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HOT-WIRE ANEMOMETERS: DESIGN AND ENGINEERING APPLICATIONS

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Abstract. *Fluid velocity measurement systems with low-cost are desired in industry and scientific research applications. Thermal anemometry is an appealing option, once its able to measure low speeds conditions and its fluctuations, for velocities (as in turbulent flow) or temperature (as in magnetic field interference). In this work, design HWA prototypes are built with Constantan and Tungsten filament materials, providing measurements when operating in very low speeds (< 2 m.s-1). In-house fabrication intends to have a low-cost device in comparison to commercial HWA, and data acquisition through Arduino. Main conclusions are: a) Electrical voltage is practically constant in the test range conditions, approaching an HWA-CVA behavior; b) The temperature achieved in higher airspeed (Constantan, 1.5 and 1.7 m.s-1) approach to HWA-CCA behavior with constant ΔT; c) Tungsten filament presents better behavior than Constantan, in low speeds (< 1.0 m.s^{-1}); d) Constantan achieves higher temperature variation, thus better indicated for CTA design; e) Tungsten wire achieves constant temperatures for lower speeds, thus better indicated for CCA design.*

Keywords: *calibration, turbulence, data acquisition system, airspeed measurements, experimental engineering.*

1. INTRODUCTION

Fluid flow measurements are possible by using different methods, typically for speed (global) or velocity vectors (x, y, and z directions), the following instruments and principles are applied (Figliola and Beasley, 2007): Pitot tube (static pressure), Hot-wire anemometers (HWA, thermal anemometry), Laser Doppler Anemometry (LDA) and, most recently, Particle Image Velocimetry (PIV).

Thermal anemometry is a method used by scientific research and industry; in this technique, the velocity measurement is possible by heat transfer between airflow with a sensor, which generally consists in one heated wire (Khamshah, *et al.*, 2011). Constant Temperature Anemometers (CTA) have a higher frequency response, when compared to Constant Current Anemometer (CCA) or Constant Voltage Anemometer (CVA), that allows identifying measurements fluctuations inside the fluid flow, as happens in turbulent flows. A typical compensation technique is to increase the electrical current in the Whetstone bridge (Panait, 2014). Commercial CTA has high cost and, when available for automated data acquisition its costs increases even more (Omega, 2018).

When operating in low speeds (< 2 m.s^{-1}), HWA has their accuracy limited and are difficult to calibrate (Al-Garni, 2007). Prototypes for calibration are usually presented in the scientific literature for specified conditions, for example velocities lower than 1.0 m.s^{-1} and temperatures between 10-20°C (Ferreira and Pepe, 2009).

Typical HWA applications in industry include, for example, process monitoring and control of processes when chemical reaction occurs; consists of 2 temperature sensors and a resistance to heating of the fluid (Balbinot and Brusamarello, 2010). Industrial applications are usually limited to frequency response less than 1 Hz (s^{-1}).

In fluid mechanics, scale experiments can determine velocity profiles in real flows as atmospheric ones (Çengel and Cimbala, 2015). For wind energy assessment, wind speeds at different heights need to be known, but at the same time are difficult to obtain considering that sites have their topography, which can be complicated.

In this work, an HWA is designed and built with results for Constantan and Tungsten filaments as materials, providing measurements when operating in very low speeds (< 2 m.s-1). In-house fabrication intends to have a low-cost device in comparison to commercial HWA, and data acquisition through Arduino. Engineering applications using many devices are possible, including temperature and velocity field measurements inside automotive vehicles (distribution and characterization), scale-up experiments in wind tunnels looking for wind energy assessment and boundary layer measurements. Also it is intended to have preliminary calibration (comparison to commercial HWA measurements) and uncertainties determination.

2. METODOLOGY

2.1 Thermal mass flow measurements

Hot-wire anemometers (HWA) consists of a thin wire (~5 µm, average diameter), electrically heated up to 200°C or higher temperatures, with ±2% uncertainty (Morris and Langari, 2016; Popiolek, *et al.*, 2007). It is used for gas (clean) flow measurements (mass or volume rate), has a breakneck speed response (ideal for velocity changes conditions, as found in turbulent flow). Also present high-frequency response (~400kHz), allowing measurements of turbulent velocities fluctuations that are similar to Laser Doppler Velocimetry (LDA, ~200kHz), a more expensive measurement system (Eguti and Del Rio, 2005; Lomas, 2011). For liquids flow rate measurements, such as water or rugged gas, hot-film anemometers (HFA, platinum, diameter 25-150 µm) presents increased robustness in comparison to HWA.

HWA infer mass flow rate in two operation modes: a) by measuring the heater power to achieve a constant ΔT in the flow, i.e., Constant Temperature Anemometer (CTA); b) by measuring the temperature rise (ΔT) in the flow, i.e., Constant Current Anemometer (CCA). The first one (CTA) can vary the power supply voltage (U, Volts) to keep constant temperatures (T, Kelvin), thus obtaining quick, continuous, and automatic compensation for wire thermal inertia; the electrical current passing trough the wire is adjusted to keep constant temperature, which is proportional to the fluid velocity (indirect measurement) and it is non-linear, see King´s Law (or calibration curve or transfer function). The second one (CCA) is more sensitive to temperature fluctuations, wire electrical resistance changes as function of convective heat transfer (h, $W.m^{-2}.K$) between wire and flow, with the advantage that cable length does not affect the electric circuit stability; there are ongoing research applications in thermoacoustic systems to evaluate small temperature changes due to electromagnetic fields (Cleve, *et al.*, 2017).

2.2 Measuring device design and built (CCA & CTA)

In this work, HWA actual design is on CCA mode, for preliminary results assessment; CTA mode is the next research step (first author´s ongoing studies, graduate program in Mechanical Engineering, PEM/UEM).

The building materials typically applied in HWA are platinum and tungsten (Chen and Liu, 2003), which are supported by prongs; in this work, tungsten and constantan are evaluated, with future configuration also in platinum. Constantan is a metallic alloy generally constituted for 55% of copper and 45% of nickel (Incropera and DeWitt, 2014). Electrical resistance (R, Ω) and resistivity (R_e, Ω.m) are functions of temperature, but coefficients ("α", K^{-1}; "β", K^{-2}) for constantan and tungsten coefficients for temperature variations are zero or close to zero, thus with minor influence on those parameters (Callister and Resnick, 2016). Table 1 indicates the heat transfer and electrical properties required for the HWA design, built and operating.

Table 1. Thermophysical properties for hot-wire materials.

Wire material [(1)]	Melting point (K)	ρ ($kg.m^{-3}$) specific mass	Cp ($J.kg^{-1}.K^{-1}$) specific heat	k ($W.m^{-1}.K^{-1}$) thermal conductivity	$\alpha.10^6$ ($m^2.s^{-1}$), thermal diffusivity	$R_e.10^7$ (Ω.m), electrical resistivity	"α".10^4 (K^{-1})
Constantan (55%Cu; 45%Ni)	1,493	8,920	384	23.0	6.71	4.7	33.0
Platinum (pure)	2,045	21,450	133	71.6	25.1	53.0	38.0
Tungsten	3,660	19,300	132	174.0	68.3	106.0	45.0

[(1)] Properties at 300 K or 27°C (Incropera and DeWitt, 2014; Callister and Resnick, 2016);

Figure 1 shows a skecth for design and built device (probe dimensions and electrical circuit control), Wheatstone bridge electrical resistors are indicated as R1 (potentiometer for bridge balance), R2 and R3, while R_W is probe´s electrical resistance. It was built in a phenolic plate, with wires mounting in a series configuration; thus probe´s electrical resistance corresponding to the sum of each filament resistance (10 pieces); it increases the electrical power dissipated for the set. Total electrical resistances are: $R_{W,Constantan}$ = 26.6 Ω and $R_{W,Tungsten}$ = 2.0 Ω, each one connected to a Wheatstone bridge with 30 Ω or 15 Ω resistors (R1, R2 and R3), respectively for Constantan and Tungsten.

Design probe has the following wire dimensions, see Figure 1: L_{total} = 0.200 m (20 mm filament length, 10 pieces), $D_{Tungsten}$ = 0.15 mm, $D_{Constantan}$ = 0.08 mm, thus resulting in $(L / D)_{Tungsten}$ ~ 1333 and $(L / D)_{Constantan}$ ~ 2500. Aspect ratio (AR = L / D) is an important parameter, related to probe´s sensibility, high values implies measurement stability (low gain amplifier), while low AR values implies in noise input into measurements; typical values are 200 < AR < 800 (Bruun, 1995), while 160 < L < D < 310 are indicated for heat loss minimization from wire to the prongs (Anderson, *et al.*, 2003). Recent works looking for temperature fluctuations measurements in thermoacoustic systems (Cleve, *et al.*, 2017) compare CTA and LDA, with the in-house fabrication of CVA (Constant Voltage Anemometer), with three different AR (500, 1000 and 2000). Those authors used as wire material a tungsten alloy (7% and 10% platinum), presenting resistivity and its respective temperature coefficient as $5.5.10^{-8}$ (Ω.m) and $37.10^{-4}(K^{-1})$, while their reference resistance at ambient temperature (22.1 °C) given by R_0 (Ω) = 10.4, 22.4, and 43.3.

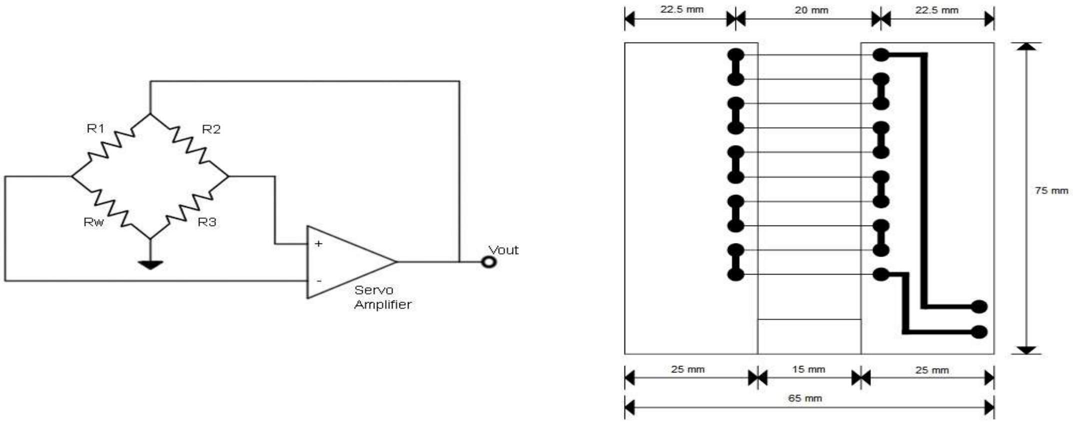

Figure 1. Sketch for circuit and design of probe sensor for an HWA, CCA mode for preliminary tests.

Figure 2. HWA probes, thin wires - Constantan (left) and Tungsten (right)

The higher the aspect ratio, the better the response to variation in fluid flow conditions (Goldstain, 1983). Typical dimensions are in the range of 1-2 mm (length), and 2-5 μm (wire diameter), i.e. $0.2.10^6 < AR < 1.0.10^6$ (Eguti and Vieira, 2005)

2.3 Parameters calculation

The HWA measurements are based on physical phenomena of heat transfer between the sensor and the fluid flow, where the electric power generated by the heated filament is balanced with the heat exchange between the hot surface and the fluid. Heat released by the electric circuit is absorbed by the fluid flow (Khamshah, *et al*., 2011), thus resulting in Eq. (1), where: A (m^2) is the surface area; T_w (°C) is the surface temperature; $T_{f,\infty}$ (°C) is the fluid temperature; I (A) is the electrical current; R_w (Ω) is the electrical resistance; h ($W.m^{-2}.K^{-1}$) is the convection heat transfer coefficient. All "W" indexes refer to wire parameters.

$$I^2.R_W = h.A_W.(T_s - T_{f,\infty}) \qquad (1)$$

Equation (2) corresponds to a solution for a heat loss from an infinite cylinder in an incompressible low Reynolds number, as developed by King (1914). Eq. (3) is the correlation between Eqs. (1), and Eq.(2), where: "a" and "b" are calibration coefficients, while "c" is assumed to be 0.5 for a wide velocity range (< 100 $m.s^{-1}$) as suggested by King (1914). Electrical voltage (E_{Output}, V) passing through the electrical circuit (Fig. 1) is given by Eq. (4). The electrical source provides 12 V as output voltage (E_{Output}, V).

$$(E_{Output})^2 = a + b.v^{\,c} \qquad (2)$$
$$a + b.v^{\,c} = (I^2.R_W).[h.A_W.(T_s - T_{f,\infty})]^{-1} \qquad (3)$$
$$E_{Output} = I.\,(R_W + R_1) \qquad (4)$$

Eq. (5) arises from the relationship between Eq. (3), and Eq. (4), which shows the output voltage concerning the fluid velocity (Khamshah, *et al*., 2007). Wire overheat if indicated by Eq. (6), and the in-house fabrication HWA-CTA in the actual work has low overheat values, thus enabling to use the device as a resistance thermometer, what allows temperature fluctuation measurements (Cleve, *et al.*, 2017).

$$E_{Output} = (R_W + R_1) \,.\, [\, A_W.(a + b.v^{c}).(T_W + T_{f,\infty}).(R_W)^{-1} \,]^{0.5} \quad (5)$$
$$a_W = (R_W - R_0).(R_0)^{-1} \quad (6)$$

The sensor (wire) is assumed to be a cylinder in a crossed external flow (King, 2014). For this case, it is possible to find Reynolds number in Eq. (7), where: v ($m.s^{-1}$) is for fluid velocity; L (m) is for a flow characteristic length; ρ ($kg.m^{-3}$) is the specific mass; μ (Pa.s) is for dynamic (or absolute) viscosity. Using the Reynolds number it is possible to apply an adequate empirical correlation to find a Nusselt number, and then apply Eq. (8) to find a convective heat transfer coefficient using a certain fluid velocity (Incropera and DeWitt, 2014).

$$R_e = (\rho.v.L).(\mu)^{-1} \quad (7)$$
$$N_u = (h.L).(k)^{-1} \quad (8)$$

Correlations to estimate Nusselt number are Eq. (9), and Eq.(10), the last one valid for the range $10^{-1} < R_e < 10^5$ (Holman, 2010). Coefficients "C" and "m" are according to Reynolds number values in Table 2.

$$N_u = C.R_e^{m} Pr^{1/3} \quad (9)$$
$$N_u = (0.35+0.56R_e^{0.52})Pr^{0.3} \quad (10)$$

Table 2. Coefficients N_u assessment (Holman, 2010).

R_e	C	m
0.4 – 4	0.989	0.330
4 – 40	0.911	0.385
40 – 4000	0.683	0.466
4000 – 40000	0.193	0.618
40000 – 400000	0.027	0.805

2.4 Auxiliary measuring instruments, uncertainties and calibration

Electrical current measurements were registered by a multimeter (Minipa, ET-1110), with an accuracy of ± (3.0% +5D) and resolution of 10 mA. Temperatures were by a K-type thermocouple (Instrutemp, ITCAL 9900), with an accuracy of ± (0.3°C + 10 uV). A commercial hot-wire anemometer was used for airflow speeds comparison to the values obtained by using HWA device built in the present work (Figures 1 and 2).

Uncertainty in functions of two or more variables is the total differential of function (Figliola and Beasley, 2007). Temperature differences uncertainty, u(ΔT), is given by Eq. (11). Were ΔT is temperature gradient between surface (T_w) and fluid ($T_{f,\infty}$).

$$u(\Delta T) = [\, (2RI/Ah)^2 + (I^2/Ah)^2 + (-RI^2/Ah^2)^2 + (-RI^2/A^2 h)^2 \,]^{0.5} \quad (11)$$

Calibration for HWA correspond to obtain the relationship between an output signal (E_{Output}, V) and the measuring quantity (v, $m.s^{-1}$), and can be done in several ways (Eguti, 2005):

1) Static calibration (1^{st} order) by free flow jet (1-90.s^{-1}), allowing to obtain uncertainties in the order of ± 1.0% (v < 4 $m.s^{-1}$) or ± 0.1% (0-13 $m.s^{-1}$), as indicated by Brunn*, et al.* (1988). This method presents a limitation for calibration of lower speeds (< 2 m/s), since low pressures in the lead to stagnation, which implies high uncertainties;

2) Dynamic calibration (2^{nd} order, or in frequency);

3) Swinging arm, presents good accuracy and calibration time reduced (and reproducibility), measuring the angle of the arm and tension (Guellouz and Tavoularis, 1995);

4) Fully developed laminar pipe flow configuration (± 0.2% on the calibration curve), by Pluister and Nagib (1975).

3. RESULTS AND DISCUSSION

Figure 3 presents temperatures increases when using Constantan filaments in HWA-CCA, and its respective electrical current (measured); airflow velocities are from calculations, as details in methodology section. As velocities increases, higher electrical current occurs is the HWA (Wheatstone bridge) to obtain heat balance in accordance to heat transfer theory (Incropera and DeWitt, 2014), with lower ΔT once there is convection heat transfer improvements (see

Figure 4). Also in Figure 4, electrical voltage (E_{output}) is practically constant in the test range conditions under evaluation (I = 0.2, 0.3 and 0.4 A for Constantan), approaching to a HWA-CVA model (Cleve*, et al.*, 2017). As for temperature behavior, its increases are more prominent for lower airspeed (0.3 and 0.5 m.s^{-1}) and tends to a singular and constant value for higher airspeed (1.5 and 1.7 m.s^{-1}), thus approaching to a HWA-CCA model with constant ΔT.

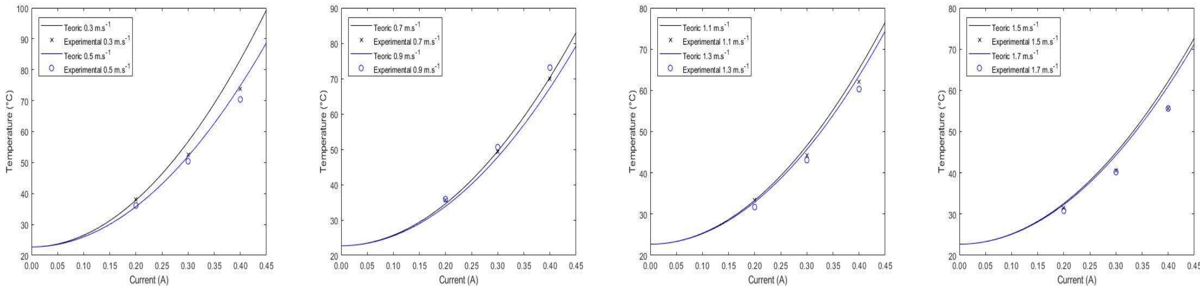

Figure 3. HWA-CCA (Constantan): ΔT for air speeds (0.3-1.7 m.s^{-1}) and electrical current (0.2-0.4 A).

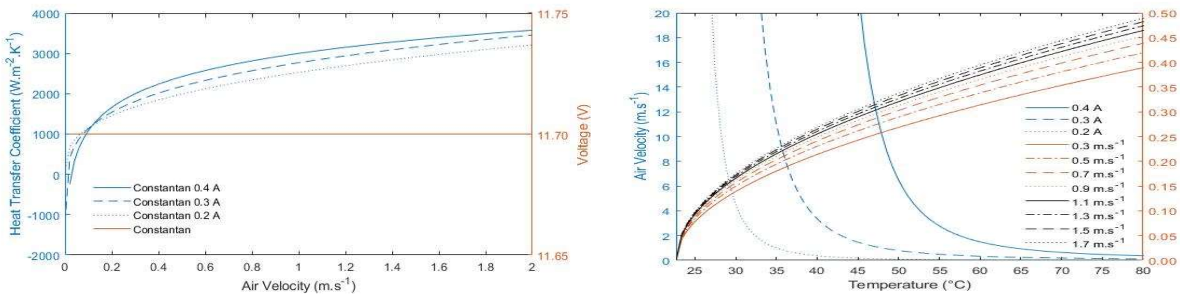

Figure 4. HWA-CCA (Constantan): Convection heat transfer coefficient and ΔT behaviors for test conditions.

Similar results for Tungsten filament are in Figures 5 and 6. Lower ΔT also occurs when velocity increases, as well as constant electrical voltage (E_{output}) in the test range conditions under evaluation. Temperature reaches lower values to obtain heat balance, when compared to Constantan; even with higher electrical current (I = 0.5, 0.7 and 0.9 A) differences are mainly due to in specific heat ($Cp_{Constantan}$ / $Cp_{Tungsten}$ ~ 2.9) and thermal conductivity ($k_{Tungsten}$ / $k_{Constantan}$ ~ 7.6), resulting in quite fast thermal equilibrium at constant current in the electrical circuit (Wheatstone bridge). As for constant ΔT behavior (HWA-CCA model), it occurs clearly when airspeed is 0.5 m.s^{-1}, or higher; thus, indicates that Tungsten presents better behavior than Constantan in low speeds (< 1.0 m.s^{-1}).

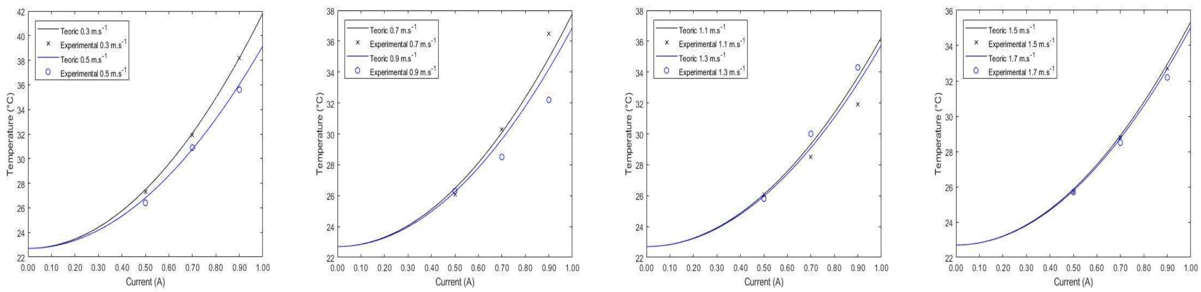

Figure 5. HWA-CCA (Tungsten): ΔT for air speeds (0.3-1.7 m.s^{-1}) and electrical current (0.5-0.9 A)

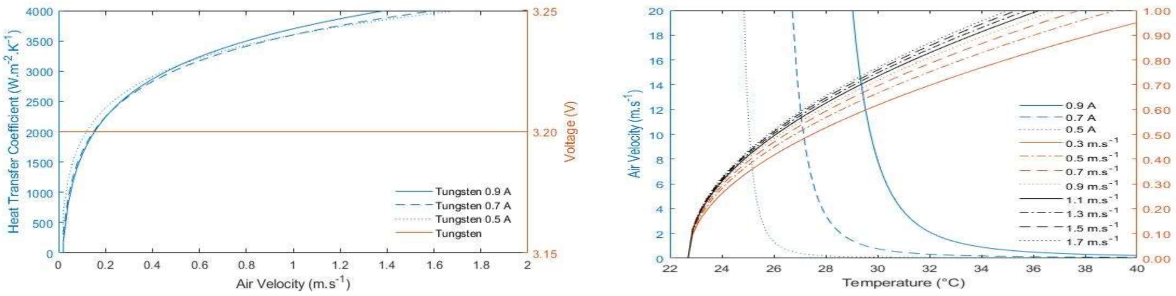

Figure 6. HWA-CCA (Tungsten): Convection heat transfer coefficient and ΔT behaviors for test conditions.

Regarding curves fitting, its approach quite well to experimental results in low velocities, while it is not very close for airspeed higher than 1.0 $m.s^{-1}$ (Constantan wire). As for Tungsten wire, in the same velocities range, is better fitted to very low (0.3 and 0.5 $m.s^{-1}$) or higher airspeed (1.5 and 1.7 $m.s^{-1}$), needing better fitting in the middle range (0.7 up to 1.3 $m.s^{-1}$).

Wheatstone bridge design was for electrical current lower than 1 A, due to circuit limitations for in-house fabrication. Thus, results for probe´s temperature do not achieve typical values for HWA (~200°C, Popiolek, *et al.*, 2007). Constantan wire achieves higher temperature variation, thus better indicated for CTA model; while Tungsten wire achieves constant temperatures for lower speeds, thus better indicated for CCA model.

Identification of the best wire material (Constantan, Tungsten or Platinum) is expected to confirmation in calibration tests (curves fitting and coefficients), still to be performed in the author´s research advances (ongoing studies on graduate program in Mechanical Engineering, PEM/UEM). An interesting engineering application is to determine the velocity profiles for scale experiments, inside the boundary layer of atmospheric flows (wind speeds) resulting in wind energy experimental assessment, which is the final goal of the research presented herein.

4. CONCLUSIONS

Main conclusions are:

a) Electrical voltage is practically constant in the test range conditions, approaching an HWA-CVA behavior;
b) The temperature achieved in higher airspeed (Constantan,1.5 and 1.7 $m.s^{-1}$) approaches to HWA-CCA behavior with constant ΔT;
c) Tungsten filament presents better behavior than Constantan, in low speeds (< 1.0 $m.s^{-1}$);
d) Constantan achieves higher temperature variation, thus better indicated for CTA design;
e) Tungsten wire achieves constant temperatures for lower speeds, thus better indicated for CCA design.

Improvements in next steps of the research include: 1) platinum wire HWA; 2) CTA electrical circuit design; 3) higher velocities tests; 4) calibration; 5) uncertainties for primary results, including u(I) for electrical current, u(E) for output voltage, and (v) for airflow velocity, as well as calibration procedure comparison; 6) boundary layer speeds measurements for wind energy assessment.

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7. RESPONSIBILITY NOTICE

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