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DEVELOPMENT OF A BASIC CIRCUIT OF A HOT-WIRE ANEMOMETER

Carlos Cesar Aparecido Eguti
UNESP – Ilha Solteira, Departamento de Engenharia Mecânica, 15385-000 – Ilha Solteira, SP, Brazil
eguti@dem.feis.unesp.br

Edson Del Rio Vieira
UNESP – Ilha Solteira, Departamento de Engenharia Mecânica, 15385-000 – Ilha Solteira, SP, Brazil
delrio@dem.feis.unesp.br

Abstract. *Hot Wire Anemometers are thermal transducer capable to relate the transfer rate of thermal energy of a small metallic filament, submitted to an electric current and submerged in a fluid, with the speed of the flow around the filament. Working with constant temperature, the hot wire anemometry offers a form of flow measurement widely used by research laboratories and nowadays, by several industrial, aeronautical, automotive and military environments. In this work, a constant temperature hot wire anemometer was developed, composed by a probe of platinum wire with diameter of 25 mm and an electronic circuit of control, it was projected and built for measurement of profiles of speed and turbulence in homogeneous flows of gases fluids. An experimental apparatus was also set up for calibration of the probes composed of a free jet, with axial symmetry, discharging in atmosphere. The prototype was tested in the measurement of air speeds below of 40 m/s with 10 kHz of frequency response. Comparative measurements with the StreamLine system supplied by Dantec Dynamics Inc. of Denmark they were accomplished, showing good agreement in the results and with costs many times smaller.*

Keywords*. hot-wire anemometer, instrumentation, flow measurements, thermal transducer.*

1. Introduction

Hot wire anemometers have been well known for almost one century and currently remain an important tool for theoretical and experimental analysis of the fluid flow with relative free stream turbulent levels below 25%. The hot wire anemometry (HWA), have countless advantages when compared with other techniques of measuring the speed fluid flows, mainly, it is cheaper relative acquisition cost, comparing to LDA – Laser Doppler Anemometers, and to the modern systems of PIV – Particle Image Velocimetry. The frequency response of HWA is typically from 20 up to 50 kHz, unlike LDA, in which the frequency response is limited to 30 kHz. Some special hot wire anemometers can even operate above a hundred of kHz, accord to Brunn (1971).

Low maintenance costs and easy operating are another relevant features making HWA for use in research laboratory the preferred choice, among other techniques of obtaining of the speed fluid flow, representing a safe investment for engineers and researchers looking for fast and practical results in the fluid dynamics measurements.

2. Hot wire anemometry

A hot wire anemometer is basically a thermal transducer. An electrical current crosses a fine metallic filament, which is exposed against the movement of a fluid. The heat generated by the passage of the electric current in the filament is transferred to the fluid when your thermal balance varies, modifying the electrical resistance. Such variation can be quantified and monitored using several electronic circuits, able to correlate to the speed of the fluid.

Basically there are two modes of operation of the hot wire anemometers: (1) Constant Current Anemometer or CCA; and (2) Constant Temperature Anemometer of or CTA.

In the constant current anemometers a constant electrical current is supplied to an exposed filament, however this circuit is very sensitive to temperature variations in the fluid. The operation needs special attention because abrupt variations of the fluid velocity can burn the filament due to critical heat flux.

The electronic circuit of hot wire anemometer widely used is the constant temperature mode (CTA). According to Bruum (1995), the constant temperature anemometers are capable of providing a fast compensation for the thermal inertia of the warm filament, accomplishing this there is an automatic and continuous adjustment in the point of operation of the circuit when the conditions of the fluid change. Since the coefficient of convection of the filament is a function of the fluid flow, the balance of the temperature of the filament correspond to the measure of fluid flow. Figure (1) shows a typical diagram of CTA circuit called by Citrinti *et al.* (1994) as “sketch of Perry’s anemometer”, present in a variety of technical centers around the word, e.g. University of Melbourne, Graduate Aeronautical Laboratories, Imperial College, second Perry (1982). In the same figure, there is a typical transfer function or calibration curve.

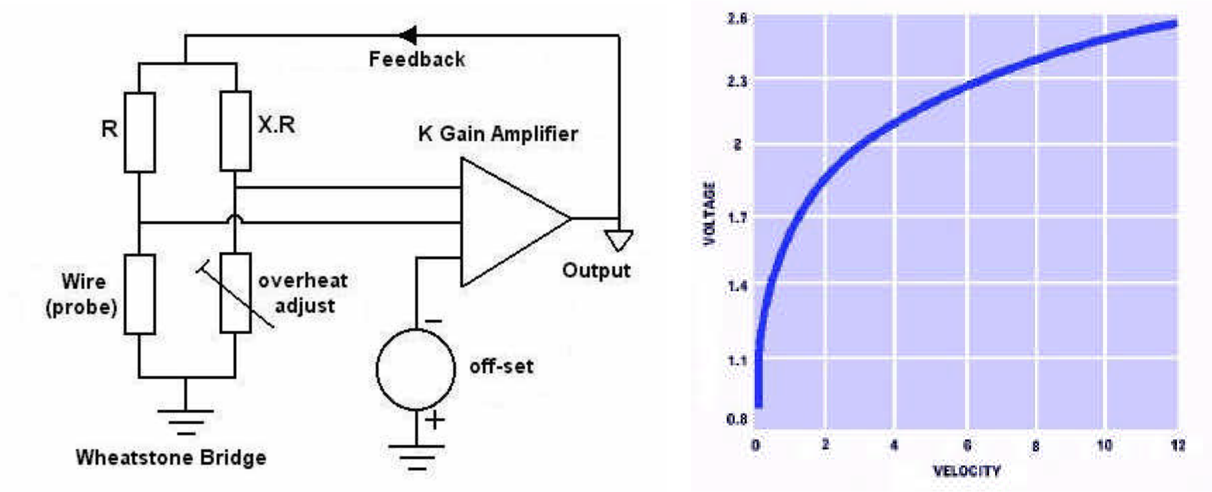

Figure 1. Sketch of Perry's anemometer and typical transfer function.

The temperature of the wire can be obtained in terms of the electric resistance and the fluid characteristics. In the constant temperature mode, the current through the wire is adjusted to maintain constant temperature in such a way that, the value of the necessary current to maintain such condition is proportional the speed of the fluid. However such relationship is non linear following an equation called "King's Law", as shown in Eq. (1), In which A, B and n are coefficients, found through experiments, E is a voltage output form CTA circuit and U the fluid velocity.

$$E^2 = A + BU^n \tag{1}$$

The core of this instrument is the filament sited in the anemometric probe. A deepened study of the behavior and of the physical performance of this filament is the key for the construction of a good anemometer. Perry (1982) is a excellent reference for this purpose.

Typical 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, necessary for laboratory conditions, 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.

The probes for an industrial application are protected from flow contamination action. These probe sensors are frequently enveloped (cladded) by a ceramic coating or metal capsule hoods that protect the heated filament. The sensor protection performs a long time of utilization without calibration but the major disadvantage of protect probes used in industrial plants are their size, much larger than non protected probes usually employed in laboratories. This size and the involved coating of sensor elements impacts the frequency response of probes. In industrial thermal anemometry the frequency response is usually limited to less than 1 Hz.

Figure (2) shows a usual laboratorial probe of *Dantec Inc.*, model 55P11 and an industrial sensor of HWA made by *Kurtz Instruments Inc.*, model 430. The first probe has a tungsten wire of 4µm diameter for 1.2 mm length and in the other, the wire is completely shielded with ceramic and mechanical protected by a stainless tube of 10 mm of diameter. The Kurtz's probe also has built-in a small platinum temperature sensor for automatic temperature correction of the output signal.

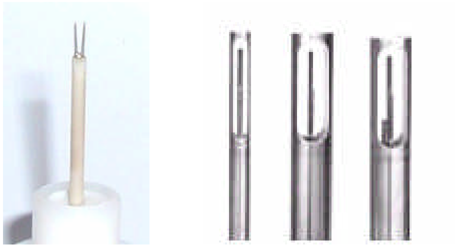

Figure 2. Typical laboratorial (left) and industrial (right) probes of HWA systems.

Hot-wire anemometers have a number of applications in industrial environment for measurement of fluid velocities and volumetric or mass flow. Because the advantages of this equipment in terms of low cost, easy conditioning signal, 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 environment with chemical reactions or presence of solid particles in the fluid they are intensely utilized in industrial process. Industrial hot-wire anemometers have the additional advantage of rarer calibrations. Because of these advantages, in the last years, hot wire anemometry shows a lot of new applications for mass and volumetric flow meter of several gases, especially the atmospheric air, in accord to Sasayama *et al.* (1983). Several advanced new applications have been possible to hot-wire apparatus in air velocity measurement utilizing the new available electronic components. Of course, modern air conditioning and refrigeration assemblies, electronic applications, electronic control of internal combustion engines, pollution control devices and several others can be cited as examples of new hot-wire anemometry. A development of an electronic circuit and the probes of a hot wire anemometer for air measurements suitable to many laboratorial applications and with few modifications possible to industrial use is the principal goal of this effort of work.

3. Circuit Design

Figure (3) shows the developed CTA circuit of HWA. As the speed of the fluid varies, the electric resistance of wire (R3) modifies, causing a variation in the value of the voltage at points (Va) and (Vb) of Wheatstone bridge with ratio 1:20, adjusted by (R2/R1). Such variation is measured by the first differential amplifier (X2 – Burr-Brown INA 131 Precision Instrumentation Amplifier), which amplifies 100 times this value. Second Goldstein (1983), the bridge ratio is related with frequency response of the circuit and ratio near to 1:1 assurance better frequency response however, because of stability, many anemometers use values with bridge ratio of 1:10 or 1:20.

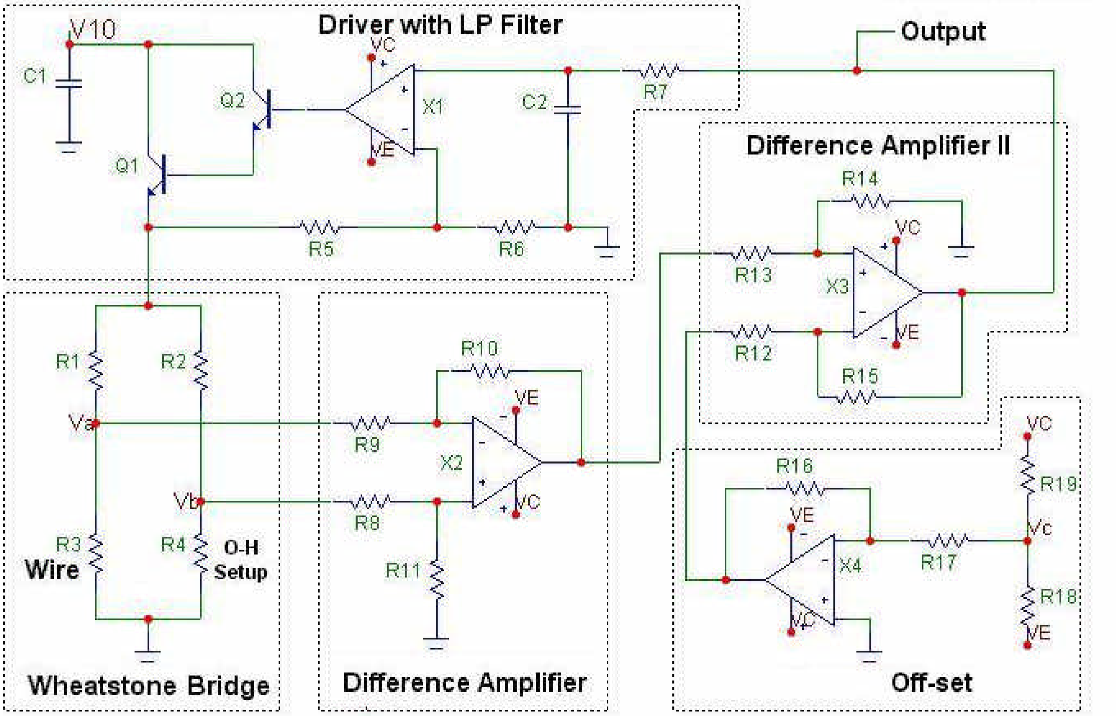

Figure 3. The constant temperature circuit of HWA.

The adjustable resistance (R4) allows the adjust of “overheating” factor of the anemometer. This value defines the temperature of work of the filament, based on the fluid property, as swown in Eq. (2). For use of the probe in air or gases, (*a*) = 0.8, with operation temperature of approximately 220 °C. For water, (*a*) = 0.1, placing the filament in a temperature close to 30 °C. In Eq. (2), (BR) is the bridge ratio, (R_{wire}) is the filament resistance, (R_{cable}) the probe cable resistance and (R_{prongs}), the resistance of the support of the wire.

$$R4 = BR[(1+a).R_{wire} + R_{cable} + R_{prongs}] \tag{2}$$

The output voltage of Difference Amplifier (X2) is sent to another amplifier (X3 – Burr-Brown OPA-177 Precision Instrumentation Amplifier) in order to summing this voltage to the off-set adjust. After this, a sub-circuit convert this voltage variations in current variations in the bridge circuit and maintains constant this difference by means of another operational amplifier (X1 – Burr-Brown OPA-177 Precision Instrumentation Amplifier) that drive a Darlington transistor which is used to control the current in the feedback loop. Point (V10) makes the supply of Wheatstone bridge.

Set point adjusts or offset is made by another sub-circuit thought operational amplifier (X4 – Texas TL-071 JFET Operation Amplifier) through (R18). This initial value puts the driver circuit of the bridge in the operation point.

According to Weidman & Browand (1975), the frequency response of first operation amplifier, in this case X2, is directly related to the global frequency response of the anemometer since, the specification sheets of INA 131 assure 70 kHz of operation frequency with bandwidth of –3dB and CMRR of 120 dB. This device is specific to use in bridge circuits, data acquisition, medical instrumentation and other high precision applications.

There are no compensations on the bridge inductance and capacitance effects due to cable lengths because they were found minimal and negligible during the initial tests.

Special attention is given to resistance (R1) due to heat dissipation. For the projected circuit, we have that R6 = 25.6 Ω, causing an electric current of approximately 200 mA. This power dissipation (about to 1 Watt) is somewhat high for most of the electronic circuits. To minimize the effects of the resistance variation in consequence of temperature increase, the use of a resistance bank represents a great solution, once the total dissipation of the bank is directly proportional to the power dissipation of each resistance. Figure (4) shows this resistance bank up to 10 W, suggested by Perry (1982).

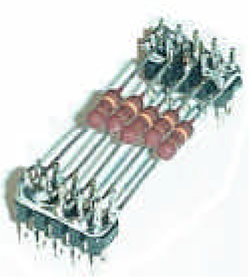

Figure 4. Resistance bank of R1.

Figure (5) shows a prototype assembly of the CTA circuit of this work with a brief description of the adjustments points and connections.

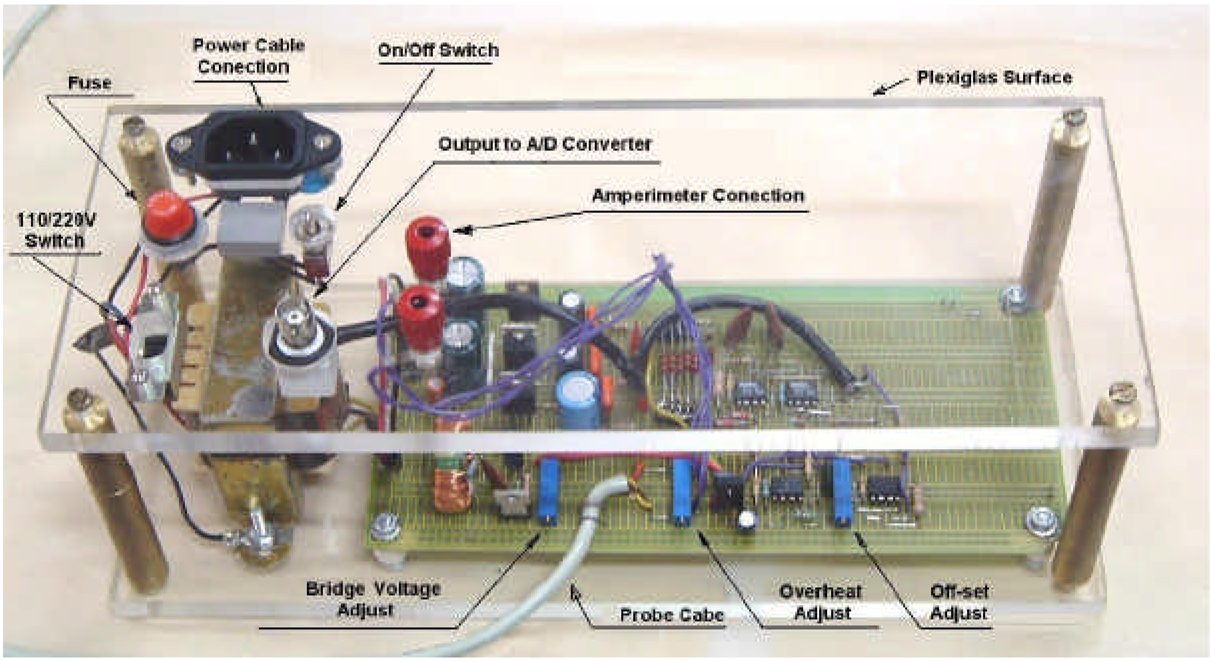

Figure 5. Full view of CTA circuit (prototype assembly).

The circuit was built in a standard print circuit board and fixed in a plexiglas structure in order to gain easy access to all component of the circuit. Voltages to all operation amplifiers are supplied by low noise symmetric 15 Volts (± 15V). This apparatus have only 230×120×100 mm of external dimensions and 0.4 kg of weight without the cables and probe. The probe has been connected to the CTA circuit utilizing a 4 m cable long shielded.

4. Probe design

An important relationship for the probe is the filament length (l) and diameter (d), which is directly linked to the probe's sensibility, as Bruun (1995). High values of (l/d) imply an amplifier with relative low gain and this way, improving the stability of the instrument. According to Goldstein (1983), amplifiers with high gain introduce a lot of noise in the circuit. In fact, the higher the gain of amplifier, higher is the noise inserted in the signal output. So, a good project of a hot wire probe takes so much in consideration the relationship (l/d) and the overheat ratio. Typical values for (l/d) depend on the type of wire used (platinum, tungsten, steel, nickel, etc). In the work of Citriniti *et al.* (1994), the (l/d) value was 1000. According to Bruun (1995), typical values are between 200 and 800.

Figure (6) shows two views of the probe developed for this work. The left figure shows a zoom view of the wire and prongs. Right image shows a probe with guard chamber. This probe was made with platinum wire of 25 μm of diameter and 5.6 mm of length, given a (l/d) ratio of 224. According Anderson *et al.* (2003), $160 \leq (l/d) \leq 310$ are suitable to minimize the heat loss from wire to the prongs.

Figure 6. Sensor view. Wire and prongs (at left) and probe body (at right).

The manipulation and welding of wire with small diameters are complex jobs and demand a lot of time. Micromanipulators with optical system to guarantee a necessary positioning are absolutely necessary. In this work however, the construction of the probe was done manually and consumed a lot of time in the execution. In a future work, a new micromanipulator will be built in order to promote an easy welding of wire in the prongs. Figure (7) shows a full view of the developed probe.

Figure 7. Full view of the developed probe.

5. Calibration Procedure

All HWA systems need to be calibrated to correct operation in order to establish a validated relationship between the CTA output voltage and the flow velocity. Following Bruun (1995), there exist many different techniques to perform an adequate calibration. The work of Eguti *et al.* (2002) shows several calibration methods utilized by different researchers. Many other propositions to calibrate hot-film/wire probes can be found in an extensive literature about the theme, as in Lekakis (1996), Lomas (1986), Menut (1998), Möller (2000) and Persen & Saetran (1984).

A useful procedure for hot-wire probes calibration can be carried out utilizing a free jet and it is performed by exposing the probe to a set of known velocities and then recording the voltage output. A curve fit through these points represents the transfer function or calibration curve and is valid to each specific probe. Figure (8) shows a diagram of this procedure for incompressible gas flows. In practice, the delicates probes utilized in fluid mechanics research should be daily calibrated before their utilization. In many cases, the literature relates several calibrations difficulties of this devices and loss of calibration is cited as the “Achilles’ heel” of the hot-wire anemometry, see, for example, Perry (1982), Eguti *et al.* (2002) and Vieira (2000). This statement is shared by several fluid mechanics investigators, especially for water and unclean gas flows.

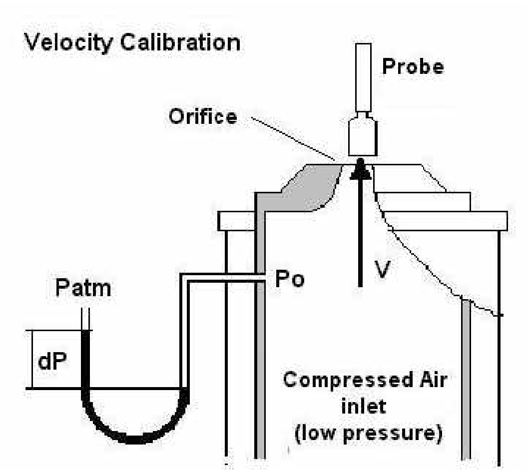

Figure 8. Velocity calibration of HWA probe.

Basically we have employed an asymmetric free jet of air discharging in infinite media (atmosphere) where its velocity could be easily obtained by Bernoulli's equation for incompressible flows, showed in Eq. (3), where (ρ) is the air density. The experiment temperature must be carefully controlled in order to assurance goods results and low output signal variations.

$$V = \sqrt{\frac{2}{r}(P_o - P_{atm})} \tag{3}$$

The differential pressure (dP) equal to (P_0 – P_{atm}) should be precisely measured by a differential manometer. We recommend the use of a manometer of Betz or an equivalent electronic micro manometer able to measure variations of about 1 Pa. This experimental air velocity calibration is well documented in Bruun *et al.* (1988). The curve fit choose for this calibration called power law or simple exponent power law, according Bruun *et al.* (1988) is the best choice for almost HWA calibrations. To obtain the A, B and n coefficients of the Eq. (1), graphical computer software has been used with success in order to promote a fast and optimized tune.

The calibration of the developed probes has been made by traditional free jet calibration device. A free jet calibration apparatus is commercially available by several suppliers and is usually a very expensive equipment. An apparatus, constructed entirely in Plexiglas plates in our laboratory, was made and exhaustively tested by Gonçalves (2001) showed in Fig. (9), at left. This device is based on a commercial version made by *TSI* kindly loaned by Uberlândia University thermal laboratory. A second commercial apparatus has been utilized in this work for hot-wire probe calibration made by *Dantec Inc.*, showed in Fig. (9), at right. Both devices work following the same principle showed in Fig. (8).

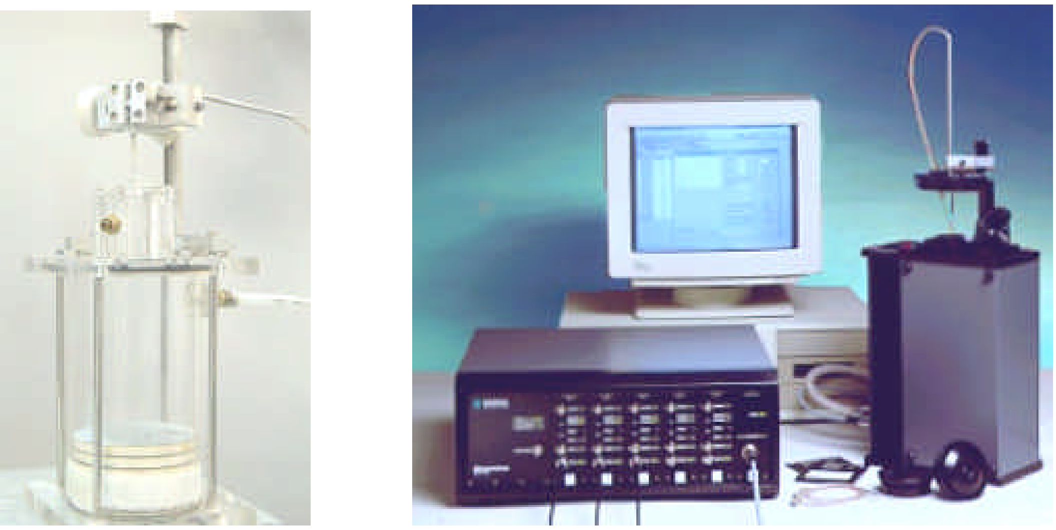

Figure 9. Free jet calibration device developed in this work (left) and
the StreamLine HWA System and Calibration Unit by *Dantec Inc.* (right).

Figure (10) shows the experimental assembly to perform a calibration of CTA developed circuit and they probe. These results are compared with *Dantec StreamLine* system, also calibrated by the same procedures.

Figure 10. Experimental velocity calibration of HWA probes for this work.

In this procedure a Yokogawa differential manometer, model EJ-110 has been utilized with pressure max. of 110 mmH_2O and precision of ± 0.1%. Figure (11) shows two detailed view of probe positioning near by nozzle exit. At left we have a developed probe for this work and at right, a *Dantec Inc.* probe, 55P11.

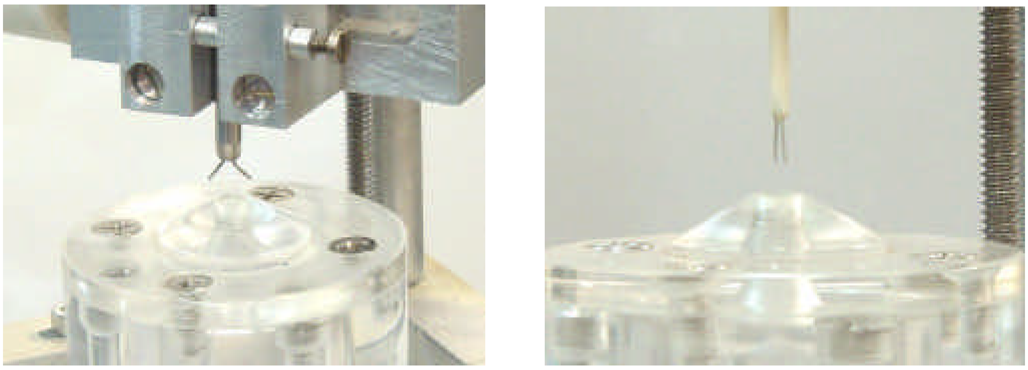

Figure 11. Experimental velocity calibration of HWA probes for this work.

The data acquisition of these experiments was made with a data acquisitions system from *National Instruments Inc.* AT-MIO_16E-1 board. A special program script was made with the software *LabVIEW 4.1.* in order to produce accurate data sets.

5. Calibrations Results

Figure (12) (left) shows a calibrations curve of the probe developed for this work. Fig. (12) (right), we have a calibration curve to Dantec 55P11 probe.

The transfer function of platinum probe is showed in Eq. (4) and the Dantec 55P11 probe, in Eq. (5).

$$e_{platina} = 2.57 + 0.08V^{0.4378} \tag{4}$$

$$e_{dantec} = 0.52 + 0.65V^{0.3285} \tag{5}$$

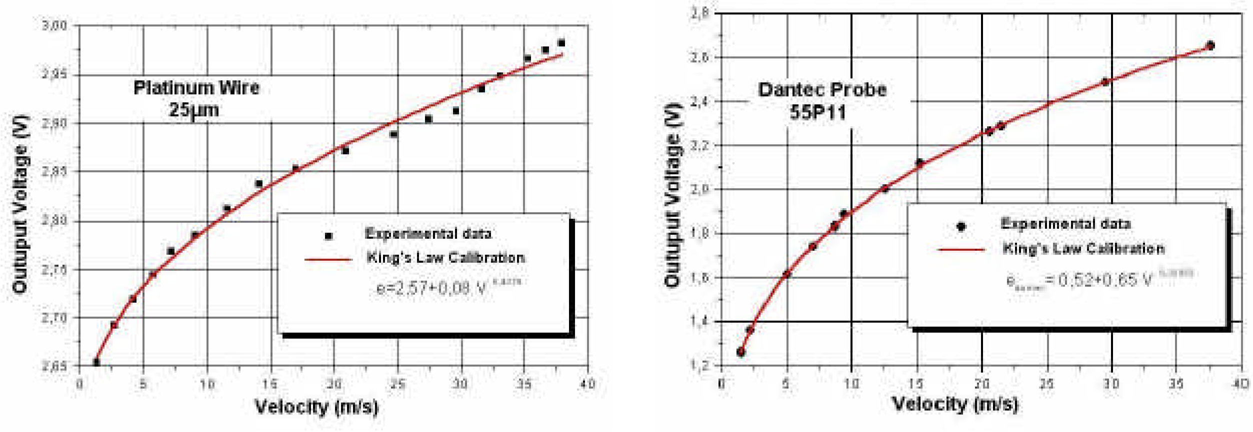

Figure 12. Calibrations curves of platinum probe (left) and a Dantec 55P11 probe.

According to Bruun (1971), a practical way to verify if a calibration curve from HWA have a good gain is to perform two simple variable changes: velocity (V) it was extracted velocity square root and of the voltage (e), square. This way, Fig. (13) shows a "linearized" graphs from calibrations dada of the probes.

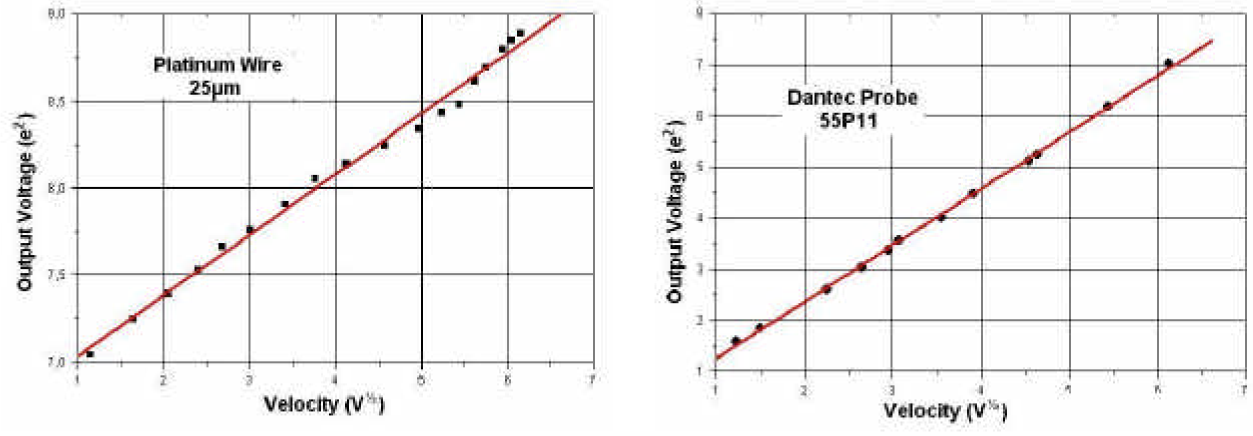

Figure 13. "Lineared" graphs of calibrations curves of platinum probe (left) and Dantec 55P11 probe.

6. Conclusion

The weak spot of a hot-wire anemometer is the frequent loss of probe calibration. Several new protected probes permits the utilization of HWA in aggressive mediums and new electronic circuits permit a precise construction while keeping affordable costs. In this work, a prototype of the new proposed hot-wire anemometer has been showed. Several points can be attacked in order to promote improvements in the apparatus. First of all, a new digital switched source of energy must be implemented to minimize the noise. Shielded devices should also be employed in order to increase the signal to noise ratio. A new compact probe utilizing a wire of 5 ìm diameter and 3 mm of length is presently in construction. Finalizing, with the purpose of determine the frequency response of pressure gauge usually is utilized a shock tube. A new proposed technique for frequency response determination of the anemometer should be also implemented with a shock tube albeit in a modified formulation.

7. Acknowledgement

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