

COB-2019-1474

DEVELOPMENT OF A LOW-COST APPARATUS FOR LOW SPEED ANEMOMETER CALIBRATION

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Abstract. A modified version of the laminar pipe flow method is used to provide an accessible and inexpensive apparatus to calibrate hot-wire anemometers with low speed velocities. The apparatus consists of a PVC pipe, a flow conditioner, a container for storing water with a flow control valve, a graduated tank to store the exiting water, and a stopwatch for mark the time. The air enters the PVC pipe, passes through the flow conditioner and is measured by the anemometer, while the valve is open, flowing water from the container to the graduated tank. The velocities obtained were very close to the manufacturer curve. The standard measurement uncertainties obtained for velocity ranged from 0.51 % to 0.85 %, which was considered small for this type of experiment.

Keywords: Anemometer, Calibration, Flow measurement, Low speed.

1. INTRODUCTION

Anemometry is a technique used worldwide as a research tool in fluid mechanics. Despite the availability of non-intrusive velocity measurement systems, it is still widely applied, due to improvements of electronic technology and to increased interest in detailed description of turbulence flow fields. Nevertheless, it is still the only instrument delivering at the output a truly analogue representation of the velocity up to high frequencies fluctuations.

The measuring procedure is an indirect method, deducing the instantaneous velocities from local heat-transfer information of the sensor, requiring a comparison versus some reference velocity (Yue and Malmström, 1998). Calibration of hot-wire sensors at low velocities regimes (< 1 m/s) have some issues, once Pitot tubes and pressure-sensing devices became inaccurate, causing values of 4 – 50 % smaller than the real ones using a calibration jet (Lee and Budwig, 1991).

Different techniques for low speed calibration of hot-wire anemometers have been developed over the years. The most commonly used are laminar pipe-flow method, shedding-frequency, and moving the hot-wire anemometer with a known velocity in a stagnant medium. Other alternative is a low speed calibrator, such as TSI 1125, with current range of 0.02 to 0.9 m/s (Ôzahi *et al.*, 2010).

Pezzotti *et al.* (2011) designed a wind tunnel with a contraction, meaning that two sections have been built: a low-speed and high-speed section. The calibration was performed by means of comparison of airspeed at the test cross section (or low-speed) and at the reference cross section (high-speed). This method is very similar with another wind tunnel created by Ômori (1956), once the calibration device consists of a wind tunnel and a shaped nozzle.

Tsanis (1987) and Chua *et al.* (2000) mounted hot-wire probes on a traversing mechanism that is driven by a servo motor and travels at constant speed, from a velocity range of 0.1 – 0.5 m/s. Similar to that principle, Al-Garni (2007) and Bruun *et al.* (1989) developed a swinging arm that moves the probe in a stagnant air.

Using an alternative to the laminar pipe flow method studied by Lee and Budwig (1991) and, Yue and Malmström (1998) developed a system that produces the effects of laminar pipe flow generated by draining water from an airtight container at a constant rate. The authors also studied the influence of the humidity variations between calibration and application, comparing the calibration results with another available device.

The present research group has been developing some studies on the performance of solar chimneys for indoor ventilation (Malta *et al.*, 2014; Villas-Bôas *et al.*, 2017; Villas-Bôas, 2019). The chimneys are created in cavities inside the wall, through which the air flows, coming from the internal environment. For the study of its performance, the air velocity profile and the total air flow are obtained in different situations. The group has been using commercial anemometers similar to those used in the literature for the study of solar chimneys, shown in Tab. 1. Because velocities are low, the group believes that it would be important to have a calibration equipment that could calibrate the anemometer before a series of tests, to achieve greater confidence in the results. This was the main motivation for the development of the present work.

Table 1. Studies of solar chimney experiment with hot wire anemometer.

| Author | Study | Sensor | Accuracy | Velocity Range |
|------------------------------|--|------------------------------------|---------------------|---------------------|
| Ong and Chow (2003) | Mathematical model to simulate thermal performance of a solar chimney | Hot wire anemometer ⁽¹⁾ | ±0.03 m/s | 0.25-0.39 m/s |
| Mathur <i>et al.</i> (2006) | Solar chimney experiments with nine different gaps and height absorbers | Hot wire anemometer ⁽¹⁾ | ±0.01 m/s | N.S. ⁽¹⁾ |
| Burek and Habeb (2007) | Performance of a solar chimney varying the heat input and channel depth | PSI model 521L | N.S. ⁽¹⁾ | N.S. ⁽¹⁾ |
| Chen <i>et al.</i> (2003) | Solar chimney with variable gap-to-height ratio and different heat flux and inclination angles | TSI8455 | ±5% at 0.05 m/s | 0.10-0.80 m/s |
| Susanti <i>et al.</i> (2008) | Inclined heated cavity model under steady condition | Kanomax model 6201 | ±0.02 m/s | 0.01-0.32 m/s |
| Arce <i>et al.</i> (2009) | Solar chimney in full scale and real meteorological conditions | TSI8475 | ±5% at 0.05 m/s | N.S. ⁽¹⁾ |
| Zhu and Chen (2015) | Full scale passive solar house with a color change wall | Kanomax model 6004 | ±0.01 m/s | N.S. ⁽¹⁾ |

N.S.⁽¹⁾ - Not specified by the author(s)

In this paper, a modified version of the laminar pipe flow method is presented. The focus of the study is to provide an accessible and inexpensive apparatus to calibrate hot-wire anemometers with low speed velocities, once it is recommended a direct calibration of the anemometer each time it will be used.

2. METHODOLOGY

A sketch of the experimental apparatus for calibration is shown in Fig. 1. It consists of a PVC pipe, a flow conditioner, a container for storing water with a flow control valve, a graduated tank to store the exiting water, and a stopwatch for mark the time. All the components used were obtained through stores of building materials.

The principle of operation occurs from the existence of only one input and one output. Air enters from the top through the PVC tube ($D_o = 20.10$ mm, $D_i = 16.85$ mm, $L_T = 530.00$ mm), from the environment, through a flow conditioner consisting of 12 small tubes ($d_i = 4.30$ mm, $\epsilon = 0.15$ mm, $L_t = 248$ mm), until passing through the anemometer. The objective of flow conditioning is to create a know and repeatable velocity profile of the air measured in order to improve the accuracy of the flow metering process. To do this process, the container must be completely sealed, since both water and air can only have one inlet and one outlet. The anemometer is connected to a National Instruments[®] CompactDAQ, model NI cDAQ-9172, which can acquire the data directly to the computer, using a LabView[®] interface at 2 Hz.

To test the calibration device, an OMEGA FMA-904-I hot wire anemometer, with calibration certificate traceable to the U.S. National Institute of Standards and Technology (NIST), was used. The sensors are type RTD, with 2 sensors PT1000 (1000 ohms at 0 °C) to measure the temperature before and after the air passage and 1 PT100 sensor (100 ohms at 0 °C) used to make a temperature compensation attached to the internal anemometer system. The probe is made of platinum and is coated by Alumina. The relationship between current and velocity is linear.

Before starting the tests, the container is filled with water and after that, the current value was collected for the stagnant air, with no flow occurring. The graduated tank must be empty after each measurement, ensuring that the volume measured is the amount of water left the system. With everything ready, the test is started by opening the valve in a random position, turning on the timer and the acquisition system. The volume of water was measured up to 20 L each time, noting the time required for this to occur. When it reaches 20 L, the timer and the measurement stop, being saved to the computer. Twenty tests were performed with randomly dispersed flows in the range of velocity values found in solar chimneys (0.4 – 1.2 m/s).

An analysis of the uncertainties of the device was developed for each point tested, aiming to obtain the standard measurement uncertainty of the air velocity obtained from the proposed calibration device. The velocity uncertainty was obtained from the combination of the uncertainties from measurements of the tube diameter, the volumetric graduation of the water tank and the stopwatch, following a standard procedure (Instituto Nacional de Metrologia, Qualidade e Tecnologia, 2008). The following equations show the velocity calculation and the combined uncertainty:

$$v = \frac{Q}{A} = \frac{\Delta V}{A \Delta t} = \frac{4 \Delta V}{\pi D^2 \Delta t} \quad (1)$$

$$\left(\frac{u_v}{v}\right)^2 = \left(\frac{u_{\Delta V}}{\Delta V}\right)^2 + \left(\frac{u_{\Delta t}}{\Delta t}\right)^2 + \left(\frac{u_A}{A}\right)^2 = \left(\frac{u_{\Delta V}}{\Delta V}\right)^2 + \left(\frac{u_{\Delta t}}{\Delta t}\right)^2 + 2\left(\frac{u_D}{D}\right)^2 \quad (2)$$

where v is the velocity (m s^{-1}); Q is the volumetric flow rate ($\text{m}^3 \text{s}^{-1}$); A is the tube cross section area (m^2); ΔV is the

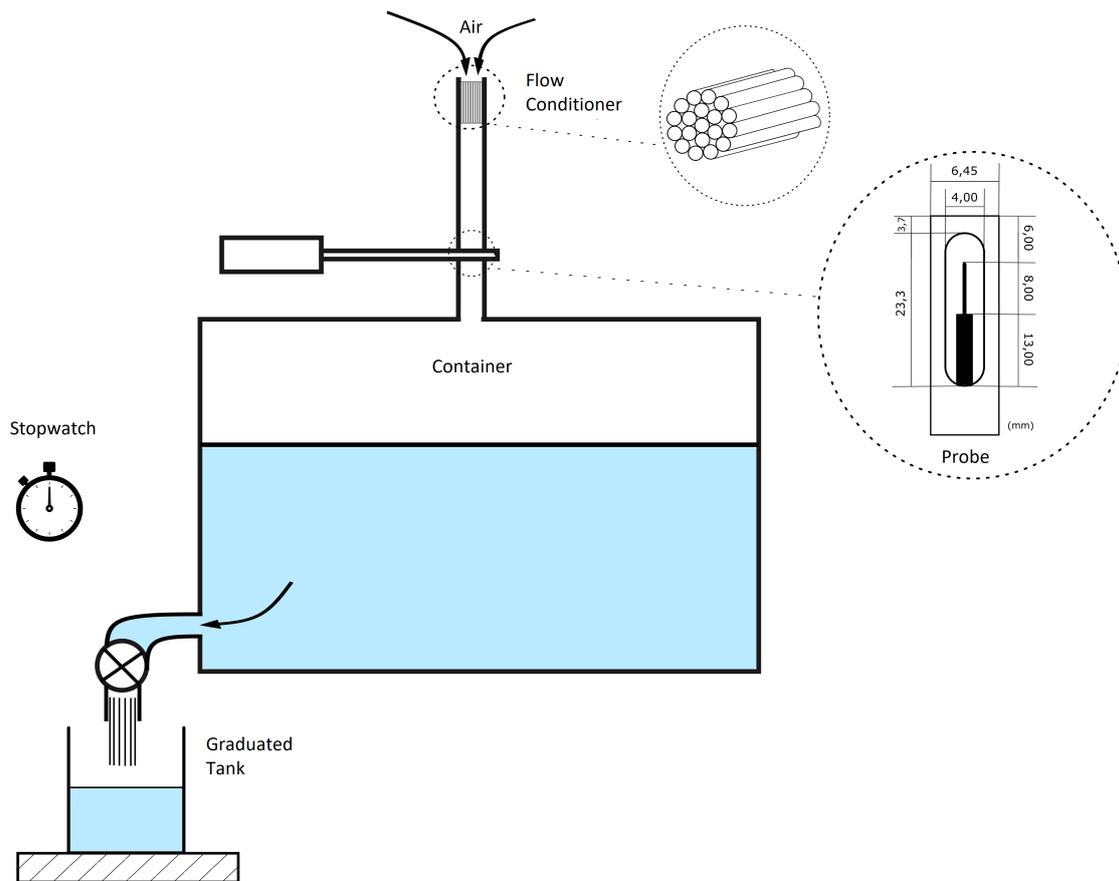


Figure 1. Sketch of the apparatus for the calibration of hot-wire anemometers at low velocities.

water volume filled in the graduated tank (m^3); Δt is the filling time (s); D is the tube diameter (m); u_v is the standard uncertainty of the velocity ($m s^{-1}$); $u_{\Delta V}$ is the standard uncertainty of the water volume filled in the graduated tank (m^3); $u_{\Delta t}$ is the standard uncertainty of the filling time (s); u_A is the standard uncertainty of the tube cross section area (m^2); and u_D is the standard uncertainty of the tube diameter (m).

From the manufacture manual, the OMEGA FMA-900 series air velocity transducers have accuracy of $\pm 1.5\%$ of full scale at room temperature, adding $\pm 0.5\%$ of reading from 0 to 50 °C, and also adding 1 % of full scale below 5.08 $m s^{-1}$. The repeatability of the transducers are 0.2 % of full scale. The full scale of the FMA-904-I is 10.16 $m s^{-1}$.

3. RESULTS & DISCUSSION

Figure 2 shows the results obtained with the proposed calibration device. The blue line shows the manufacturer's calibration curve, and the blue filled range shows the accuracy and repeatability reported by the manufacturer for this sensor. The red dots are the results of the velocities obtained with the calibration device, with the current supplied by the anemometer. Each point presented in the graph was obtained by averaging 50 consecutive points, which would have previously had at least 50 points to stabilize the speed of that given test. It turns out that all points are within the manufacturer's range of values.

In order to verify in detail the effect of each measurement parameter on the uncertainty of the results, the Table 2 shows the standard uncertainties for the calibration device of each of the measured points, along with the measurement values. The standard measurement uncertainties obtained for velocity ranged from 0.51 % to 0.85 %. These values are low and are considered adequate for the research group demands, as shown in Figure 3. The low uncertainty is mainly a result of flow measurement, since the 20 L volume used in the tests was measured with a limit of error of 100 mL, and the uncertainty of the timer, that is small compared to the measurement time, which varied from 1.2 to 5.6 min. It is possible to observe that in Figure 3 the increase is exponential, although with very small values. This is mainly due to the fact that as the speed increases, less time is required for the container to be completely filled as its volume remains at 20 L.

These values are consistent with similar work, such as Al-Garni (2007), who obtained an uncertainty around 4.1 % with confidence level of 95 %. On the other hand, in the work proposed by Pezzotti *et al.* (2011), the uncertainties were much larger, being less than 10 %. Nevertheless, the highest value obtained was 0.06 m/s, which was considered suitable for the equipment. In Yue and Malmström (1998) apparatus, which is very similar to the one proposed in this paper,

the uncertainties presented was below 1.5 %, which is consistent with the values found. In both studies, the amount of uncertainty is small, mainly because it involves few items that would allow the increase of this uncertainty.

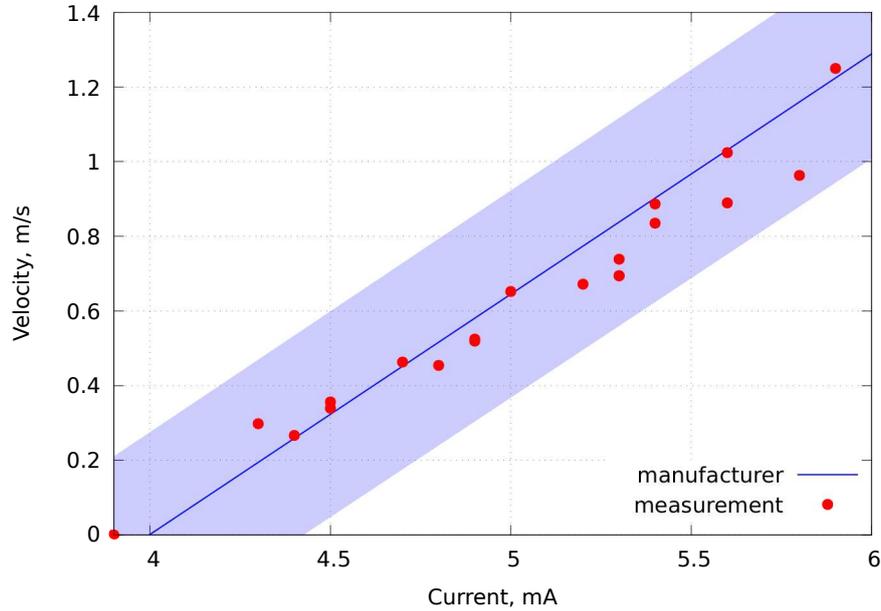


Figure 2. Mean values of the results obtained, the calibration certificate and the manufacturer’s range of values. The error bars are very small and have been removed as they would be inside the marker.

Table 2. Test results and their standard uncertainties for the proposed calibration device.

| Volume (ΔV) | | | Time (Δt) | | | Tube Area (A) | | | Flow Rate (Q) | | | Air Velocity (v) | | |
|-----------------------|-------------|------|---------------------|-------------|------|--------------------|--------------------|------|-------------------|-------------|------|----------------------|-------------|------|
| value | uncertainty | | value | uncertainty | | value | uncertainty | | value | uncertainty | | value | uncertainty | |
| (L) | (L) | (%) | (s) | (s) | (%) | (cm ²) | (cm ²) | (%) | (L/s) | (L/s) | (%) | (m/s) | (m/s) | (%) |
| 0 | 0 | 0.00 | 0.0 | 0.0 | 0.00 | 2.230 | 0.009 | 0.42 | 0.0000 | 0.0000 | 0.00 | 0 | 0.000 | 0.42 |
| 20 | 0.05 | 0.25 | 129.2 | 0.5 | 0.39 | 2.230 | 0.009 | 0.42 | 0.1548 | 0.0007 | 0.46 | 0.694 | 0.004 | 0.62 |
| 20 | 0.05 | 0.25 | 71.8 | 0.5 | 0.70 | 2.230 | 0.009 | 0.42 | 0.2787 | 0.0021 | 0.74 | 1.250 | 0.011 | 0.85 |
| 20 | 0.05 | 0.25 | 197.4 | 0.5 | 0.25 | 2.230 | 0.009 | 0.42 | 0.1013 | 0.0004 | 0.36 | 0.454 | 0.002 | 0.55 |
| 20 | 0.05 | 0.25 | 101.2 | 0.5 | 0.49 | 2.230 | 0.009 | 0.42 | 0.1977 | 0.0011 | 0.55 | 0.887 | 0.006 | 0.69 |
| 20 | 0.05 | 0.25 | 129.2 | 0.5 | 0.39 | 2.230 | 0.009 | 0.42 | 0.1548 | 0.0007 | 0.46 | 0.694 | 0.004 | 0.62 |
| 20 | 0.05 | 0.25 | 93.1 | 0.5 | 0.54 | 2.230 | 0.009 | 0.42 | 0.2148 | 0.0013 | 0.59 | 0.963 | 0.007 | 0.73 |
| 20 | 0.05 | 0.25 | 264.1 | 0.5 | 0.19 | 2.230 | 0.009 | 0.42 | 0.0757 | 0.0002 | 0.31 | 0.340 | 0.002 | 0.52 |
| 20 | 0.05 | 0.25 | 100.8 | 0.5 | 0.50 | 2.230 | 0.009 | 0.42 | 0.1984 | 0.0011 | 0.56 | 0.890 | 0.006 | 0.70 |
| 20 | 0.05 | 0.25 | 172.7 | 0.5 | 0.29 | 2.230 | 0.009 | 0.42 | 0.1158 | 0.0004 | 0.38 | 0.519 | 0.003 | 0.57 |
| 20 | 0.05 | 0.25 | 301.0 | 0.5 | 0.17 | 2.230 | 0.009 | 0.42 | 0.0664 | 0.0002 | 0.30 | 0.298 | 0.002 | 0.52 |
| 20 | 0.05 | 0.25 | 121.4 | 0.5 | 0.41 | 2.230 | 0.009 | 0.42 | 0.1647 | 0.0008 | 0.48 | 0.739 | 0.005 | 0.64 |
| 20 | 0.05 | 0.25 | 87.6 | 0.5 | 0.57 | 2.230 | 0.009 | 0.42 | 0.2284 | 0.0014 | 0.62 | 1.024 | 0.008 | 0.75 |
| 20 | 0.05 | 0.25 | 251.8 | 0.5 | 0.20 | 2.230 | 0.009 | 0.42 | 0.0794 | 0.0003 | 0.32 | 0.356 | 0.002 | 0.53 |
| 20 | 0.05 | 0.25 | 137.6 | 0.5 | 0.36 | 2.230 | 0.009 | 0.42 | 0.1454 | 0.0006 | 0.44 | 0.652 | 0.004 | 0.61 |
| 20 | 0.05 | 0.25 | 336.5 | 0.5 | 0.15 | 2.230 | 0.009 | 0.42 | 0.0594 | 0.0002 | 0.29 | 0.267 | 0.001 | 0.51 |
| 20 | 0.05 | 0.25 | 193.6 | 0.5 | 0.26 | 2.230 | 0.009 | 0.42 | 0.1033 | 0.0004 | 0.36 | 0.463 | 0.003 | 0.55 |
| 20 | 0.05 | 0.25 | 171.0 | 0.5 | 0.29 | 2.230 | 0.009 | 0.42 | 0.1169 | 0.0004 | 0.38 | 0.524 | 0.003 | 0.57 |
| 20 | 0.05 | 0.25 | 133.5 | 0.5 | 0.37 | 2.230 | 0.009 | 0.42 | 0.1498 | 0.0007 | 0.45 | 0.672 | 0.004 | 0.62 |
| 20 | 0.05 | 0.25 | 107.4 | 0.5 | 0.47 | 2.230 | 0.009 | 0.42 | 0.1862 | 0.0010 | 0.53 | 0.835 | 0.006 | 0.67 |
| average | 0.25 | | | 0.37 | | | | 0.42 | | | 0.45 | | | 0.62 |
| minimum | 0.25 | | | 0.15 | | | | 0.42 | | | 0.29 | | | 0.51 |
| maximum | 0.25 | | | 0.70 | | | | 0.42 | | | 0.74 | | | 0.85 |

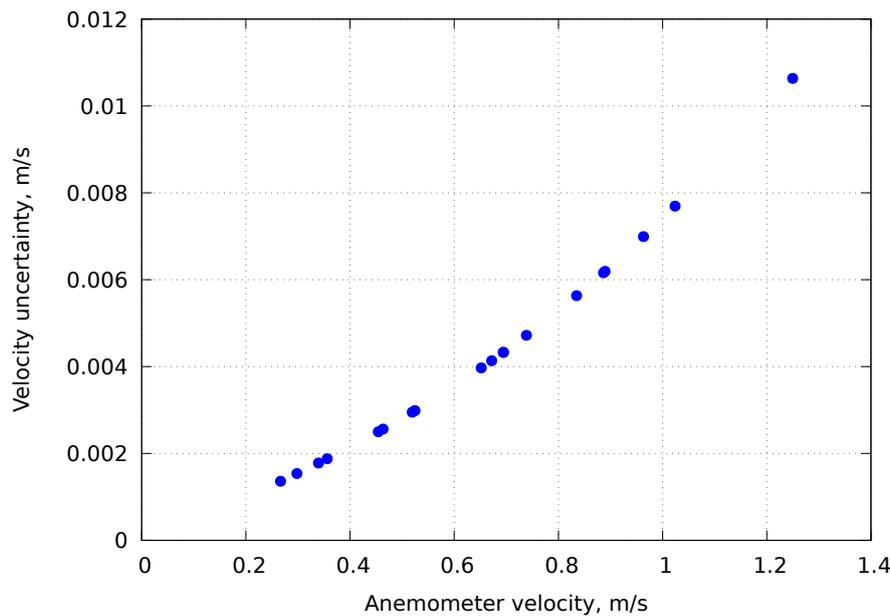


Figure 3. Evolution of the experimental apparatus measurement uncertainties, calculated from the volume and time measurement uncertainties.

4. CONCLUSION

In this study it was presented the construction of a low-cost apparatus for calibrating anemometers at low speed. It was observed that this model presented a low uncertainty, ranging from 0.51 % to 0.85 % for speed measurements. Also, the results were very close to the manufacturer's curve and the expected range, demonstrating that it is possible to use it for others similar equipments.

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