneously so that a least-square curve-fitting could be used to find $A_1$, $B_1$, $A_2$, $B_2$. The X-probe calibration map is shown in Figure 6.

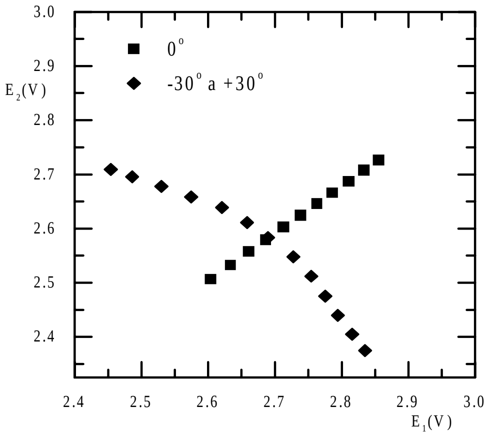

Figure 6. Calibration map for the X-wire probe.

### 4.2. Measurements

Boundary layer measurements were conducted in the stratified wind tunnel of COPPE/UFRJ. The main features of the wind tunnel is shown below.

- Circuit: open.
- Test section: 0.67 m high, 0.67 m wide and 10 m long.
- Wind speed: continuously variable from 0.5 to 3 m/s.
- Longitudinal pressure gradient: adjustable to zero by means of an adjustable ceiling.

- Turbulence intensity: 2%.
- Surface heating capacity: 5 kW $m^2$.
- Lenght of wall heating section: 6 m.
- Wall temperature: variable from 21 to $100^oC$.
- Number of resistences used to heat the incoming air: 10.
- Resistances capacity: 2 kW.
- Vortice generators: rods with 1/8" diameter and 16 mm lenght spaced by 10 mm. One or two trailing transversal trips were also used.

A general view of the stratified wind tunnel can be seen in Figure 7 and 8, together with a picture of the the heating elements.

Figure 7. General view of the stratified wind tunnel and the heating elements.

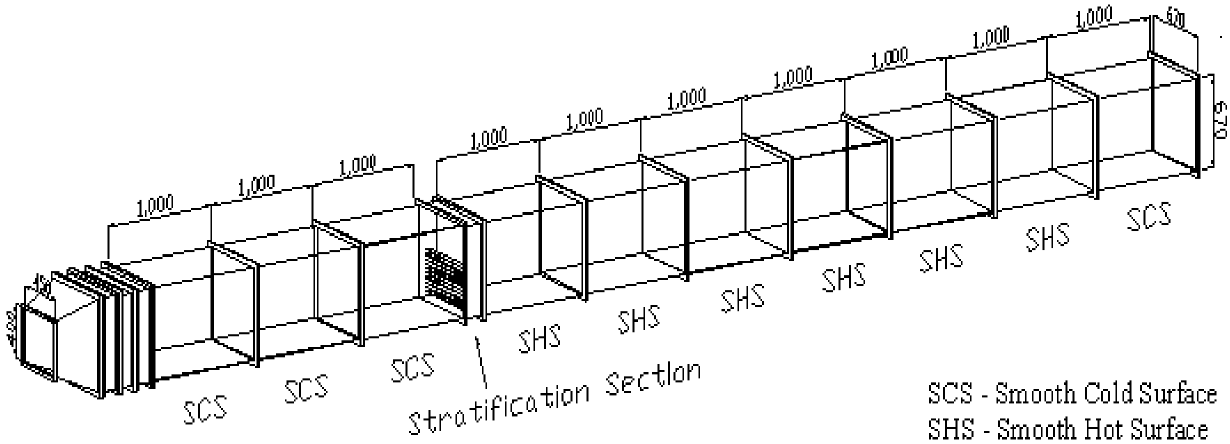

Figure 8. Schematic view of the stratified wind tunnel and heating elements.

The mean velocity profiles for the stable, neutral and unstable boundary layers are shown in Figure 9 in linear and logarithmic coordinates respectively. The temperature profiles also in linear and logarithmic coordinates are shown in Figure 10.

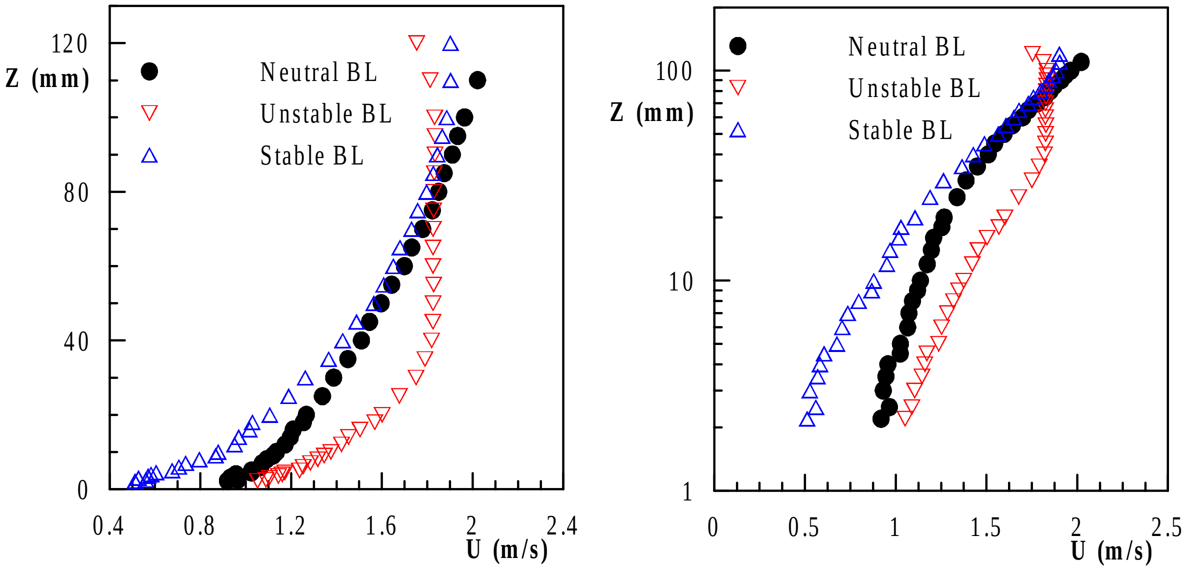

Figure 9. Velocity profiles in linear and logarithmic scales; stable, neutral and unstable conditions.

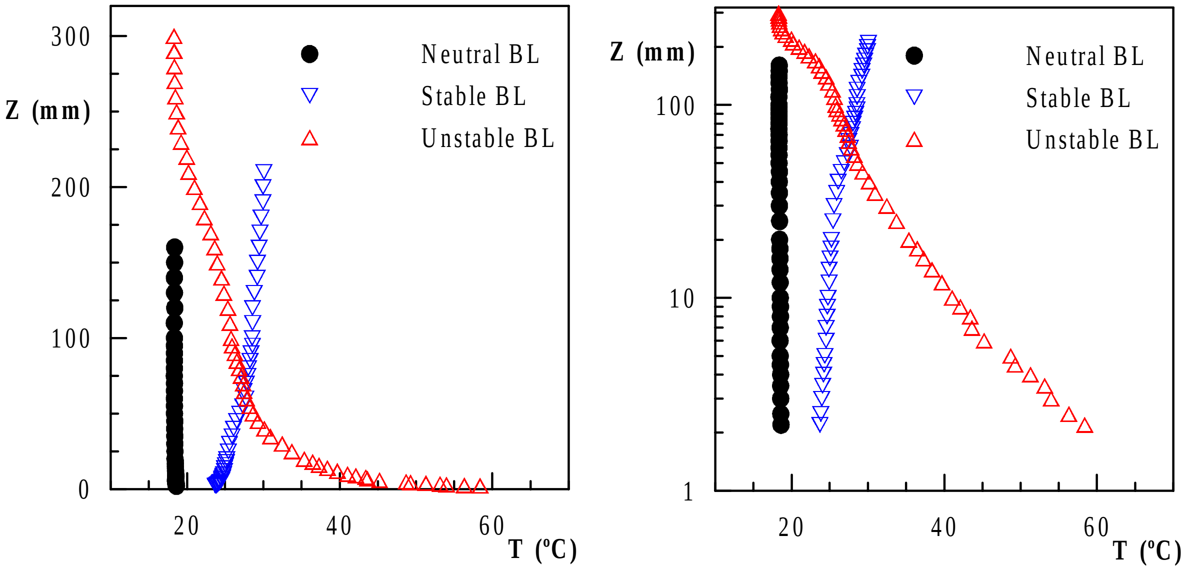

Figure 10. Temperature profiles in linear and logarithmic scales; stable, neutral, unstable conditions.

The results show that the logarithmic wind profile is strictly valid for neutral conditions. For stable or unstable atmospheres the profile departs from the logarithmic shape.

## 5. Final Remarks

The present work has reported the recent progresses made at COPPE/UFRJ to develop packages for the measurement of flows with change in temperature. Results are presented for the longitudinal velocity profile and the temperature profile in stratified environments. The measurement of turbulent quantities will be presented opportunaly.

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