Low cost anemometers for wind tunnel and ventilation applications

Anemômetros de baixo custo para aplicação em túnel de vento e ventilação

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Resumo

Neste artigo, são descritos anemômetros de corrente constante e de temperatura constante de baixo custo. Os anemômetros propostos são construídos a partir de termistores. Para a aquisição de dados e para o controle são utilizados microcontroladores de baixo custo facilmente encontrados no mercado. Um modelo de transferência de calor simples é utilizado para simular as características principais dos sensores. Testes em laboratório mostraram que as curvas de calibração apresentam resultados repetitivos e que, embora os sensores sejam de formato esférico, a sensibilidade direcional não é desprezível.

Abstract

Low-cost and simple-constant-current and pulsed-constant-temperature anemometers are described. The proposed anemometers use a self-heated thermistor as a flow sensor as well as very simple electronics. Data acquisition and control use commonly available micro-controllers. A simple heat transfer model is used to simulate the main characteristics of the sensor and laboratory tests show that the calibration curves of the sensors are repeatable and, even though the sensor has a spherical shape, a directional sensitivity is noticeable.

1 *Introduction*

Thermal anemometers are very common in wind engineering and ventilation. In particular, their ability to measure very low wind speeds is a distinctive advantage when compared to Pitot tubes. Depending on sensor element dimensions, very high frequencies and speeds can be measured as well. Two simple thermal anemometers using small thermistors as sensors are proposed and analyzed. The objective of this work is to develop low cost and simple arrays of velocity probes using readily available micro-controllers for data acquisition. A further objective is to find a replacement of the Irwin probes for pedestrian level wind measurements.

While thermal anemometers are common, they usually consist of hand-held versions and are not very suitable for making sensor arrays. Some models cost US\$50 a unit, but quality meters usually cost US\$200 or more. Arrays of rugged and disposable sensors that can be easily installed inside wind tunnel models are harder to come by.

2 *Modeling thermal anemometers*

The loss of heat of a warm body exposed to air depends on the velocity of the air: the higher the velocity, the larger the heat loss. Newton's law of cooling provides a simple, empirical relationship for the heat loss (INCROPERA; DE WITT, 1996). Nevertheless, if an electric current is passing through the body, heat is generated according to Joule's law of heating. These two phenomena, along with thermal inertia of the body, result in a differential equation for the temperature of the body:

$$mc_p\frac{dT}{dt} = -h \cdot A \cdot (T - T_a) + R \cdot i^2 \qquad \textbf{(1)}$$

In this equation, T *is the temperature of the body,* m *is its mass and* c_p *its specific heat. The convection coefficient is given by* h, A *is the external surface area of the heated body and* T_a *is the room temperature. Finally,* R *is the electric resistance of the body and* i *is the electric current density circulating through it.*

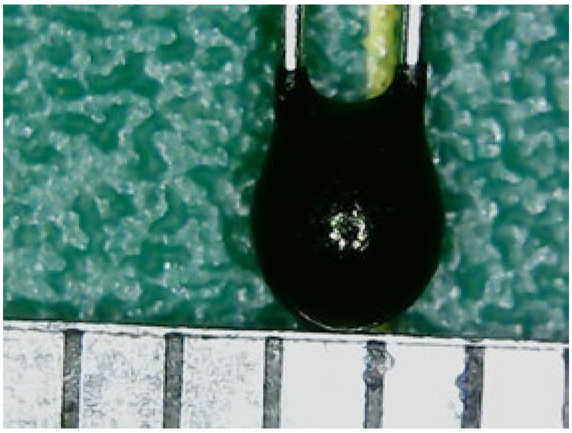
This simplified model assumes that the temperature of the body is uniform. This is valid if the Biot number Bi = hL/k is small enough (where k is the thermal conductivity of the body and L is a typical dimension). As it will be seen later, this hypothesis is not always true. A major drawback in this model is the value of the convection coefficient h: it is not known but it strongly depends on the fluid velocity. While the literature abounds with correlations for the convection coefficient, most of them have high uncertainty and are valid for very specific geometries. The practical result of these observations is that a thermal anemometry cannot be a primary standard for fluid velocity: a calibration will always be necessary; but this simple model and literature correlations are enough to understand the behavior and to design a thermal anemometer.

***Equation 1** can be used in several ways to implement a thermal anemometer but usually, the anemometer depends on the variation of the electrical resistance (R) with the temperature. In a wide range of temperature around room temperature, most solids present a linear relationship between the resistance and the temperature where the resistance gradually increases with the temperature. Some semi conductive materials, nonetheless, might present strong nonlinear variations of the resistance with the temperature which, while presenting a more complicated behavior, also respond much better to small variations in the temperature. These materials are often called thermistors and often have a negative temperature coefficient (NTC), i.e., the resistance decreases with the increase of the temperature. The anemometers developed in this study use NTC thermistors as sensor elements. A semi empirical relationship between the resistance and the temperature is given by the following equation (SANDBORN, 1972):*

$$R = R_0 \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_0}\right)} \qquad (2)$$

where R_0 is the resistance of the thermistor at the reference temperature, usually 293,15 K = 20 °C and B is an empirical coefficient which varies for different thermistors.

Figure 1 – Photo of a thermistor with an approximate diameter of 2 mm. R_0 = 5 kΩ and B = 3000 K



Source: the authors

*Thermistors come in all sizes and shapes. **Figure 1** shows a photograph of a thermistor with an approximate diameter of 2 mm. Its spherical overall shape suggests that it can be used as an omni-directional probe. It will be shown later that this specific thermistor has a directional sensitivity which cannot simply be discarded.*

The strong dependence of the resistance on the temperature and its small dimensions make the thermistor shown in ***Figure 1a*** *a strong candidate for an anemometer sensor element. In steady flow,* ***Equation 1*** *reduces to:*

$$R(T) \cdot i^2 = h(U) \cdot A \cdot (T - T_a) \qquad \textbf{(3)}$$

There are two common ways to use this equation to measure velocity:

- *Constant Current (CCA)*
- *Constant Temperature (CTA)*

Today, most hot wire anemometers are CTA but CCA still have a wide use. We will analyze both since simple circuits using both principles are suggested.

2.1 *Constant Temperature Anemometer (CTA)*

For now, no mechanism is proposed on how to keep a constant temperature. But if the temperature is constant, so is the resistance. An operating temperature is selected (T_w) and the circuit tries to keep the resistance constant and equal to $R_w = R(T_w)$. The voltage (E_0) across the sensor element is, according to ***Equation 3****:*

$$E_0 = \sqrt{R_w h A (T_w - T_a)} \qquad \textbf{(4)}$$

Figure 2a *shows the response of a constant temperature anemometer for different operating conditions. It is clear that the diameter has a large effect on the output. The power (and voltage) required is much larger but the sensitivity isn't any better. The operating temperature also affects the power requirements but higher operating temperatures present an advantage: the effect of room temperature variation is smaller as shown on* ***Figure 2b*** *where the effect of a 1 °C room temperature increase is shown as an anemometer output difference.*

2.2 *Constant Current Anemometer (CCA)*

When operating at constant current, the temperature will vary, even though the current is constant. In this case, no simple explicit equation for the output voltage exists and a nonlinear algebraic equation must be solved for each wind velocity. ***Figure 3*** *shows the general behavior of the constant current anemometer.*

Figure 2 – Simulation of a constant temperature anemometer for different diameters and operating temperatures (T_w). R_0 = 5 kΩ and B = 3000 K

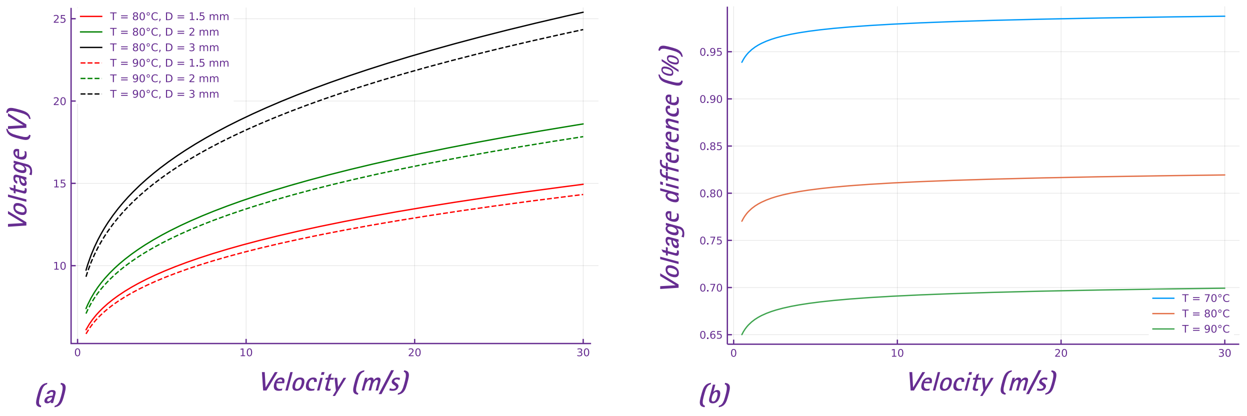


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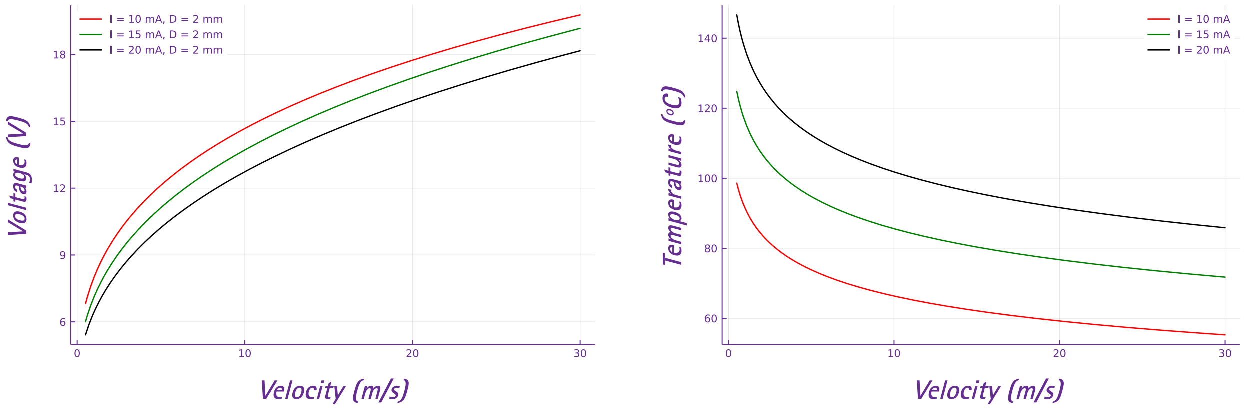
Figure 3 – Simulation of a constant current anemometer for different currents. R_0 = 5 kΩ and B = 3000 K



(a) Effects of probe current on anemometer output

(b) Temperature of a thermistor for constant current operation

Source: the authors

The output voltage of the CCA behaves as expected ***(Figure 3a)*** *but there is one important aspect: the temperature increases significantly for lower velocities* ***(Figure 3b)****. Since the thermistor used has a maximum operating temperature of 120 °C, a burn out of the sensor is a real possibility if the currents are high or the sensor is used in a small confined space. These high temperatures may also change the calibration curve. Since the operating temperature changes considerably with wind speed, corrections due to room temperature (*T_a*) are more complicated and may be large for higher speeds.*

2.3 *Time constant of the sensor*

Up to this point, a steady flow and a stable anemometer were assumed. If the flow velocity changes, the response of the anemometer will depend on the dynamic of the sensor. This dynamic is also important when designing the circuit. The simplest way to assess the dynamic of the sensor is to estimate how long it takes for the sensor to cool down from a given higher than room temperature. The time constant depends on the velocity and using ***Equation 1*** *with fixed h, a time constant of the order of 1 s is obtained. The time that it takes for the temperature difference to drop 10 % is given by*

$$\tau = -ln(0,9) \cdot \frac{m \cdot c_p}{h \cdot A} \qquad (5)$$

For $U = 10\ m/s, \tau \approx 0,5\ s$.

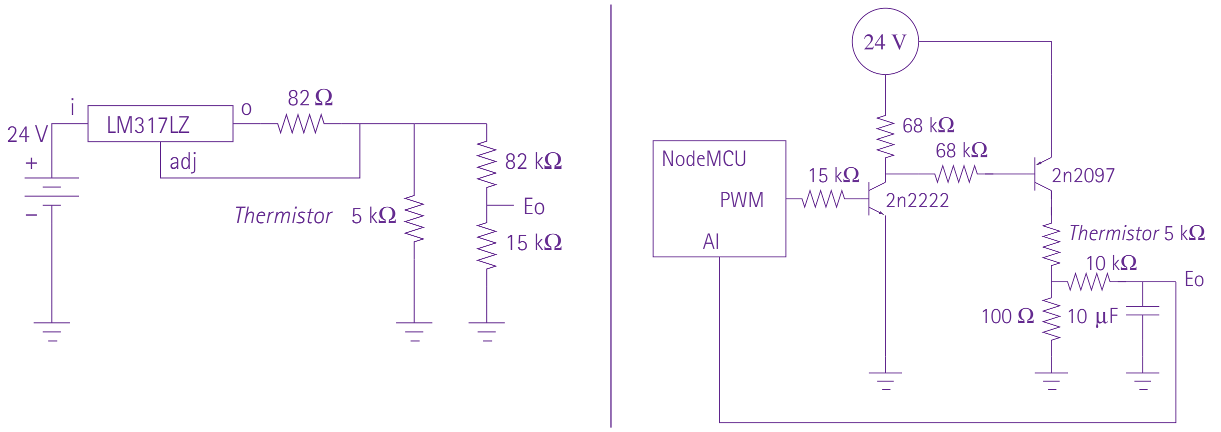
3 *The electronics of the low cost anemometers*

The idea behind this project is the design of low cost and easy to manufacture anemometers. If arrays of sensor are to be used, it is interesting to have a simple computer data acquisition system. This project uses the NodeMCU 32s microcontroller board to control and to acquire data from the anemometer. This board has 16 analog 12-bit inputs and several other digital inputs/outputs. Besides USB communication, the NodeMCU board has both built-in wi-fi and Bluetooth. The development environment is the same used by Arduino so that reference materials are easily available.

3.1 *The Constant Current Anemometer*

The low time constant of the thermistor and the low current involved make it possible to use commonly found integrated circuits (IC) to generate a constant current source. The LM317LZ is a cheap, easy to use and widely available voltage regulator which can be easily used to design a constant voltage current source. This IC tries to maintain a constant voltage of 1.25 V between its output and adjust terminals but with a resistor it can be used as a constant current source. ***Figure 4*** *shows the circuit that implements the anemometer. The 82 Ω resistor ensures an output current of approximately 15 mA. Since the output voltage can be as high as 20 V and the analog inputs of the microcontroller are limited to 3.3 V, a voltage divider is used to ensure a lower voltage at the analog input of the NodeMCU 32s.*

Figure 4 – Anemometer electronic circuits



(a) Constant current anemometer (CCA) ***(b) Pulsed constant Temperature anemometer (PCTA)***

Source: the authors

3.2 *The Pulsed Constant Temperature Anemometer*

A typical constant temperature anemometer uses analog electronics to implement the feedback control of the temperature. The electronics for this feedback control can be quite complicated for a non-expert. The usual approach is to use a Wheatstone Bridge which is balanced when the sensor resistance equals the preset operating resistance (R_w*). When the resistance drifts off, the bridge is unbalanced, and this unbalance is used to control the input to the bridge. The general layout can be seen in Lomas (1986) and a specific implementation is provided by Palma and Labbé (2016). Even though the large time constant of the thermistor and the large resistance change with temperature* *may allow for a simpler circuit, its design and implementation are much more complicated than the constant current anemometer proposed here. Another approach is to implement the control in the microcontroller using a high-level language programming. Most microcontroller do not have analog output. But they do have PWM output. Pulse Width Modulation (PWM) is a rectangular wave a with constant frequency and amplitude where the time percentage in which the pulse is at a high voltage, it may vary between 0 % (always off) and 100 % always on.*

The idea behind the pulsed constant temperature anemometer (PCTA) is to control the percentage of a time current fed from a constant voltage source (in this case a 24 V easily available source). The control variable is the fraction of time x which the circuit is on (therefore, $0 \le x \le 1$). The PCTA was implemented using the circuit shown in ***Figure 4b****. The transistors in this circuit operate in saturation so they work in on/off conditions depending on the instantaneous output of the PWM signal from the controller. The circuit is basically used to turn on and off the current to the thermistor. If the resistance of the thermistor starts to fall, its temperature increases and x should be lowered. However, if the resistance rises, the temperature would increase and x should be increased.*

The trick is to measure the resistance. This done by a low pass filter that measures the current on a small resistor in series with the thermistor. If the PWM frequency is high, the output from the filter will oscillate slowly and the mean current will be obtained by $i = E_o/100\ \Omega$*. With this information, the thermistor resistance can be estimated as:*

$$R = 100\ \ \Omega \cdot \left(x \frac{24V}{E_0} - 1 \right) \qquad \textbf{(6)}$$

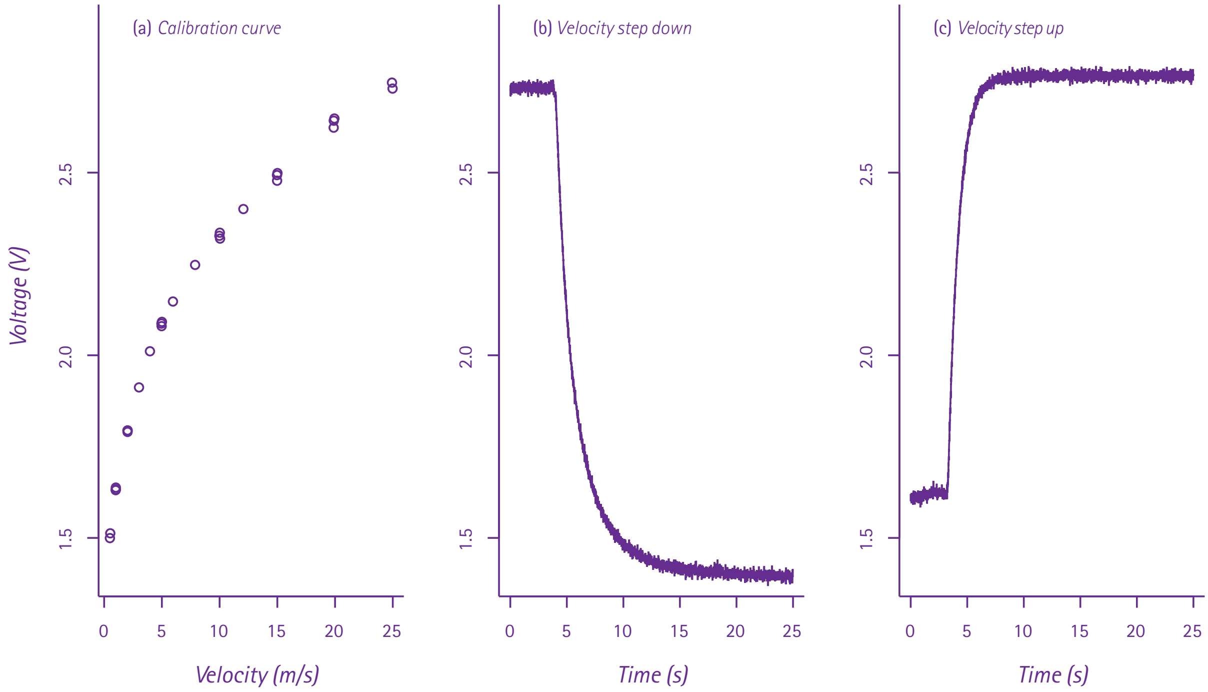
This can be compared to the expected resistance of the thermistor $R_w = R(T_w)$*. Since the response of the thermistor is slow, this can be easily monitored in commonly available microcontrollers which will adjust the PWM accordingly (x).*

It is interesting to note that, since in steady state the stable value of x varies with the velocity of the fluid, a simple proportional controller will operate very poorly. A digital proportional/integral controller was implemented to keep the resistance constant.

4 Results and discussion

Both anemometers constructed were calibrated and a few tests were carried out. ***Figure 5*** *shows the results of the CCA. The calibration is repetitive and, when large change of velocity occurs (both up and down), the sensor responds accordingly. The sudden downward change in velocity was obtained by shutting off a 25 m/s flow. The upward-step velocity change in was obtained by rapidly moving the sensor into a 25 m/s flow. In the case of the CTA* ***(Figure 6)****, the calibration curve is still good but not as good as observed for the CCA. When a large change in velocities occur, the implemented controller has some difficulty for a while but recovers after a few seconds. The tuning of the PI controller is an on-going work and better results are expected. The calibrations were carried out using a Dantec Dynamics calibrator.*

Figure 5 – Calibration curves and step down and step up velocity changes for the constant current anemometer



Source: the authors

*Even though the thermistor has a general spherical shape, the probe is not omni-directional as is shown in **Figure 7**. A support used for the directional calibration of 3D hot wire probes was used to vary the wind incidence. There is a 30 % variation in velocity depending on the orientation. It is interesting to note both cusps on the curve. These directions happen to coincide with a flow parallel to the plane formed by the thermistor lead (flow parallel to photo shown in **Figure 1**). While asymmetries in the shape and flow around the thermistor can cause some directional sensitivity, the presence of abrupt cusps in the curve suggests that the internal current flux inside the thermistor is the cause to the directional sensitivity. Further research using numerical simulation is ongoing to better understand this result.*

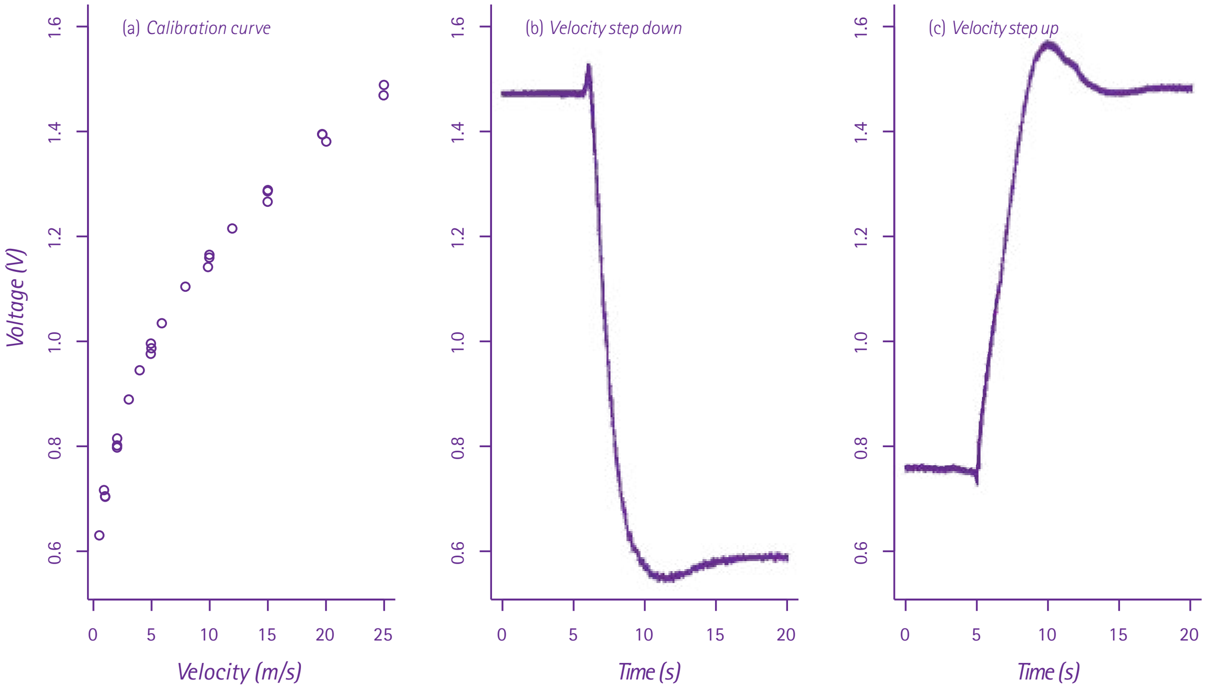
5 Conclusions

Two different simple and cheap circuits to measure air velocity were proposed and analyzed. The calibration curves showed little dispersion which indicates that both circuits have potential. The ability to build cheap array velocity sensors opens up several possibilities in wind engineering and ventilation, both in a wind tunnel and in field measurements. The cost of the micro-controller is around US$20 in Brazil and each sensor costs an additional US$2 with the possibility of using 12 to16 sensors per microcontroller. Manufacturing requires elementary soldering capabilities.

The controller of the constant temperature anemometer could certainly be improved. An issue that was not dealt up to this point is the effect of changes in room temperature. Since the operating temperature is low (much lower than typical operating temperature of research hot wire systems), the effect of changes in room temperature will be more significant. The expression suggested by Jorgensen (2002) can be used for the PCTA but an expression using the calibration curve of the sensor itself could be developed (the calibration curve is a sort of convection coefficient curve). In the case of the constant current sensor, the variation of the operating temperature with the velocity introduces complications but an approximate temperature correction might be possible.

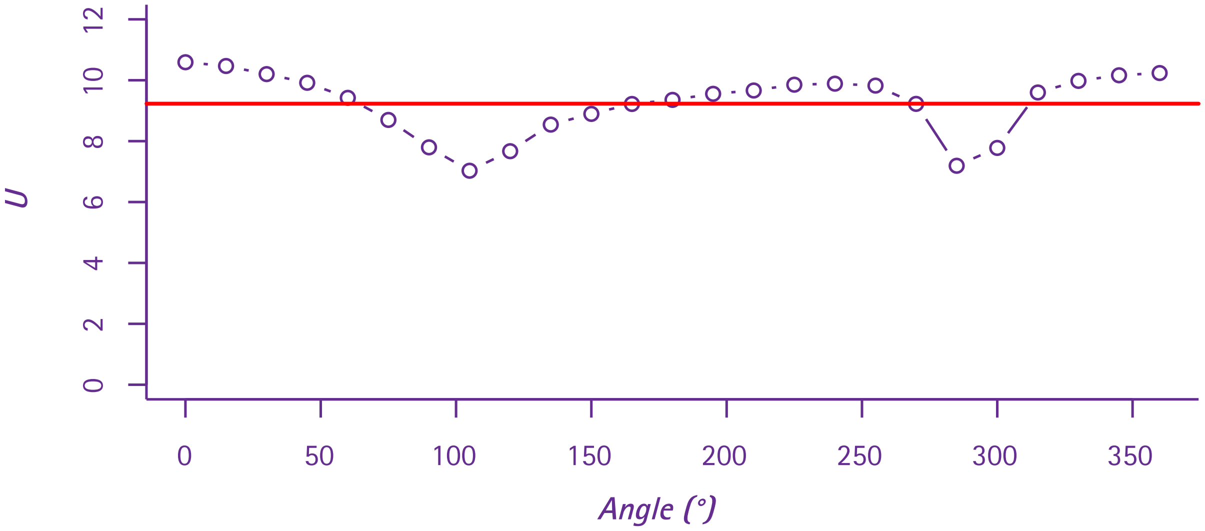
*It is not clear if the sensitivity to the direction is due to the geometry or the internal structure of thermistor which causes asymmetric heat exchange. Perhaps a simple probe support could improve this. The cusps, visible in **Figure 7**, suggest that the current flux between the thermistor leads is responsible. If that is the case, thermistors with different shapes, where leads arrive and leave in the same direction, could solve part of the directional sensitivity. This problem will require further research. While a 30 % variation is not too large, without further studies, this probe can not simply replace the Irwin probe (IRWIN, 1981) for mean pedestrian level velocity measurements.*

Figure 6 – Calibration curves and step down and step up velocity changes for the pulsed constant temperature anemometer



Source: the authors

Figure 7 – Directional calibration of the anemometer



Source: the authors

This project is open sourced and any contributions are welcomed. See https://github.com/pjabardo/ThermistorHW.jl for further developments.

6 References

INCROPERA, F. P.; DE WITT, D. P. ***Introduction to heat transfer***. 3rd ed. John New York: Wiley and Sons, 1996.

IRWIN, H. P. A. H. A simple omnidirectional sensor for wind-tunnel studies of pedestrian-level winds. ***Journal of Wind Engineering and Industrial Aerodynamics***, v. 7, p. 219–239, 1981.

JORGENSEN, F. E. ***How to measure turbulence with hot-wire anemometers – a practical guide***. Skovlunde: Dantec Dynamics, 2002. 73 p.

LOMAS, C. G. ***Fundamentals of hot wire anemometry***. Cambridge: Cambridge University Press, 1986.

PALMA, J.; LABBÉ, R. Rugged constant-temperature thermal anemometer. ***Review of Scientific Instruments***, v. 87, n. 12, p. 125112, 2016.

SANDBORN, V. A. ***Resistance temperature transducers***. Fort Collins, Colorado: Metrology Press, 1972.