IX CONGRESSO BRASILEIRO DE
ENGENHARIA E CIÊNCIAS TÉRMICAS

9th BRAZILIAN CONGRESS OF THERMAL
ENGINEERING AND SCIENCES

Paper CIT02-0411

A LABORATORY CLASS FOR INTRODUCING HOT-WIRE ANEMOMETRY IN MECHANICAL ENGINEERING COURSE

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Abstract *HWA (hot wire anemometry) is a very important tool for fluid mechanics research, and even today several industrial, aeronautical, automobile and military applications have been found for this thermal anemometer, substituting with advantages a number of traditional flow measurement ways like orifice plates and Pitot tube. Nowadays, the crescent use of HWA in practical engineering applications has reawaken the interest of mechanical engineering graduate teachers in providing the inclusion of this thermal anemometer in a laboratory class.* ***.*** *Therefore the authors have set the intention to fully describe a practical laboratory setup for introducing HWA in a typical mechanical engineering course. To accomplish that, CTA (constant temperature anemometer) methods for laboratory classes will be presented in two parts. The first one, which is the subject of this paper, introduces the students to the HWA theory, apparatus and calibration techniques and the second part, still to follow, will be dedicated to describing some actual experiments themselves. The probe calibration is carried out in a special device utilizing tap water. This calibration apparatus produces a free jet with moderates Reynolds numbers (up to* 10^4*) and the probe is inserted into the root jet, permitting the calibration process. It is shown that the use, under adequate supervision, of a very sophisticated tool, such as hot-film anemometer, for laboratorial research application, in a mechanical engineering undergraduate course can be perfectly possible and it is highly motivating.*

Keywords*. hot-wire anemometer, hot-film anemometer, free jet, flow visualization, fluid mechanics learning*

1. Introduction

Nowadays, near a century after of use of the first HWA (hot-wire anemometer), this thermal anemometer remains the principal tool for research in turbulent flow measurements. Because of the low cost, high frequency response – up to several hundred kilohertz, small sensor size, wide range velocity, temperature correction, high accuracy, high signal-to-noise ratio and a large variety of probes, HWA still is the appointed research instrumentation for moderate turbulence flows. In the past, an experimental flow investigation only obtained global information, that is, integral formulation. Recently, the growing of computer fluid dynamics (CFD), generating accurate and physically realistic solutions e involving turbulence modeling, have caused a hard impact in turbulence flow experimental investigation. In the present, CFD provides high-quality data implicating in a need of new accurate and detailed experimental data and instigates further developments in experimental techniques in fluid mechanics, the reason for the appearance of several ways of measurements in contemporary flow studies.

The hot-wire anemometer is the most well known thermal anemometer, measuring a fluid velocity by recording the heat convected away by the fluid. Compared to others research anemometers, like laser Doppler anemometer (LDA) or modern particle image velocimetry (PIV) systems, HWA remains the cheapest and the most employed choice.

The core of the anemometer is an exposed hot wire either heated up by a constant current (CCA) or maintained at a constant temperature (CTA). In either case, the heat lost to fluid convection is a function of the fluid velocity. By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with a adequate convective change heat equation. Typicallly commercially available hot-wire anemometers, for laboratory applications, have a flat frequency response (< 3 dB) up to 17 kHz at the average velocity of 9.1 m/s, 30 kHz at 30.5 m/s, or 50 kHz at 91 m/s. Due to the tiny size of the wire, available for laboratory applications, it is fragile and thus suitable only for clean gas flows. In liquid flow or rugged gas flow, a platinum hot-film coated on a 25 ~ 150 μm diameter quartz fiber or glass tube can be used. Theory and broad practical aspects of hot-wire anemometry have been described in many reviews and books on the subject, for example, Perry (1982), Fingerson (1983), Lomas (1986) and Bruum (1995). Unfortunately, these reviews are directed to laboratory and research applications of HWA. Other important information about HWA utilized in research applications are available in the proceedings of the ABCM's meetings. Spring Schools of Transition and Turbulence, held every two years, are also a good example, producing several text in experimental anemometry for research and didactical utilization – see Menut (1998) and Möller (2000). In consequence of the several advantages of this thermal anemometer, several new applications for measurement mass and volumetric flow are found, and a large number of models of HWA for hundred of industrial applications are commercially available today.

Hot-wire anemometers have quite a few applications in industrial ambient for measurements fluid velocities and volumetric or mass flow. Because of the advantages of this equipment – low cost, easy signal conditioning, electrical linear output signal, all solid state components, low loss pressure in the flow, automated fluid temperature compensation, absence of rotating parts and possibility of work in aggressive means with chemical reactions or presence of solid particles in the fluid – they are intensely utilized in industrial process. Moreover, industrial hot-wire anemometers exhibit the advantage of non-necessity of frequent calibration, while compared to laboratory applications. The probes to industrial application are guarded from flow contamination by being enveloped by a ceramic coating or metal capsule hoods. The sensor protection performs quite well for a long time without the need of calibration. The major disadvantage of protected probes used in industrial plants are their size, much larger than unprotected probes usually employed in laboratories, responsible for the dumping of the protected probes frequency response. That is the reason why in industrial thermal anemometry the frequency response is usually limited to less than 1 Hz.

Owing to the increment of use of this kind of thermal anemometers in several industrial, motoring, military and aeronautical applications, hot-wire has had the interest reawaken. In this work effort, the authors' experience of the practical use of HWA in fluid mechanics laboratory class in an mechanical engineering undergraduate course is described in details. CTA (constant temperature anemometer) methods are introduced for two laboratory classes, the first, which is the subject of this paper, introduces the students to the HWA theory, apparatus and calibration techniques.

2. Constant temperature anemometer bridge

Hot wire anemometry is a well-established technique in which the speed of a fluid flow is measured by sensing the rate of cooling of a fine electrically heated wire. The typical basic elements of the constant temperature anemometer (CTA) bridge are shown in Figure 01. Resistor (R_2) represents resistances of the cables, contacts, prongs and additional internal resistances in the anemometer. Resistor (R_w) represents only the resistance of the probe sensor, i.e. the fine heated wire. Amplifier (A_2) is included to decouple output reading (E_{out})from the CTA-circuit. The anemometer works according to the following steps: Input voltage (E_{in}) induces an electric current through the Wheatstone bridge with components (R_1, $R_2 + R_W$, R_3, R_4). If voltage (E_1) is smaller than (E_2), then differential amplifier (A_1) will increase (E_3). As a consequence of this, (E_1) will be larger, resulting in a larger current through the hot-wire probe, which will heat up. The warmer hot-wire has larger resistance, bringing the Wheatstone bridge more in balance. Theses steps are repeated until equilibrium is achieved. The bridge with feedback coupling pursues equilibrium by keeping the resistance of the hot-wire at a constant value. This implies that the wire maintains its temperature. Usually the amplification of amplifier (A_1) is taken to be large, resulting in quick frequency response. Apart from frequency response, there is another advantage of CTA–anemometers: the constant temperature of the wire leads to a constant heat loss of the wire to other parts of the probe. The resistance (R_0) represents only the current limiting circuit.

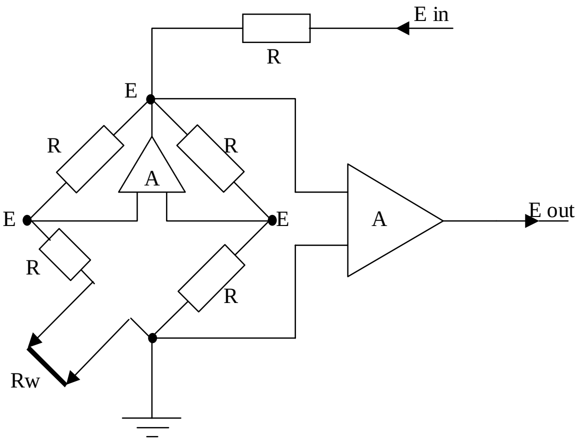


Figure 1. Typical constant temperature anemometer bridge.

3. Calibration

The hot-wire probe utilized in laboratory applications, is an extremely delicate sensor and will break at the slightest touch or small electrical pulse. Hot-film probes, generally utilized in water medium, are sensors of an elevated cost, limited useful life and nonsupport maintenance. In other side, hot-wire probe utilized in industrial plants, have protect probes and sensor protection permits a more robustness manipulation. The calibration of this probes are an arduous work in industrial ambient which generally has no laboratory of flow measurements. Even so, several hot-wire industries sales equipment for calibrating probes, this calibration devices are mch alike a simple small wind tunnel of open circuit kind. Technical literature is rich on information about several different techniques and procedures for hot-wire probe calibration, but the hot-wire and hot-film anemometry in water have received considerably less attention from professionals than the application of the same procedure in air. Evidently, the use of hot-wire probes in air medium is a more easy task when compared of the use of hot-film probes in water medium.

Example of use of water medium for probes calibration is the work of Persen & Saetran, (1984), utilizing a water tank where a small carriage rolls, in constant velocity, on two parallel rails. The support probe and the probe was firmly fixed in the carriage and immersed on the calm water. The carriage velocity is accurately measured using two photocells. This procedure has the following advantages: no turbulence level in the “free-stream”; the fluid velocity relative to the probe is very easily and accurately determined and this facility is inexpensive and simple to construct.

Lee & Budwig, (1991) calibrated a hot-wire probe at low speed wind tunnel using the relation Strouhal – Reynolds relationship proposed by Roshko (1954). The flow velocity has been obtained by measuring the vortex-shedding frequency, provoked by a circular cylinder, a polished drill rod, and using the Roshko’s relationship. Obviously, calibrations performed with non-parallel vortex shedding can lead to significant inaccuracies.

Several different ways can be utilized in order to promote the probe calibration. A example are the work of Bruun *et al.* (1989) and Guellouz & Tavoularis (1995), utilizing a swinging arm, like a Charpy impact test device. During the oscillatory motion of the probe, the output signal is recorded simultaneously with the position angle (α) of the arm. The knowledge of the variation of position angle (α) permits to determine the probe velocity. Their proposed method permits a good accuracy, repeatability and apparently reduces the calibration time.

Vieira (2000) proposes the use of a low turbulence vertical water tunnel as a first experience of the use of a hydrodynamic tunnel to calibrate hot-film probes in a laboratory class. The tunnel, with 146 × 146 × 500 mm of test section, a hot-film probe is adequately positioned in a non-perturbed free-stream in the centerline of the test section. The volumetric flow was measured by means of a sensible electromagnetic flowmeter (*Yokogawa*), permitting to determine the flow velocity in the test section. It has to be said that, unlike water tunnels, the use of wind tunnels to calibrate several flow measurements devices is a current practice, especially Pitot tubes and many others airflow anemometers.

Pluister & Nagib (1975) show two calibration procedures. In their first apparatus, hot-film probes are calibrated using a fully developed laminar pipe flow configuration, procedure also used for Lee & Budwig (1991) and Samways *et al.* (1994). The maximum velocity on the centerline of a fully developed laminar flow in a circular pipe is two times the area-averaged velocity; consequently, by placing a probe on the centerline, the corresponding velocity can be evaluated by measuring the flow rate either by a flowmeter. In the second procedure, the one also employed in this work to calibrate hot-film probes, a free-jet configuration is utilized which provides a very low level of turbulence (less than 0.1 %). A small free-jet tunnel has been constructed by Pluister & Nagib (1975), and the probe has been inserted on the jet centerline. Centerline jet velocity (i.e., the velocity utilized for calibration of the hot-film probes) can be known for a large number of different processes. This procedure allows to a very good accuracy of the resulting calibration curve better than ±0.2 %.

Many other propositions to calibrate hot-film/wire probes can be found in a extensive literature about the theme. A review showing the different ways of accomplishing this task has been distributed, in digital format utilizing Intranet tools, to the students. This review offers a good opportunity to demonstrate the distinct ways an experimental problem can be solved utilizing the same physical principles.

The calibration of a hot-film probe involves obtaining a set of calibration points (*E*, *U*), where (*E*) is the voltage output and (*U*) is the temporal mean velocity of the flow. Generally, hot-wire probes calibration fitting responds according to King's Law:

$$E_{OUT}^{2} = A + B\,U^{n} \tag{1}$$

where (A), (B),and (n) are constants obtained by the fitting process, usually minimum square curve adjusting. You may assume (n) around 0.45, a common choice for hot-wire/film probes. Equation (1) permits a good fitting and substituting (E^2) for (y) and (U^n) for (x), it reduces to a convenient linear equation.

4 Experimental probes calibration device.

All calibration experiments, in the context of this work, have been carried out in a facility developed and constructed specifically to produce an axisymmetrical low-turbulence free jet with 24 mm of diameter in the jet root. The calibration apparatus is described in details in the work of Lindquist (2000). In the Fig. 2 is depicted a schematic sketch of this device, showing the principal components.

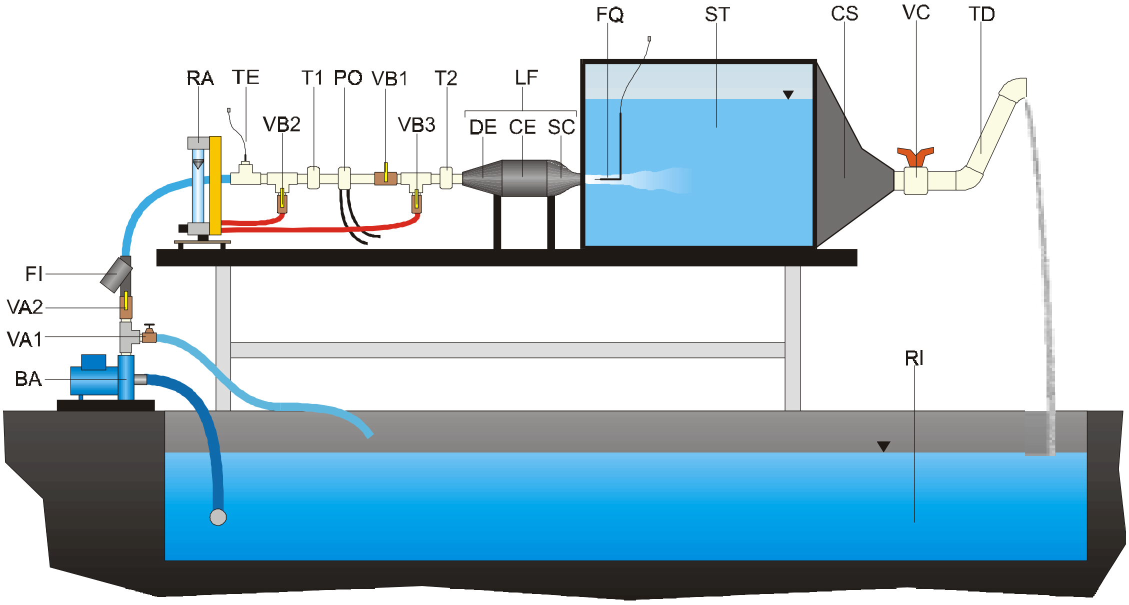


Figure 2 Apparatus for hot-film probes calibration.

A small centrifugal pump (*BA*) collect the water from an protected underground reservoir (*RI*), and the flow rate is controlled by means of two ball valves (*VA1*) and (*VA2*) and a fine filter (*FI*) provides solid particles retention up to 20 µm. Small solid particles and metallic ions provoke surface contamination causing changes in the calibration curve.

The (*TE*) connection permits the injection of colored liquid dye or a solution of water with solid micro particles in suspension order to promote flow visualization. The valves (*VB1*) to (*VB3*) permits the access to two different ways to measure of the flow rate. For low water flow velocity (up to 1,000 l/h) the valve (*VB1*) is closed and (*VB2*) more (*VB3*) are opened and a laboratorial high-precision rotameter (*RA*) (accurate to less than 0.5 %) is utilized to measure the flow. For high velocity, (*VB1*) is opened and (*VB2*) more (*VB3*) are closed and an orifice plate (*PO*), adequately calibrated, is utilized. (*T1*) and (*T2*) are conventional PVC connections utilized only to permit a more easily maintenance. After the filter *(FI)*, a flexible tube is connected in order to isolate the vibrations produced by the centrifugal pump (*BA*).

In order to produce a relative low turbulence level in very low-velocity flow regime several aids have been needed. An adequate design of stagnation chamber (*LF*), compounded by a diffuser (*DE*), with 3 fine wire screens to prevent boundary layer detachment problems in the diffuser section, a stagnation section (*SE*) with 100 mm of internal diameter contains 4 sections of hexagonal honeycombs made in aluminum with 4 mm of cell diameter and, to finish, the contraction (*SC*).

Contraction is a very important compound of a fluid experimental device because promotes several benefits in order to create a homogeneous velocity profile, reduces the relative turbulence level and make a stable boundary layer with small thickness. A project and detailed instructions to produce axisymmetrical small dimension contractions using composite material is found in the practice article by Vieira & Aparecido (1999).

The flow produces inlet the test section (*ST*) a free jet. In order to minimize the fluid recirculation problem, the test section is constructed with a relative large dimensions (1.00×0.60×0.65)m providing more than 0,3 m^3 of water in the superior level. The walls of the test section have been constructed in a special high abrasion-resistance Plexiglas permitting optical access to the free jet. A hot-film probe (*FQ*) is adequately positioned, with aid a conventional support L type, closely to the jet root in order to realize the calibration procedure. A temperature sensor (ST) permits a precise (within 0.1 °C) water ambient-temperature reading. A contraction of escape (*CS*) with a special design has been projected in order to promote a minimal fluid recirculation in the test section. A ball valve (*VC*) made in PVC controls the outlet flow and normally remains fully open. The water level in the test section is controlled by the outlet tube (*TD*), in other words, the length of the out tub (*TD*) can be easily altered, and this operation permits the level control in the test section. A level indicator shows when the inlet flow to the apparatus reaches a permanent regime. The storage tank (*RI)* has a capacity of about 5 m^3 of water and is large enough to maintain a constant temperature under continuous running conditions. Of course, the temperature remains constant during the experimental run and the mechanical energy dissipation in the pump or small ambient atmospheric temperature increasing produce a negligible temperature increment in the water. Even so, the water temperature in all the experiment runs is constantly monitored.

This experimental device can be adapted for several proposals. The first of all, described in this work, is oriented to calibrate the hot-film probes. The second utilization of this apparatus is in the jet studies. Several experimental works can be realized for isothermal axisymmetric jet studies utilizing this experimental device. A free jet and an impinging jet against a solid wall are two examples of flow which can be studied, just by slightly adapting the experimental device. In the same way, changing the support mounted in the jet root, this experimental equipment can be easily modified to test heart valves biomedical prosthesis. Valves prosthesis can be made of biological or mechanical materials and their test can be done in permanent or pulsated regime. In fact, the work of Vieira *et al.* (1997) shows a test of two kinds of heart biological valves realized in this device.

In all experiments we utilized the 55R11 fiber-film probe made by *Dantec Measurement Technology*, with 70 μm diameter quartz fiber coated with 2 μm nickel film and with an overall length of 3 mm. This is a very delicate sensor, and the students are constantly advised to take the most care to not touch it and always set the bridge selector to “stand by” mode when not actually making measurements. The 55R11 *Dantec* is a straight general-purpose type sensor which permits a wide measurement range in water medium – velocities up to 10 m/s and frequency up to 30 kHz.

A *Dantec StreamLine* 90C10 frame with 3 CTA modules 90C10 permits simultaneously measurements in 3 channels. An A/D board AT MIO 16E (16 bits), made by *National Instrument,* has been utilized in order to record the output voltage signal.

5. Flow visualization of the free jet

Flow visualization is a very useful tool generally utilized to qualitative flow analysis. In order to promote the understanding of the free jet flow by the students flow visualization is a quite useful tool in fluid mechanics learning and many workers use this technique for didactical purposes, see the work of Truchasson (1989) for example. Of course, the authors of this work have a previous experience in the use of flow visualization in several different situations in relationship to fluid dynamics teaching, examples are the papers of Vieira & Woiski (2001) and Lindquist *et al.* (1999).

Flow visualization techniques generally are employed to reveal basic flow structures in a qualitative way and hot-wire anemometry is capable of supplying quantitative results about the flow, in a limited amount. The two techniques, the hot-wire output and visual images complement each other strongly. Flow visualization provides a lot of information with very little hard numerical data and a hot-wire anemometer provides numerical information with very limited flow physics. An effort to link flow visualization and quantitative flow data obtained by anemometry is explained by Freymuth *et al.* (1983).

In order to promote the flow visualization of the jet, the injection of solid micro particle visualization technique has been employed in this work. Details about this useful flow visualization technique can be obtained in several classical flow visualization reviews, as Freymuth (1983) and Merzkirch (1974). The micro particles utilized have 30 μm and a specific density of 1.0 ± 0.02. Made by *Optimage NB* this seeding powder shows a polycrystalline structure producing a scattering effect up to 5 time more of the latex micro spheres with similar reflection level. *Optimage* seeding power is indicated too PIV and LDA applications. When the particle in suspension in the fluid are illuminated by the light sheet the scattering phenomena occurs. The scattered light is recorded in a high sensible chemical photographic roll film in order to capture and process the images.

The light sheet illumination producing a thin light-cutting plane sheet was obtained using two *Kodak Carrousel* slide projector and a specially prepared high-contrast all opaque black – except for a transparent slit – slide, although the use of high power laser sheet would be much more indicated due to its very intense illuminating power.

The image pictured in the figure 3 has been captured utilizing a single lens reflex (SLR) *Nikon* F4s camera equipped with a high luminosity 60 mm *Nikor* macro lens using a high speed black and white (B&W) photographic roll film type 135. The image capture was carried out utilizing 4 seconds of exposure. A long exposure time permits recording the particle tracking as visualized in the image. *Kodak T-max* p3200 films for B&W prints have a new technology of the T-grain and they permit to obtain elevated fine grain and high sensibility – ISO 3200 – i.e. 5 times more sensible than conventional ISO 100 film. Additionally, this film was pushed using high sensitizing technique to ISO 25000 and developed in *Kodak T-max* developer.

A profusion of beautiful flow images can be found in several fluid mechanics books, many of they especially directed to flow visualization and flow image processing and, nowadays, in Internet. But, images produced in the laboratory by the students themselves is highly exciting and motivating to all of them.

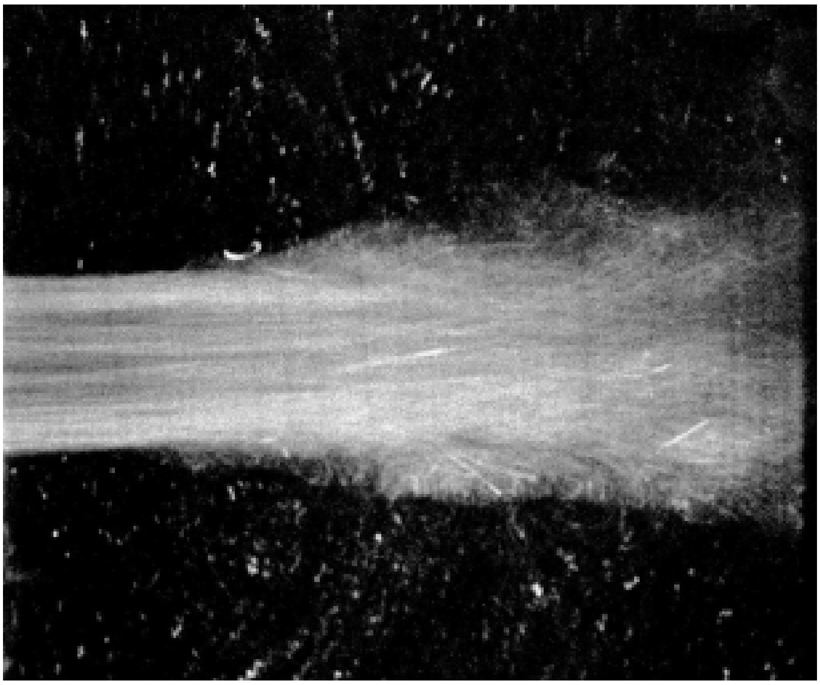


Figure 3 Axisymetric flow image showing a alongside cut view of the jet center plane.

Figure (3) shows a jet image captured with Reynolds number (*Re*) equal to 1920. Potential region where the hot-film probe to be calibrated is positioned can be clearly noticed close to the root jet. The particle tracking in potential region is very parallel. Potential region have approximately a length of the double of the diameter of the jet in the root. This situation is very indicated to the calibration process because no precise adjust of the probe inlet the jet is required. Out the jet, in quasi-rest fluid, very short particle tracks, considering the 4 second-exposure time, are recorded.

7. Calibration activities classroom

The hot-film probe is inserted in the jet very close the root, because the in potential flow no precise adjustment is required in the probe position. The students should see and provide that the probe sensor be perpendicularly positioned in relation to the longitudinal jet axis. The volumetric flow is measured with a precise rotameter and allows to precise determination of the flow velocity in the jet root.

The StreamLine software available by *Dantec* provides a precious help in the calibration process, reducing the calibration time. Figure (4) shows a typical calibration curve obtained in laboratory classroom activities by students.

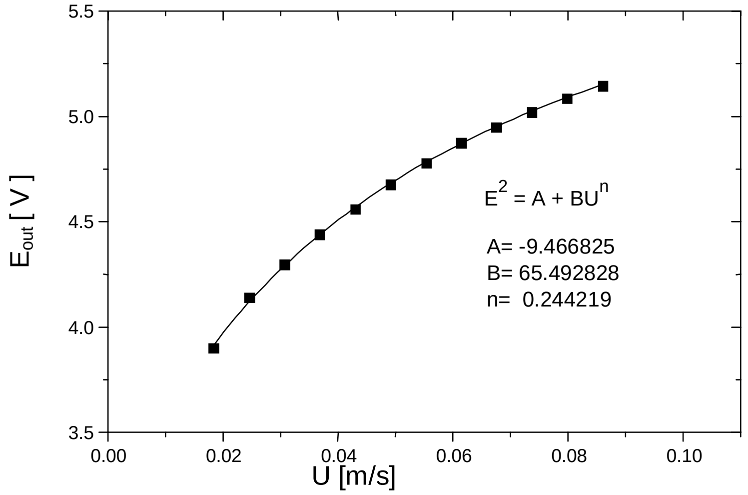


Figure (4) Typical calibration curve obtained in the laboratory activity

7. Measurements in the free jet

The Fig. 4 pictures the sketch of a free jet according to Pai (1954), the axisymetric nondimensional velocity in the jet root is denominated (U_0) and (u) represents the component of the flow velocity in the x direction. The (U_0) velocity assumes a constant value equal to one in the jet nozzle, i.e. (x) = 0. Four regions internal the jet can be classified. First of all, close the jet root, presents the potential core in cone format. In this region of the potential cone is positioned the hot-film probe destined to calibration. The mixing region I is characterized by a linear increase of the mean velocity. The transition mixing region II, after the potential cone remain the linear velocity distribution. Finally, the region III characterized by Tallmien´s solution.

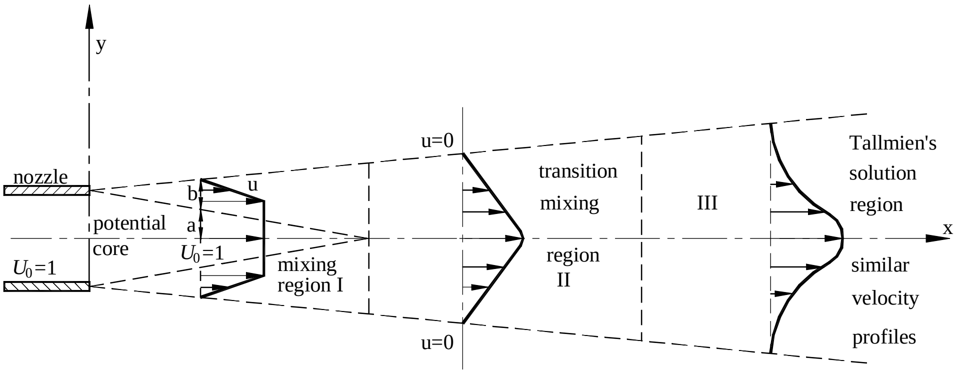
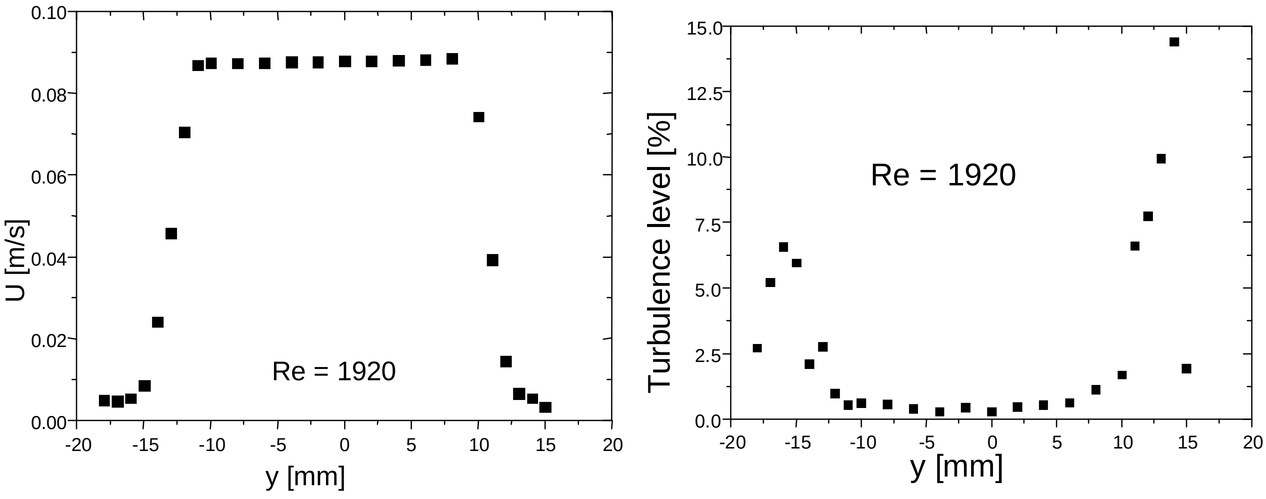


Figure 4. Axisymetric free jet.

Schlichting, (1974) shows a exact solution for an incompressible axially symmetrical laminar jet blowing in a rest surrounding fluid. Considering the pressure constant the solution can be obtained. An important result is observed in this solution, showing for (y=0) the flow velocity decreasing linearly.

A hot-film probe was positioned in (x/D) equal to 1, around one diameter of the jet root, for Reynolds number equal to 1920 (same value of the jet visualized in Figure (3)) and the probe is displacement in the (y) direction. Flow velocity has been measured utilizing a sample of 1024 points and a sample frequency of 100Hz, who permits 10.24 s of time acquisition. Figure (5) pictures (a) the mean flow velocity and (b) mean relative turbulence level versus (y) position. The jet diameter (D) in the root of the jet is equal to 24 mm. plane velocity profile can be seen in inlet jet with a relative low turbulence intensity. That is the region in which the hot-film sensor should be positioned for calibration proposes. Out the jet flow velocity is very small, the CTA anemometer remain showing a positive value close to zero in function of convection effects provoked the temperature difference between the fluid (ambient) and the sensor elements (150°C). The instructor should explain all of those effects in details for the students. In the jet interface with the rest fluid, a turbulent region is noticeable, in fact exhibiting a very high turbulence level.



(a) Transversal jet velocity in the root (x = 0) (b)Transversal turbulence level in the root (x = 0)

Figure (5) Mean velocity and mean turbulence level in (x/D) equal to 1.

In the next measurement performed, the hot-film probe is positioned in the longitudinal axis of the jet, i.e., in the y = 0 position. The probe is moved along the x axis for different values of x/D. Figure (6) shows a flow velocity in function of the time for four (x/D) values. The horizontal straight lines represent the mean velocity for different samples. Figure (7) shows the linear mean velocity decrease in the longitudinal axis in accord to Schlichting's results.

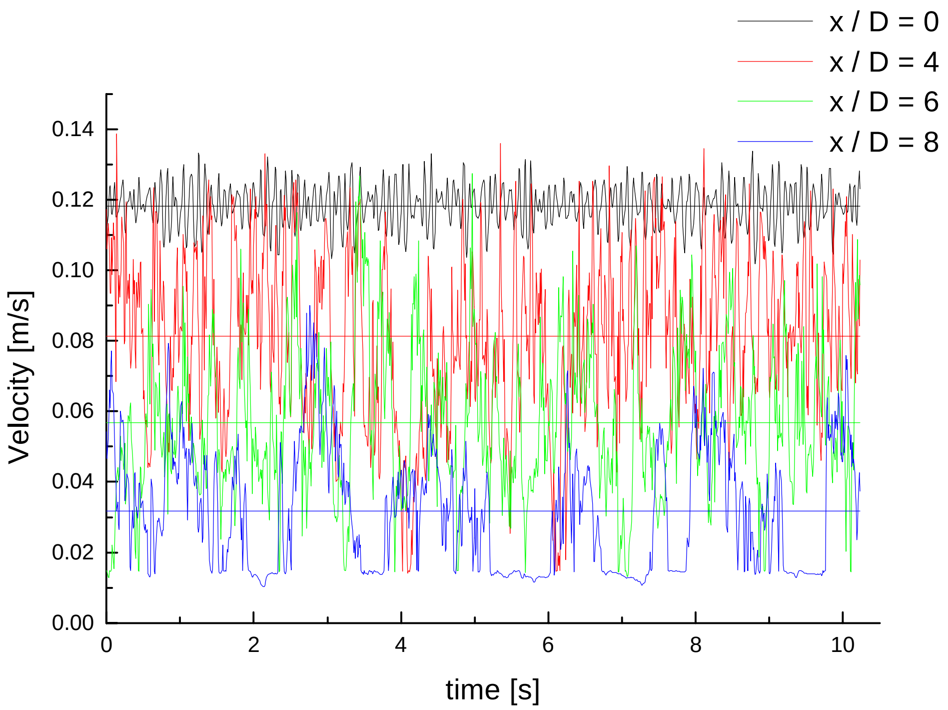


Figure (6) Flow velocity in longitudinal axis of the jet.

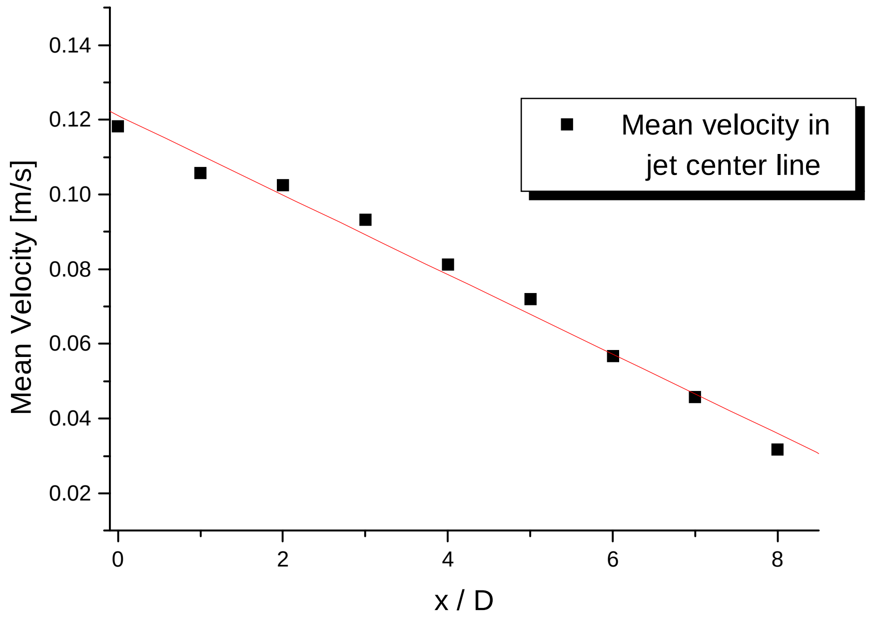


Figure (7) Mean velocity decreasing along of the longitudinal axis.

The data obtained in Figure (6) permits to determine the RMS relative turbulence level, showed in Figure (8). The horizontal straight lines represent the mean value. Only 3 samples are represented to facilitate interpretation. Closer to the jet root a relatively low level of turbulence can be obtained, whereas farther from the root a much higher level of turbulence is found. Figure (9) shows the mean value of the relative turbulence level along the (x) axis, where is observed a quasi-linear increase of turbulent level.

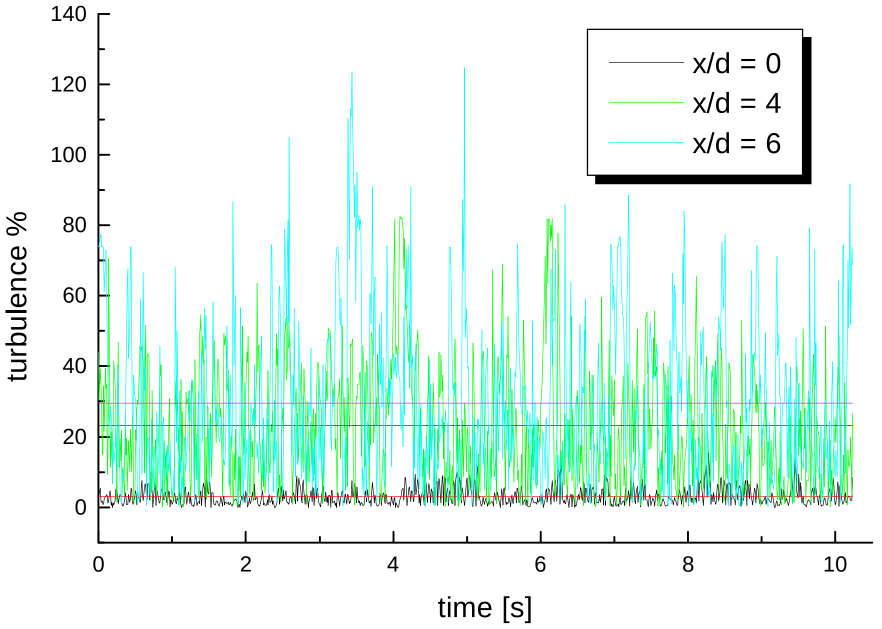


Figure (8) Relative turbulence level in percent

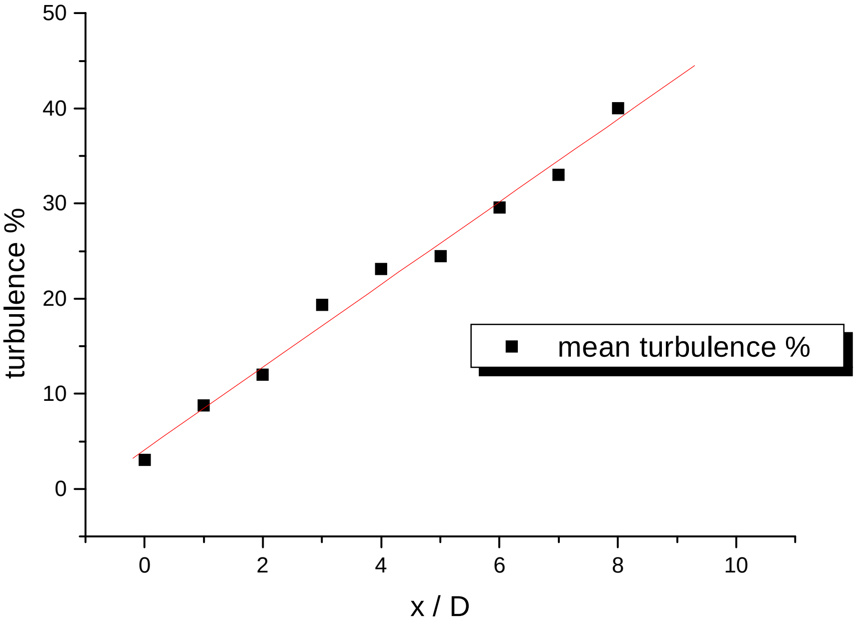


Figure (9) Mean relative turbulence level

8. Probe contamination and loss of calibration

The probe active surface is subjected to contamination caused basically by small solid particles and metallic ions present in suspension in the water. Metallic ions are emitted by metallic ducts, pump and others metallic connections in water contact. The use of PVC tubes and other non-metallic parts reduces the metallic ions. Use of filters is needed for solid particle retention. It is recommended a use of a minimal 5 μm solid particle retention filters. The effect of contamination is equivalent to a decrease in probe overheat. Cleaning occasionally the probes and using clean liquids such as the deionized, deaerated and filtered water can minimize this drift although for large quantities of water this procedure is not practical. In the beginning of the test, the contamination effects are negligible but after one or two hours of work the effects can be noticed. After several days of work the probe shows unstable readings, indicating the nearly probe failure. Figure (10) shows, for example, an unstable probe operating, the output velocity decrease quickly, and the probe failure is registered when output voltage remains fixed in a low value.

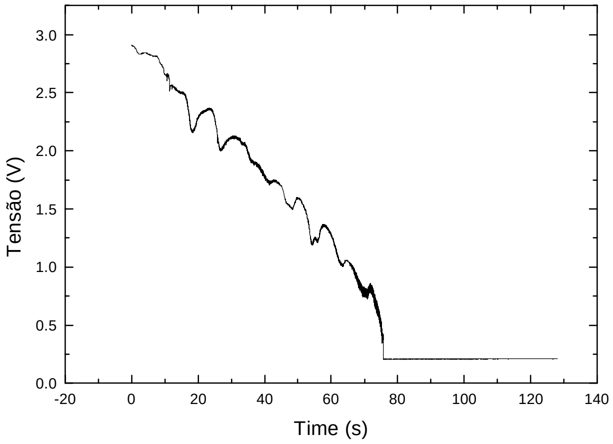


Figure (10) Typical probe failure.

9. Conclusion

Hot-wire/film anemometry is a very well established technique that permits to determine mean velocity and turbulence in gaseous and liquid flow. Utilized in several research flow laboratories, HWA find today several applications in the day-by-day of an engineer. These current engineering applications of the HWA motivate the introduction of this thermal anemometry in the fluid mechanics laboratory class.

The results presented in this work have clearly demonstrated the reliability of the proposed laboratory class activities utilizing HWA in a mechanical engineering undergraduate course. The test rig itself is very simple and the calibration experiments were relatively easy to be carried out. Utilizing the access to computational facilities no difficulties have been experimented in implementing the data acquisition and manipulation. The proposed experiments prove themselves to be a simple and reliable method for anemometer probes low velocity calibration.

However, the use of a hot-film probe in water flow is complicated by the probe active surface contamination problems, high susceptibly to fluid temperature effects and low useful lifetime of the high cost probe. The presence of contamination by impurities in the water provokes a rapid degradation in the calibration characteristics of the hot-film probe.

Previously, the first experience of the authors utilizing HWA in laboratory class has been proposed utilizing a hydrodynamic tunnel. The probe has been fixed in a appropriate point of the test section where the calibration measurements have been carried out. Nowadays the calibration is always performed (by undergraduate and graduate students themselves) in the special device described in this work and only the actual flow measurements are realized (also by the students) in the hydrodynamic tunnel. This measurement classes are object of a future publication.

HWA is shown to be an ideal mechanism to introduce good laboratory procedures as well as procedures that have wide use in technological industries and research laboratories. One attractive point of this laboratory class is related to the use of a sophisticated piece of instrumentation. In fact, the use of “real instrumentation” in order to obtain fluid flow velocity, turbulence and other important parameters in a laboratory class, in opposition to demonstration-only experiments, highly increases the student’s motivation to grasp a difficult and complex subject. In this way, the use of HWA as a teaching tool has proven to be very important to attaining the goals set by the fluid mechanics instructors in engineering undergraduate studies.

10. Acknowledgement

This work has been possible in function of the FAPESP grants. The authors are grateful too to Fundunesp and PROP/Unesp.

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