HOT FILM CALIBRATION SYSTEM USING A FREE JET IN WATER

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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. Despite the several advantages of HWA, frequent necessity of probe calibration remains the greatest difficulty in using this type of anemometer. A device for film probe calibration in water mwdium for low velocities has been proposed in the present work. 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. Several visualized images of the free jet has been captured using different flow visualization technique and several measurements of the velocity profile and turbulence is obtained. The proposed apparatus shows a good optation in an accurated and rapid hot film calibration.*

Keywords*: Hot film anemometry, Turbulence, Flow visualization, Free jet, Probe calibration*

1. NOMENCLATURE

A	Calibration constant	Re	Reynolds number
B	Calibration constant	S_t	Strouhal number
D_0	Diameter of the free jet	T_f	Fluid temperature
D	Diameter of a circular cylinder	T_w	Wire temperature
E	Output voltage	V_∞	Free stream velocity
f	Vortex shedding frequency	u	Velocity in the x direction
h	Convective heat transfer coefficient	U	Mean fluid velocity
I	Electrical current	U_0	non dimensional velocity
n	Calibration constant	x	Centerline jet axle
R	Electrical resistance		

2. INTRODUCTION

Hot-film anemometry technique is a powerful tool in experimental research in liquid fluid flows. Many advantages can be noted down using Hot-film anemometry systems in research environment. Low acquisition costs (in comparison to LDA - Laser Doppler anemometers - or PIV - Particle Image Velocimetry), high frequency response (up to several hundred kHz in ideal conditions can be obtained), small-size sensors, very wide velocity measurement range (from very low velocity to compressible flows), very accurate results, and many others advantages have been verified in H.W.A. practical books – Bruun, (1995) and Fingerson, (1983). In the last years many industrial applications have been found to hot-wire anemometry, in special, to measure clear gaseous mass flow in fluctuating temperature fields – Menut, (1998). Other important application of hot-wire anemometry is to measure airflow in internal combustion engines. Most modern engines are equipped with a mass air flow rate sensor to control the correct amount of fuel in order to improve performance and reduce harmful gas emissions – Sasayama *et al*. (1983).

Commercially available hot-wire/film 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/film 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. Other important information about hot-wire/film anemometry 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 texts 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 of clear gases are found, and a large number of models of hot-wire anemometry for several industrial applications are commercially available today. Unfortunately, all industrial applications of HWA are only to gas flow.

There are innumerous difficulties encountered in operation of hot-film anemometry in liquids, especially the water. Frequent sensor contamination due to use of non filtered liquid generates frequent loss of calibration. Deposition of dirt on the film alters significantly its frequency response as well as the mean calibration. The probe active surface is subjected to contamination caused also by 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. Since the film sensor is hotter than the water, the air solubility in the water is sensibly reduced near the probe. Bubbles formation at the film sensor changes the thermal conditions and alters considerably the calibration. Gas bubble formation in the sensors requires careful deaeration of dissolved gases and operation in very low temperature of the probes. The hot film sensor operated at temperatures well below the boiling point resulting in a delicate combined sensitivity to velocity and temperature. In this situation, small water temperature variation may significantly alter the temperature difference between the hot film and the water medium, causing significant output signal variation – Win & Prahl, (1986) and Tselentis, (1982). Because of the frequent calibration loss of the film probes in liquid application a use of hot film anemometry in industrial applications for liquid flow rate measurement is practically inexistent. Today, the greatest obstacle to the use hot-film anemometry in laboratory environment is the need to use reliable calibration devices. This paper presents a simple calibration apparatus developed for rapid hot film probes calibration in water medium at constant temperature.

3. HOT FILM PROBES CALIBRATION DEVICES

The hot-fim 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 calibrations of these probes are an arduous work because liquid flow calibration device no are commercial avaliable. Even so, several hot-wire industries sales equipment for calibrating probes, this calibration devices are much 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-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 for a circular cylinder. The flow velocity has been obtained by measuring the vortex-shedding frequency, provoked by a polished drill rod. Strouhal number (S_r)can be defend with a relation of the diameter of the cylinder (D), free stream velocity (V_∞) and vortex shedding frequency (f). For Reynolds numbers more than 300, Strouhal, number remains constant in 0.21 and, in this situation, measuring the vortex frequency is possible to obtain the flow velocity. 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 $146 \times 146 \times 500$ 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 an extensive literature about the theme.

4. EXPERIMENTAL APPARATUS

In order to implement this experiment is necessary the use of a flow generator, a calibration device, a hot-film probe, a CTA hardware and, additionally, an acquisition system software and hardware.

4.1 Flow generator

A free jet produces a stable flow with a uniform velocity profile easily controllable and a low turbulence level. For these reasons, many aerodynamic tunnels utilize a free jet to carry out the experimental tests. An open wind tunnel has the additional advantage of the absence of interference from the test section walls and the ease of physical access to model tests. In order to create a free jet with a uniform velocity profile and low turbulence level a very little axis symmetric hydrodynamic tunnel has been made with a D_0 of only 25.4 mm. The apparatus has the same parts of a hydrodynamic tunnel but in reduced dimensions. The jet diameter is sufficient to accommodate the hot film probe and to perform the calibration.

The Fig. 1 pictures the sketch of a free jet according to Pai (1954), the axisymetric no dimensional 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.

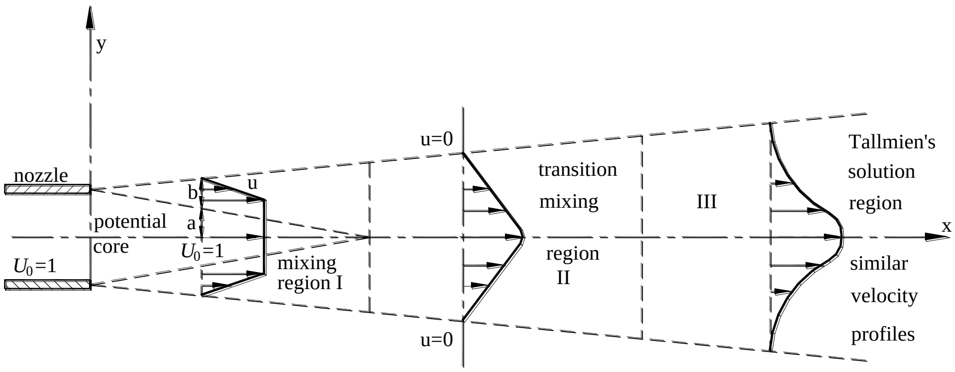
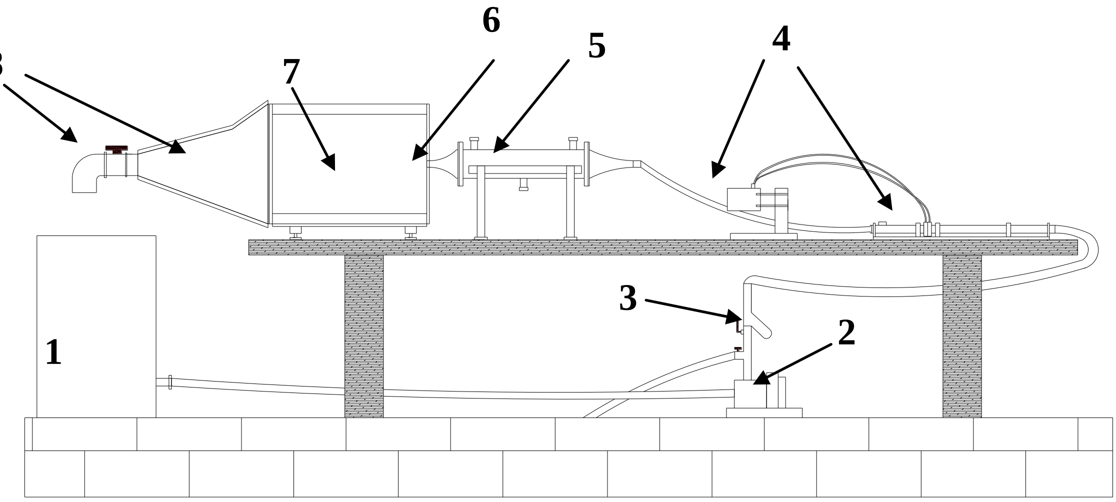


Figure 1. Axysymmetric free jet.

4.2 Calibration device

Low turbulence level and flat velocity profile are the desirable flow characteristics in the test section of a proper designed flow generator. The flow generator proposed in the present work, depicted in Fig. 2, is similar to a small horizontal water tunnel with an open section test and operated either in closed or open circuit. The steady flow setup (Fig. 2) may be divided in three main parts, namely flow straightener, test section and outlet diffuser. The upstream assembled flow straightener has been designed to generate a 25.4 mm diameter low-turbulence jet entering the test section. For that, proper flow conditions in the outlet portion of the flow straightener has been obtained by forcing the flow through a flux laminator, composed of several distinct subsections. The first one is the inlet diffuser, in which the action of fine mesh wire screens eliminates perturbations caused by hydrodynamic boundary layer separation on this divergent section. Then the flow passes through honeycombs inside the stagnation chamber to reduce the vorticity level. Finally, before entering the test section, the flow faces a contraction subsection, which is a very important component to obtain a flat velocity profile in the test section. An accurate contraction design and construction is mandatory to reduce boundary layer thickness, a most favorable condition to homogeneous velocity profile.



(1)Water reservoir (2)Centrifugal pump (3)Sphere valve (4)Flow measurement
(5)stagnation chamber (6) Free jet (7)Test section (8)Diffuser

Figure 2. Flow Generator.

4.3 CTA hardware

Since HWA is a thermal transducer, it is a rather complicated instrument. There are two types of hot-wire anemometers – the (CCA) constant current and the (CTA) constant temperature –, but the CTA is used almost exclusively nowadays. The CTA consists of a fine wire (or coated cylinder in the case of a hot-film) which is exposed to the flow. This wire is heated electrically to some constant temperature much higher than the fluid temperature. As the fluid flows over the wire, the wire is cooled by forced convection. The current applied to the wire is adjusted in order to keep the wire temperature constant. The current required to do that becomes a measure of velocity. The convective cooling must be balanced by electrical energy input (I^2R), in according with Perry, 1982:

$$I^2 R = h A (T_w - T_f) \tag{1}$$

where, (h) represents the convective heat transfer coefficient, and ($T_w - T_f$) the temperature difference between the wire and the fluid. Convective heat transfer away from a body in a moving air stream is primarily a function of the local Reynolds number (Re), and overall heat transfer increases as Re increases. For measurement purposes, the hot wire is connected to a bridge circuit and a digital controller

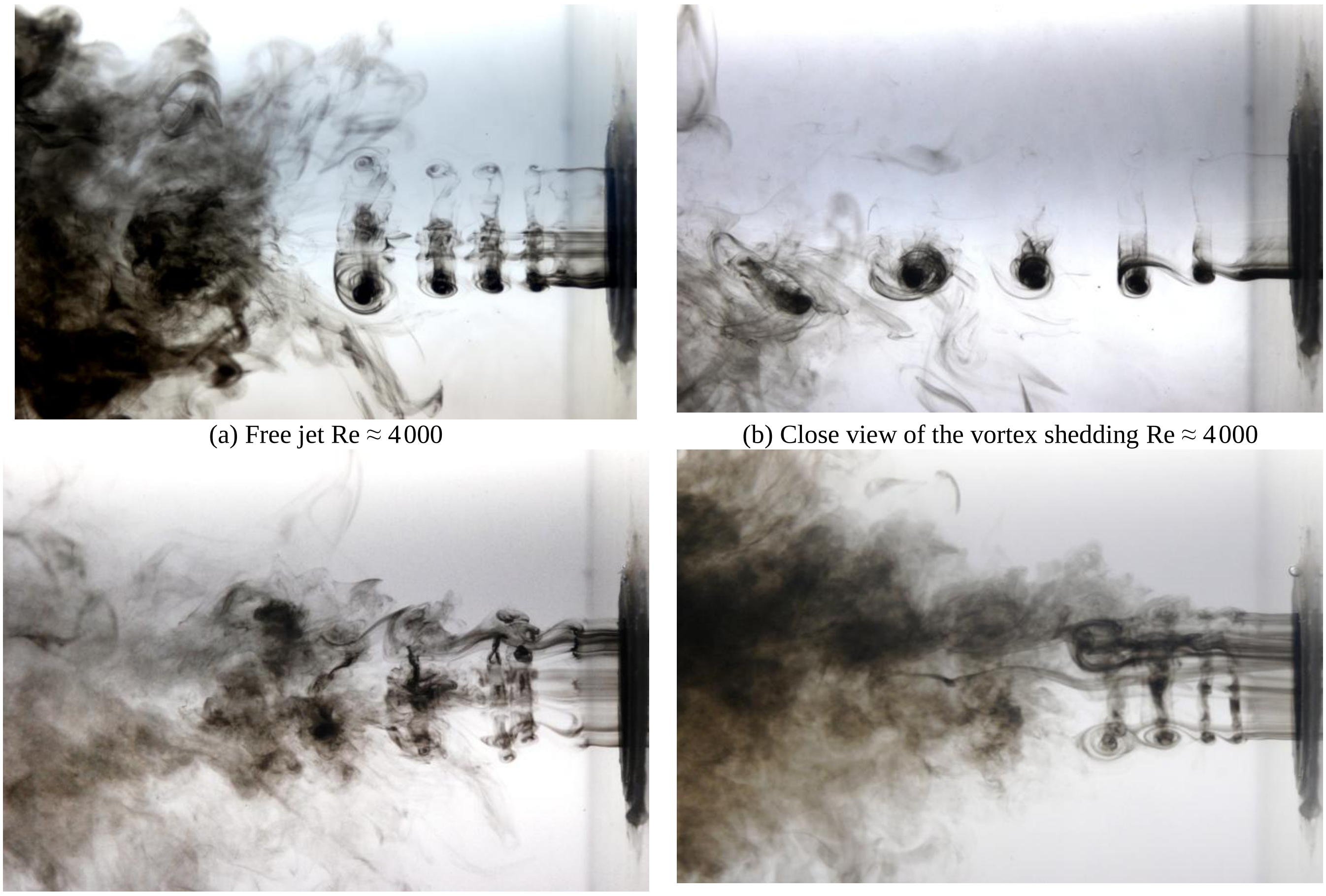
The hot-film probe resistance will increase as the temperature increases. Thus as temperature changes the bridge will become unbalanced. A DC amplifier senses the unbalance and produces a change in voltage, and then current through wire sensor to keep the bridge balanced. The resistance of the controlling resistor determines the operating temperature of the hot-film. A relation between output voltage (E) and fluid velocity (U) named “King’s Law”, in accord to Perry, (1982), is shown in (2):

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

where, (A), (B) and (n) are calibration constants. Currently, the constant (n) is choosing around 0.5, and the other constants (A) and (B) are obtained by minimizing the fitting errors. The non-linearity in the calibration characteristics of CTA instrument, showed in (2), turn the calibration process a very delicate work.

5. RESULTS

Flow visualized images of the free jet obtained by direct liquid dye injection in the stagnation chamber is depicted in Fig. 3 in several Reynolds numbers. In Fig. 4 is showed the flow visualized image using solid micro particle and laser sheet illumination for Reynolds number equal to 3400. The flow image is captured utilizing a relative long exposure time. In Fig. 5 is showed the jet flow visualized image using also solid micro particle for Reynolds number equal to 2100, but utilizing a relative short exposure time. Finalizing, in Fig. 6 is depicted a typical calibration curve using a 55R11 Dantec hot-film probe.



(a) Free jet Re ≈ 4000

(b) Close view of the vortex shedding Re ≈ 4000

(c) Free jet Re ≈ 8500

(d) Free jet Re ≈ 11300

Figure 3. Free jet visualized images using liquid dye injection flow visualization technique.

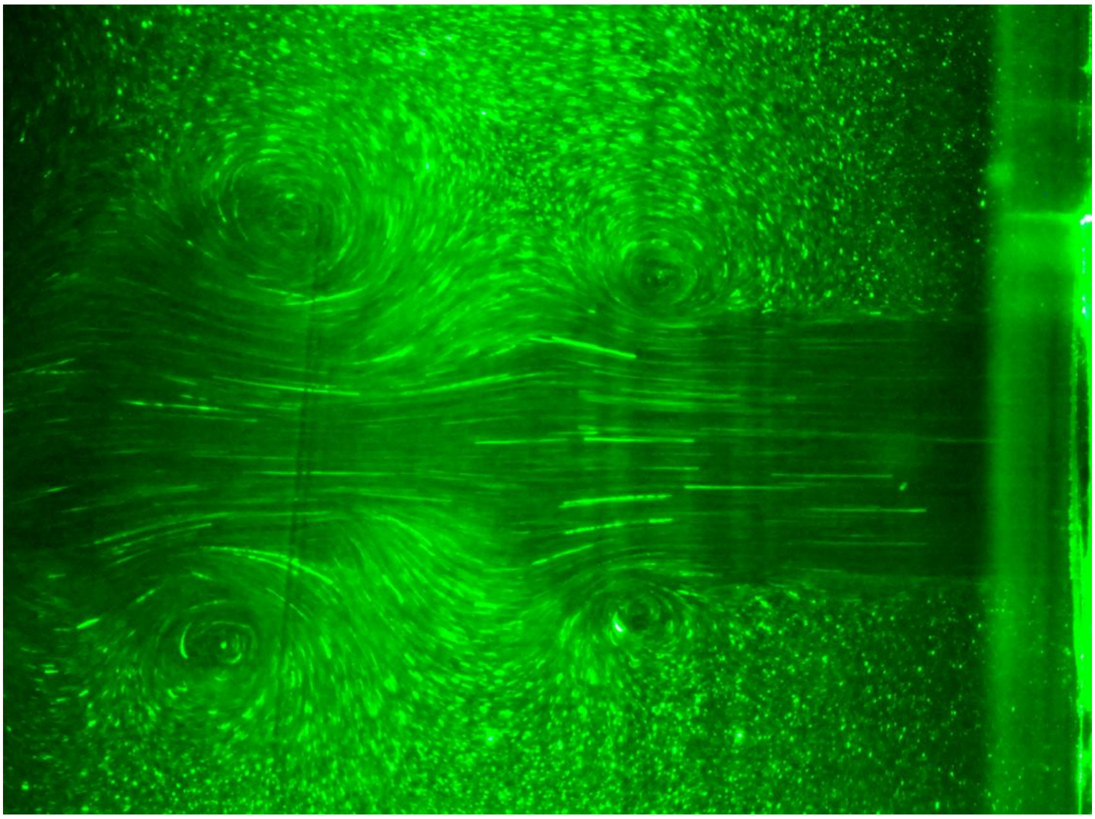


Figure 4. Visualized jet image using solid micro particle and laser sheet flow visualization technique for Re ≈ 3400.

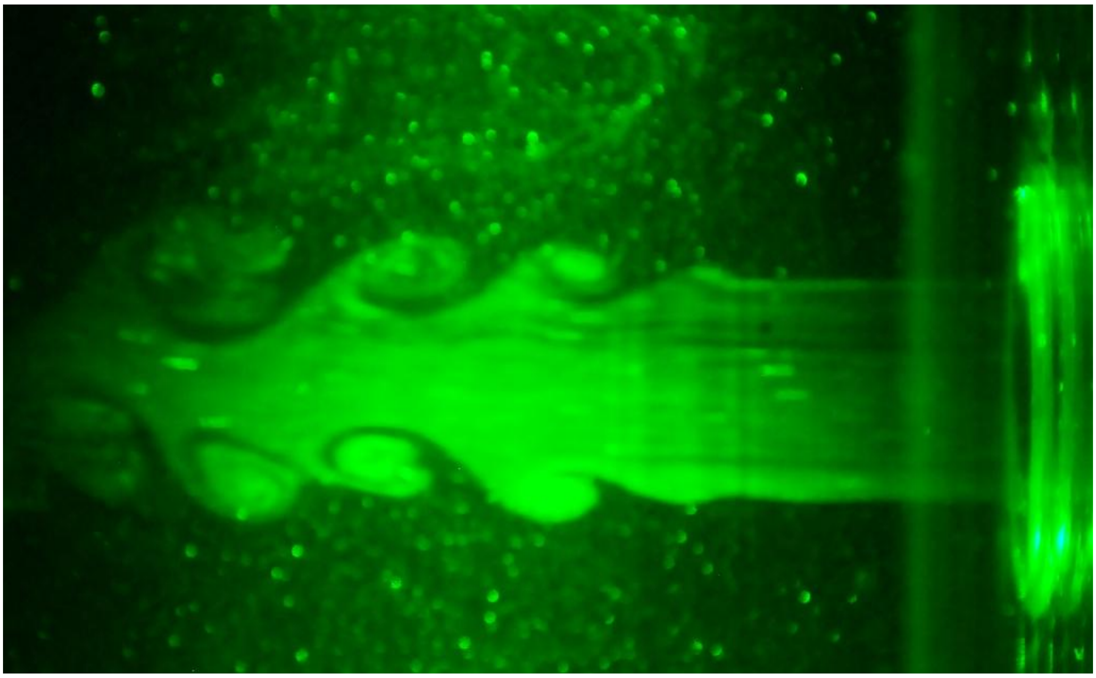


Figure 5. Visualized jet image using solid micro particle and laser sheet flow visualization technique for Re ≈ 2100.

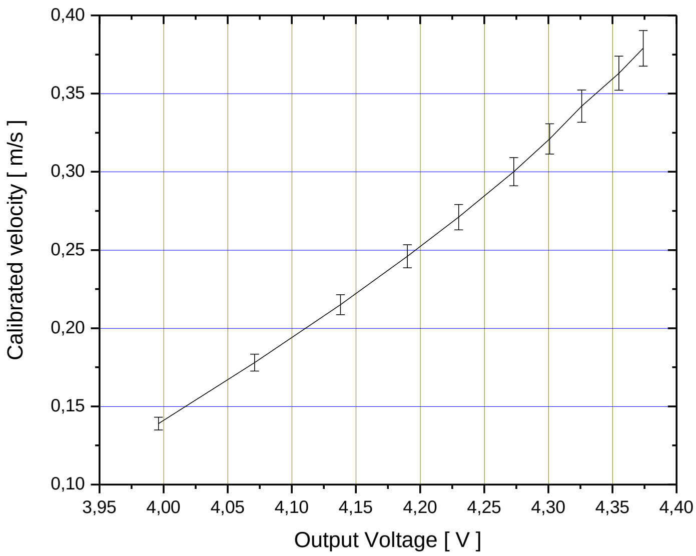


Figure 4. Hot film probe calibration.

6. CONCLUSIONS

The flow visualization image is an important way to provide a global view of turbulent flows. In other side, hot-film measurement gives only local information. The visualization overview allows an easy comprehension of the whole physics problem. Unfortunately, this flow visualization information is only qualitative. But, the hot-film probe measurements give accurate quantitative local information. The simultaneous use of flow visualization together HWA is an important work tool for fluid mechanics research.

Schlichting, (1974) shows an 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.

7. ACKNOWLEDGEMENTS

The experiments have been financed by FAPESP and FUNDUNESP.

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5. RESPONSIBILITY NOTICE