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CALIBRATION OF A LOW SPEED WIND TUNNEL.
MEASUREMENT SYSTEMS AND MEANS TO VISUALIZE
THE AIRFLOW

Rubén Silvestre Saavedra Bao

Pablo Sanchis Gúrpide

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Abstract

The main goal of this master thesis is to assemble and prepare the wind tunnel for educational and research purposes.

The first goal is to install measurement systems (like pitot tubes, hot wires or similar instruments to measure the air velocity inside the wind tunnel). The second goal is to install a means to visualize the air flow (like smoke generators to obtain streamlines, aerosols or systems based on the utilization of a laser beam).

I did a market research looking for different systems and instruments I could use to measure the pressure and the air velocity inside the wind tunnel. I also gathered some information about how they work. I compared their most important features and according to that comparison I finally selected a pitot tube and a transmitter to measure the pressure.

I calculated the margin of error of the air velocity from the accuracy of the transmitter using Bernoulli equation and statistics (Normal Distribution and the Delta Method). I also did the implementation the pitot tube and the transmitter in the wind tunnel. To achieve this, I installed first an electric circuit according to the transmitter manufacturer recommendations to convert the differential pressure to a drop voltage first and to convert afterwards this drop voltage to a digital signal using an analog digital converter. Connecting this analog digital converter to a computer and using programming software, I converted the digital signal to an air velocity value using polynomial interpolation. Finally, I did the transmitter set up according to the manufacturer's manual.

I did some measurements and tests. I calibrated the pitot tube and the transmitter and I measured the air velocity comparing the results of the pitot tube and the results of the anemometer that the university already had in the physics laboratory.

I did a new market research looking for different means to visualize the airflow. Like in the first goal of this thesis, I gathered some information about how they work and I compared their most important features. Due to there was more than one suitable means (smoke generator, fog nozzle and laser sheet), I explained different combinations with their advantages and disadvantages concluding which ones were the best.

I selected the best options among the means analyzed in the previous step. I selected the smoke generator. I did experiments to build my own fog nozzle, using cheaper materials and some stuff that I found in the mechanic laboratory. I also built a laser sheet using materials that I found in the university.

I did three experiments using the means selected with the help of a wing profile provided by Vincent De Frenne. In the first one I used the smoke generator, my own fog nozzle and the laser sheet, and I did in the light and in the darkness. In the second one I used the smoke generator and the laser sheet, and in the third one, I used the smoke generator and the fog nozzle.

I also found some problems. Some of them I were able to solve, but others I didn't know how to do it.

During the calibration of the pitot tube and the transmitter, I realized that I couldn't complete the calibration recommended by the manufacturer because I didn't have a special pressure source to set up the span. I did a first calibration using the anemometer measurements. Due to an unsatisfactory result, I did a second calibration. I changed the procedure of measuring and some parameters in the software application. I did a new test afterwards to check that the new calibration was okay.

I had problems with the materials that I used to build the fog nozzle. The materials couldn't stand the high temperature and some of the melted or deformed.

I also had problems with the fog nozzle and the streamline. Using the tip of a manual pump, I was able to create the streamline but it wasn't clear.

The laser sheet I created wasn't powerful enough. I wasn't able to see the laser through the smoke.

I obtained results after all my work. Despite of the difficulties I found, I finally could calibrate the pitot tube and the transmitter with the sources that I had. The pitot tube and the transmitter are not installed permanently and the electric circuit is provisional.

I finally created the streamlines using my own fog nozzle and I was able to build a laser, but the results are not satisfactory. The devices that I built are in the wind tunnel's room and the installation is not permanent.

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Chapter 1. INTRODUCTION

1 Introduction

The Erasmushogeschool Brussel received a wooden low speed wind tunnel from the Vrije Universiteit Brussel in 2009. This wind tunnel had no systems and instruments to measure the velocity of the air or to visualize the airflow.

The aim of this project is to equip the wooden wind tunnel with instruments to measure the velocity of the air and means to visualize the air flow.

To complete these purposes we did:

- A market research to find the most suitable instruments and tools for our purposes.
- Test and experiments to check and calibrate them when it is necessary.

1.1 Description of the Thesis

The following text is a summary of the thesis. It explains in few words the most important points of each chapter.

Chapter 1

Chapter 1 presents the general Introduction of the Thesis with the general aims and the context.

Chapter 2

Chapter 2 introduces the wooden wind tunnel, using some pictures to show how it is and giving some information, such as dimensions and operating range.

Chapter 3

Chapter 3 gives some useful information of different measurement systems and instruments, as well as a comparison of them taking into account the most relevant features. At the end of the chapter, there is a conclusion where the final decision of this chapter is detailed.

Chapter 4

Chapter 4 deals with the installation of the measurement systems and instruments selected in chapter 2, margins of error (pressure accuracy, velocity accuracy...), hardware (electronic parts, devices, computers...), software (programming, software used...), calibration and test measurements.

Chapter 5

Chapter 5 gives some information of different means to visualize the airflow. Smoke generators, aerosol generators, and laser systems are detailed in this chapter, as well as a comparison of them. Like in Chapter 2, there is a conclusion at the end of this chapter about what we should do to visualize the airflow.

Chapter 6

Chapter 6 explains what we do to visualize the airflow and how. It explains the different tests executed to check if we are in the right way or not. There are also explained the problems we find and what we do to solve them.

Chapter 7

Chapter 7 explains the experiments we do using the means the selected in the previous chapter to visualize the airflow.

Chapter 8

This chapter consists of the final conclusions after doing all the experiments and tests with the corresponding recommendations.

Appendix A

In this appendix the different measurement systems which took part in the market research are widely described with their most important features.

Appendix B

In this appendix the different elements considered to visualize the airflow which took part in the market research are widely described with their most important features.

Chapter 2. DESCRIPTION OF THE WOODEN LOW SPEED WIND TUNNEL

2 Description of the wooden wind tunnel

A wind tunnel is an important tool used in aerodynamic research. It is used to study the effects of air moving past solid objects. [5]

2.1 How a wind tunnel works

The operation is very easy; air is blown through a duct equipped with a viewing port and instrumentation where models or geometrical shapes are mounted for study. Typically the air is moved through the tunnel using a fan. This fan (or series of fans, when the wind tunnel is too large) is powered by electrical motors (with larger wind tunnels, the fans are powered by stationary turbofan). The airflow created by the fan or fans that is entering the tunnel is itself highly turbulent due to the fan blade motion, and is not directly useful for accurate measurements. The air moving through the tunnel needs to be relatively turbulence-free and laminar. To solve this problem, closely-spaced vertical and horizontal air vanes (*fig. 1*) are used to smooth out the turbulent airflow before reaching the subject of the testing. [5]



Figure 1: air vanes

2.2 Measurement of aerodynamic forces

There are different ways to measure the pressure and velocity of the air inside a wind tunnel:

- Air velocity through the test section is determined by Bernoulli's principle. Measurement of the dynamic pressure, the static pressure, and (for compressible flow only) the temperature rise in the airflow. [5]
- Direction of airflow around a model can be determined by tufts of yarn attached to the aerodynamic surfaces. [5]
- Direction of airflow approaching an aerodynamic surface can be visualized by mounting threads in the airflow ahead of and aft of the test model. [5]
- Dye, smoke, or bubbles of liquid can be introduced into the airflow upstream of the test model, and their path around the model can be photographed. [5]
- Pressures on the test model are usually measured with beam balances, connected to the test model with beams or strings or cables. [5]
- Pressure distributions across the test model have historically been measured by drilling many small holes along the airflow path, and using multi-tube manometers to measure the pressure at each hole. [5]
- Pressure distributions can more conveniently be measured by the use of pressure-sensitive paint, in which higher local pressure is indicated by lowered fluorescence of the paint at that point. [5]
- Pressure distributions can also be conveniently measured by the use of pressure-sensitive pressure belts, a recent development in which multiple ultra-miniaturized pressure sensor modules are integrated into a flexible strip. The strip is attached to the aerodynamic surface with tape, and it sends signals depicting the pressure distribution along its surface. [5]
- Pressure distributions on a test model can also be determined by performing a wake survey, in which either a single pitot tube is used to obtain multiple readings downstream of the test model, or a multiple-tube manometer is mounted downstream and all its readings are taken (often by photograph). [5]

2.3 Flow Visualization in a wind tunnel

Because air is transparent, it is difficult to directly observe the air movement. To solve this fact, a smoke particulate or a fine mist of liquid is sprayed into the tunnel just ahead of the device being tested. The particulate is sufficiently low mass to stay suspended in the air without falling to the floor of the tunnel, and is light enough to easily move with the airflow. If the air movement in the tunnel is sufficiently non-turbulent, a particle stream released into the airflow will not break up as the air moves along, but stays together as a sharp thin line. Multiple particle streams released from a grid of many nozzles can provide a dynamic three-dimensional shape of the airflow around the object being tested. As with the force balance, these injection pipes and nozzles need to be shaped in a manner that minimizes the introduction of turbulent airflow into the airstream. [5]

2.4 Our wind tunnel

The wind tunnel received by the Vrije Universiteit Brussel in 2009 has the following parts:

2.4.1 The electric motor

The fan is powered by an electric motor. This motor is connected to a variable speed drive (fig. 2).



Figure 2: variable speed drive

The motor (fig. 3) is powered by alternating current, and using the variable speed drive we are able to change the voltage sent to the electric motor. This way, we can select the rotating speed of the motor, with the purpose of controlling the rotating speed of the fan.

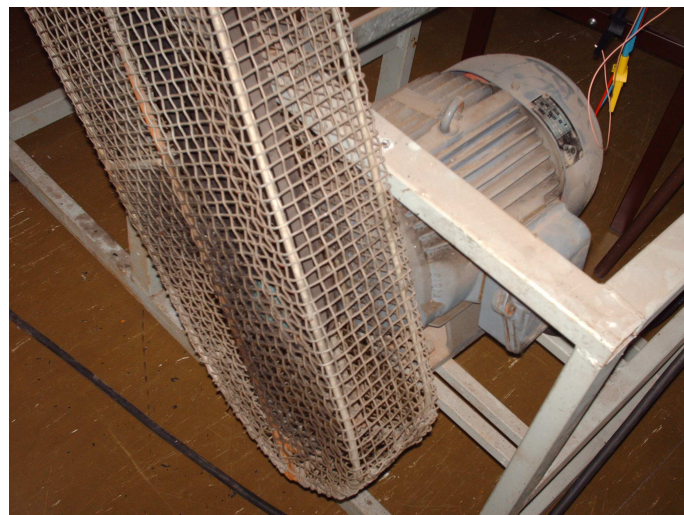


Figure 3: Electric motor

Some of the features of the electric motor are:

- 3 ~ 50 Hz
- Voltage: 220/380 Δ Y
- Amp: 27,6 / 15,9
- Power: 10 hp
- Number of pair of poles: 33
- Cos φ : 0.85

2.4.2 The fan

The fan (*fig. 4*) is placed at the beginning of the wind tunnel's duct and is the responsible of moving the air inside the duct. The range of air speed the fan can provide is from 0 m/s to approximately 15 m/s.



Figure 4: the fan

By a belt and two pulleys (*fig. 5*), the electric motor is connected to the fan.



Figure 5: The belt and the two pulleys

2.4.3 The duct

The duct (*fig. 6*) can be made of wood or metal. In our case it is made of wood. The cross-section of the duct can be circular or square. The cross-section of our wind tunnel is square. The duct has inside different parts to provide a smoother flow, like nets. Downstream, there is the testing zone.



Figure 6: The duct

The size of the cross-section (*fig. 7*) in the testing zone is approximately 640 mm width and 490 mm height.



Figure 7: The cross-section in the testing zone

This is the place where we use the measurement systems and instruments and the means to visualize the flow.

Chapter 3. MEASUREMENT SYSTEMS AND INSTRUMENTS

3 Measurement Systems and instruments

As a first step, we must do a market research to find how we can measure the speed of the air inside the wind tunnel and which instruments are necessary for this aim.

There are different systems which can be useful for our purpose:

- Pitot-tube
- Hot wire anemometer
- Air velocity transmitters

3.1 Pitot tube

3.1.1 Bernoulli's principle

Pitot tubes are used to calculate the air flow velocity measuring the difference between the total pressure and static pressure.

The pitot tube is based on the Bernoulli equation. The Bernoulli equation is an application of the Bernoulli's principle, which states that for a fluid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy, in such a way that the sum of the static pressure, dynamic pressure (due to air flow velocity) and hydrostatic pressure (due to change in elevation, potential energy), keeps constant. [6]

$$p + \frac{1}{2} \times \rho \times v^2 + \gamma \times h = const$$

p : static pressure

ρ : density of air

v : air flow velocity

γ : specific weight

h : elevation height

The first term is the static pressure, the second term is the dynamic pressure, and the third term is the hydrostatic pressure. [6] [7]

Considering that the fluid flow we want to measure is steady and the elevation along the wind tunnel doesn't change, we can state that the hydrostatic pressure doesn't change. This means that the sum of dynamic pressure and static pressure remains constant. [6] [7]

$$h = const$$
$$p + \frac{1}{2} \times \rho \times v^2 = const$$

Using a pitot tube, what we are doing is comparing two different points.

$$p_1 + \frac{1}{2} \times \rho \times v_1^2 = p_2 + \frac{1}{2} \times \rho \times v_2^2$$

The pitot tube (*fig. 8*) consists of a tube pointing directly into the air flow. The air flow goes inside the pitot tube and stagnates when it reaches the elbow of the tube. The pressure in this point is called total pressure. [6] [7]

The point 1 will be the static pressure port, where the streamlines are not affected by the pitot tube and the point 2 will be the total pressure port, where the speed of the air flow is supposed to be zero because of the stagnation. [6] [7]

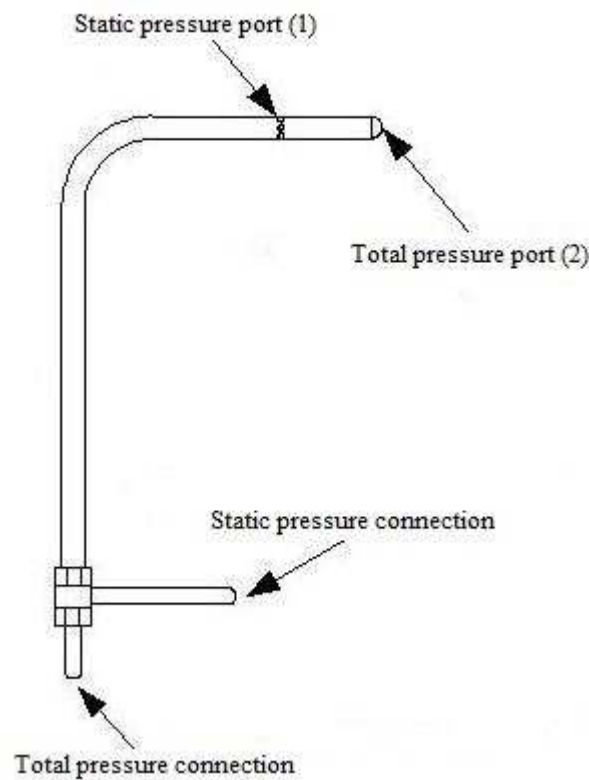


Figure 8: pitot tube [22]

$$v_2 = 0$$

$$p_1 + \frac{1}{2} \times \rho \times v_1^2 = p_2$$

- p_1 : static pressure at point 1
- ρ : density of air
- v_1 : air flow velocity at point 1
- p_2 : stagnation pressure

The pitot tube measures the difference of pressure between point 2 (total pressure) and the point 1 (static pressure). Taking into account this and the fact that we know the

density of air, we can finally calculate v_1 reordering the previous terms, obtaining the following formula:

$$v_1 = \left[\frac{2 \times (p_2 - p_1)}{\rho} \right]^{1/2}$$

The pitot tubes can be used with a manometer, or other differential pressure instruments to obtain directly an accurate value for the air velocity. [6] [7]

3.1.2 *K coefficient*

Using a pitot tube L-shaped we measure the difference between total pressure and static pressure. The accuracy of this measurement is very important, even though all experiments depend on it. The K coefficient is telling us how good the accuracy of a pitot tube is. [19]

To calculate the velocity of the air we have the formula we have obtained previously:

$$v_1 = \left[\frac{2 \times (p_2 - p_1)}{\rho} \right]^{1/2}$$

In this formula, we suppose the K coefficient is 1, so the real formula would be:

$$v_1 = k \times \left[\frac{2 \times (p_2 - p_1)}{\rho} \right]^{1/2}$$

This means the closer to 1,000, the better. [19]

The manufactured pitot tubes are supposed to be calibrated, so the K coefficient is supposed to be 1,000. The problem is that this statement is not true. It is very difficult to obtain the unit as K coefficient, but manufacturers always say that their pitot tubes' K coefficient is 1,000. [19]

In spite of this fact, the K coefficient is around 1,000, so we can consider it as 1,000 for the calculations. [19]

The K coefficient is not constant. It depends on the material the pitot tube is made of, the installation of the pitot tube, etc. [19]

To keep this coefficient as close as possible to 1,000, the pitot tube should be recalibrated periodically. [19]

3.2 Hot wire anemometer

Hot wire is one of the most common measurement devices in experimental fluid mechanics. It is used to measure velocity of the fluid. There are two different types of hot wires, CTA (constant temperature anemometer) and CCA (constant current anemometer). The most common are the CTA devices.

Hot wire anemometers use a very fine wire (on the order of several micrometers) electrically heated up to some temperature above the ambient. Surrounding the wire, there is an air flow going past. The wire transfers convective heat to the air next to it due to its higher temperature. This heat transmission doesn't end because the air is always renewing, keeping the difference of temperature that makes possible the heat transmission. The convective heat Q the wire transfers to the air is a function of the air velocity V , the difference of temperature between the wire and the ambient ($T_w - T_0$), and the physical properties of the air (thermal conductivity k , density $\rho \dots$). [1] [8]

$$Q = (T_w - T_0) \times A_w \times h$$

Where:

A_w : wire surface

h : heat transfer coefficient

When using a hot wire anemometry one of the most important aspects is calibrating the signal accurately. When calibrating several different formulas are used, such as power law, polynomial or spline fits. The most common way is by using King's law. [8]

L.V. King found a relationship between the velocity of the air V around the small cylinder (Hot Wire) and the convective heat Q from the cylinder. This convective heat is connected to the voltage over the wire, so measuring the velocity of the air V is possible. [2]

King's relationship was on the form of a simple power law.

$$Q = A + B \times V^n$$

Where A and B are used as calibration constants and n was given by King to be $n=0.5$. Now, we finally have:

$$Q = (T_w - T_0) \times A_w \times h = A + B \times V^n; n = 0.5$$

The hot wire (*fig. 9*) is normally made of tungsten or platinum, 1mm long and $5\mu\text{m}$ in diameter, mounted on two needles.

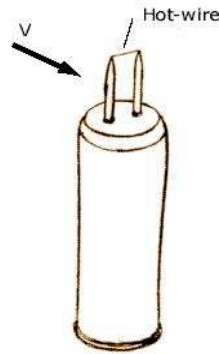


Figure 9: Hot wire mounted on two needles [23]

This wire R_w is connected to one arm of a Wheatstone bridge (fig. 10) and heated by an electrical current. A servo amplifier keeps the bridge in balance by controlling the current to the sensor so that the resistance is kept constant, independent of the cooling imposed by the air. The bridge voltage, E , represents the heat transfer. [8]

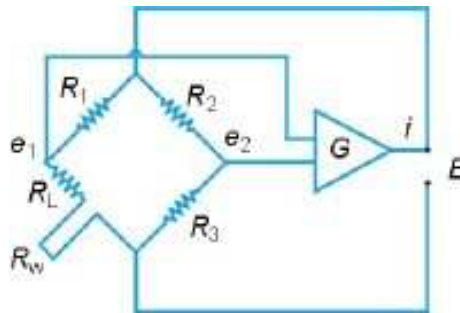


Figure 10: Wheatstone bridge [24]

Knowing the value of the bridge voltage, it is possible to calculate the air velocity using the following equation:

$$E^2 = (T_w - T_0) \times (A + B \times V^{0.5})$$

A lot of work has been done to find a better corresponding n . Collis and Williams [3] found the exponent n to be $n = 0.45$ from their experimental data. Bruun H. H. & Kahn M. A. [4] found that n is varying between 0.40 and 0.44 depending on operating conditions. Bruun H. H. says that the constants A and B only are constants over a small range of Reynolds number. To go around this problem polynomial fit and extended power law is used. When using a polynomial equation to calibrate the hot wire, the velocity is expressed as a polynomial with the voltage as variable. [20]

$$V = C_0 + C_1 \times E^2 + C_2 \times E^3 + C_3 \times E^4 + C_4 \times E^5$$

Where C 's are calibration constants.

3.3 Air velocity transmitters

Air velocity transmitters (*fig. 11*) are instruments designed for the exact measurement of air velocity. Utilizing thin film thermal sensor elements and hot wire anemometer technology, Air velocity transmitters measure air velocity with no wear to the sensor element. They are very similar to the hot wire anemometers, because both are based on the same principles, but air velocity transmitters are usually better equipped. [9]



Figure 11: Air velocity transmitter [25]

3.4 Conclusion

In this market research, we have found many systems and instruments to measure the air velocity inside our wind tunnel.

To select to most suitable option for our purposes we must take into account some conditions:

- The chosen one won't be bought on internet; it will be bought on a distributor preferably.
- The chosen one must be easy to use and install.
- The chosen one should have a good relationship between price and quality.
- The chosen one should not be expensive.
- The maintenance should not be expensive.
- The purposes are for education and research. A high technology instrument may not be necessary.

Among the different options, air velocity transmitters seem to be a good option (various speed range, large temperature range, good accuracy, interface to personal computer, etc) but the price is a disadvantage. More than 200 € is too expensive (see *Appendix A*).

Concerning the hot wire anemometers, they are very useful to measure the air velocity in a thin boundary layer, their other features are as good as the air velocity transmitters', but they are also too expensive (more than 495 €, see *Appendix A*).

Regarding pitot tubes and manometers, they seem to be the best option, because their accuracy is very good, the maintenance is not too complex, and the price is cheaper than hot wire anemometers and air velocity transmitters. A better comparison of pitot tubes and manometers is detailed next in those tables (*table 1, table 2*).

The prices correspond with pitot tubes whose insertion length is approximately 500 mm. This length is the best choice for our wind tunnel because of its dimensions.

Company	model	material	tip	Standards and specifications	K coefficient	accuracy for pressure	temperature range	temperature measurement
KIMO	TPL-XX-XXXX	stainless steel	ellipsoidal	ISO 3966	1,005	<1%	0°C-600°C	no
KIMO	TPL-XX-XXXX-T	stainless steel	ellipsoidal	ISO 3966	1,005	<1%	0°C-600°C	yes
DWYER	160-XX	stainless steel	hemispherical	ANSI/AMCA 210-99 ANSI/ASHRAE 51-1999 British Standard 1042	1,000	<1%	0°C-815°C	no
DWYER	160E-XX	stainless steel	ellipsoidal	ANSI/AMCA 210-99 ANSI/ASHRAE 51-1999 British Standard 1042	1,000	<1%	0°C-815°C	no
DWYER	160S-XX	stainless steel	Opened	EPA specification 40 CFR (ch 1.)	0,840	>1%	0°C-815°C	no
DWYER	160S-XXPM	stainless steel	Opened	EPA specification 40 CFR (ch 1.)	0,840	>1%	0°C-815°C	no
FURNESS CONTROL	FCO65	stainless steel	hemispherical	Not available	1,000	<1%	0°C-500°C	no

Table 1: pitot tubes

Company	model	Accuracy (for 250 Pa)	Temperature limits	Pressure limits	Power requirements	Display	Output	pressure connection
KIMO	MP200 P	± 0,2%	-20°C to 80°C	±500 Pa max. ± 750 Pa burst	4 x 1.5V LR6	graphic, blue screen	USB port for KIMO cable only	6.2 mm hose connection
DWYER	MS-111	±2%	-18°C to 66°C	6894 Pa max. 68947 Pa burst	17 to 36 VDC (3-wire) isolated 21.6 to 33 VAC (3-wire)	4 digit LCD	0 to 10 V (3-wire)	5 mm hose connection

Table 2: manometers

The price of each element is:

- Pitot tubes:
 - KIMO TPL-XX-XXXX: 168 €
 - KIMO TPL-XX-XXXX-T: 204 €
 - DWYER 160-XX: 167 €
 - DWYER 160E-XX: 200 €
 - DWYER 160S-XX: 230 €
 - DWYER 160S-XXPM: 470 €
 - FURNESS CONTROL FCO65: not available

- Manometers:
 - KIMO MP200 P: 820 €
 - DWYER MS-111: 95 €

Now, we have different pitot tubes and two different manometers. We can reject the pitot tube that can measure temperature, KIMO TPL-XXXX-XX-T because we don't need to measure it.

We can also reject two more pitot tubes; 160S-XX and 160S-XXPM are not designed for our purpose. Besides, they are too expensive.

Concerning FCO65, we don't have information enough, and the range of working temperature is worse.

Now, we must take into account the head of the pitot tube. We have two types, the ellipsoidal tip and the hemispherical tip. We should select an ellipsoidal tip because it allows air to pass smoothly with minimum turbulence.

We finally have two options:

- KIMO TPL-XXXX-XX
- DWYER 160E-XX

The prices are very similar (168 € and 200 € approximately) and the K coefficient are similar too (although DWYER says its product K coefficient is exactly 1, something that is quite difficult to achieve) so if we want to make the correct choice, we have to pay attention to the manometer (the best choice would be to select the same company for the pitot tube and the manometer, because this way we don't have problems of compatibility).

KIMO MP200 P has good features, but most of them are not necessary for our aim. Moreover, it is very expensive.

On the other hand, transmitter DWYER MS-111 has less accuracy, but it is cheaper and its features are enough for our purposes.

As a conclusion, the best choice seems to be:

- Pitot tube: DYWER 160E-02 (length insertion of 480 mm)
- Manometer: transmitter DYWER MS-111

Chapter 4. IMPLEMENTATION OF THE PITOT TUBE AND THE TRANSMITTER

4 Implementation of the pitot tube and the transmitter

4.1 Introduction

The selected instruments are:

- Pitot tube: DYWER 160E-02 (length insertion of 480 mm)
- Manometer: transmitter DYWER MS-111

Once the measurement system has been selected, it would be very useful to calculate the margins of error for the air velocity from the measured pressure. This part can be done without installing anything. That will help us to calibrate the wind tunnel later.

Afterwards, we must do the implementation. First, we will do a provisional installation to make sure that the instruments are not damaged and to check that they work properly.

4.2 Margins of error

It would be very useful to calculate the margins of error for the air velocity from the measured pressure.

The transmitter *DYWER MS-111* has different ranges. We are interested in a speed range from 15 m/s to 20 m/s approximately. The pressure range in which we will work is from 0 to 250 Pa. because this is the one that best fits (using Bernoulli equation, 250 Pa means 20 m/s). Attending to the specifications of the manufacturer, the accuracy for this range is $\pm 2\%$. Now, we should be able to work out the margins of error for this pressure using statistical equations.

First of all, we make a table with different values for the differential pressure (Δp), from 0 Pa until 250 Pa. we assume that all the values are discrete (0, 1, 2, 3..., 100, 101, 102..., 248, 249, 250)

We assume also that the value of measured differential pressure follows a normal distribution for each value (0, 1, 2, 3..., 100, 101, 102..., 248, 249, 250), which is the mean (μ) in each case. We know that the accuracy is $\pm 2\%$ for all of these possible values. This means that if the real pressure is 100 Pa, using our instrument the measurement is not higher than 102 Pa and lower than 98 Pa in a high percent of the cases (we suppose an engineering toleration of 95%; it means that the 95 % of the measurements must be in the $\pm 2\%$ interval around the real value).

Quantiles of the normal distribution, the mean and the standard error can be used to calculate approximate confidence limits for the mean. The following expressions can be used to calculate the upper and lower 95% confidence limits, where μ is the mean, S_E is the standard error, and 1.96 is the 0.975 quantile of the normal distribution [10] [11]:

$$\text{upper } 95\% = \mu + (S_E \times 1.96)$$

$$\text{lower } 95\% = \mu - (S_E \times 1.96)$$

Now, we can calculate the value of S_E for each value of differential pressure. In this case, S_E is the estimated standard deviation of the error in the process by which it was generated. We suppose that the differential pressure measurement is a sample statistic, so S_E is the standard deviation (σ) of the normal distribution of each value of differential pressure. Knowing that [10] [11]:

$$\mu \times (1 \pm 0.02) = \mu \pm (\sigma \times 1.96)$$

We can calculate the standard deviation for each value of the differential pressure (table 3).

$$\sigma(\Delta p) = \mu \times \frac{0,02}{1,96}$$

Differential Pressure (Pa)	$\sigma(\Delta p)$
1	0,01
2	0,02
...	...
100	0,97
101	0,98
...	...
240	2,40
241	2,41
...	...
249	2,54
250	2,55

Table 3: differential pressure and $\sigma(\Delta p)$

Now, we use the Delta Method to calculate the standard error of the air velocity. This method, in its essence, expands a function (air velocity) of a random variable (the differential pressure) about its mean (μ), usually with a one-step Taylor approximation, and then takes the variance (σ^2). In our case, we have [10] [11]:

$$v(\Delta p) = v(\mu) + (\Delta p - \mu) \times v'(\mu)$$

Where $v'(\mu)$ is the first derivate of v respect to μ . So that:

$$\sigma^2(v(\Delta p)) = \sigma^2(\Delta p) \times [v'(\mu)]^2$$

Taking into account that we can replace the term $[v'(\mu)]$ with $[\delta v / \delta(\Delta p)]$ because the good accuracy ($\pm 2\%$), we finally have [10] [11]:

$$\sigma^2(v(\Delta p)) = \sigma^2(\Delta p) \times \left[\frac{\delta v}{\delta(\Delta p)} \right]^2$$

Now, considering the Bernoulli equation:

$$v = (v(\Delta p)) = \sqrt{\frac{2 \times \Delta p}{\rho}}$$

And making his first derivate, we obtain:

$$v' = (v(\Delta p))' = \frac{1}{\sqrt{2 \times \rho \times \Delta p}} = \frac{\delta v}{\delta(\Delta p)}$$

Substituting terms in the variance equation:

$$\sigma^2(v(\Delta p)) = \sigma^2(\Delta p) \times \left[\frac{1}{\sqrt{2 \times \rho \times \Delta p}} \right]^2$$

Taking 1,225 Kg/m³ for the air density value, we can make a table (table 4) representing the air velocity and the standard deviation of the air velocity. The Velocity is calculated using the Bernoulli equation and the standard deviation ($\sigma(v)$) is calculated from the variance [10] [11]:

$$\sigma(v) = \sigma(v(\Delta p)) = \sqrt{\sigma^2(v(\Delta p))} = \sqrt{\sigma^2(\Delta p) \times \left[\frac{1}{\sqrt{2 \times \rho \times \Delta p}} \right]^2}$$

Differential Pressure (Pa)	$\sigma(\Delta p)$	Velocity (m/s)	$\sigma(v)$
1	0,01	1,27	0,00652
2	0,02	1,80	0,00922
...
9	0,09	3,83	0,01956
10	0,10	4,04	0,02062
...
100	1,02	12,77	0,06519
101	1,03	12,84	0,06552
...
109	1,06	13,34	0,06806
110	1,07	13,40	0,06837
...
240	2,45	19,79	0,10099
241	2,46	19,83	0,10120
...
249	2,54	20,16	0,10287
250	2,55	20,20	0,10308

Table 4: differential pressure, $\sigma(\Delta p)$, velocity and $\sigma(v)$

Once the standard deviation has been calculated, we can also calculate the limit of variation of the air velocity using the equations of the confidence limits for 95% (table 5) [10] [11]:

$$\text{upper 95\%} = \mu + (\sigma \times 1.96)$$

$$\text{lower 95\%} = \mu - (\sigma \times 1.96)$$

$$\Delta v = \sigma(v) \times 1.96$$

Differential Pressure (Pa)	$\sigma (\Delta p)$	Velocity (m/s)	$\sigma (v)$	Δv
1	0,01	1,27	0,00652	0,012
2	0,02	1,80	0,00922	0,018
...
9	0,09	3,83	0,01956	0,038
10	0,10	4,04	0,02062	0,040
...
100	1,02	12,77	0,06519	0,124
101	1,03	12,84	0,06552	0,125
...
109	1,06	13,34	0,06806	0,130
110	1,07	13,40	0,06837	0,130
...
240	2,45	19,79	0,10099	0,197
241	2,46	19,83	0,10120	0,198
...
249	2,54	20,16	0,10287	0,201
250	2,55	20,20	0,10308	0,202

Table 5: differential pressure, $\sigma(\Delta p)$, velocity, $\sigma(v)$ and Δv

A graphic of the limits of variation (*fig. 12*) of the air velocity is detailed next.

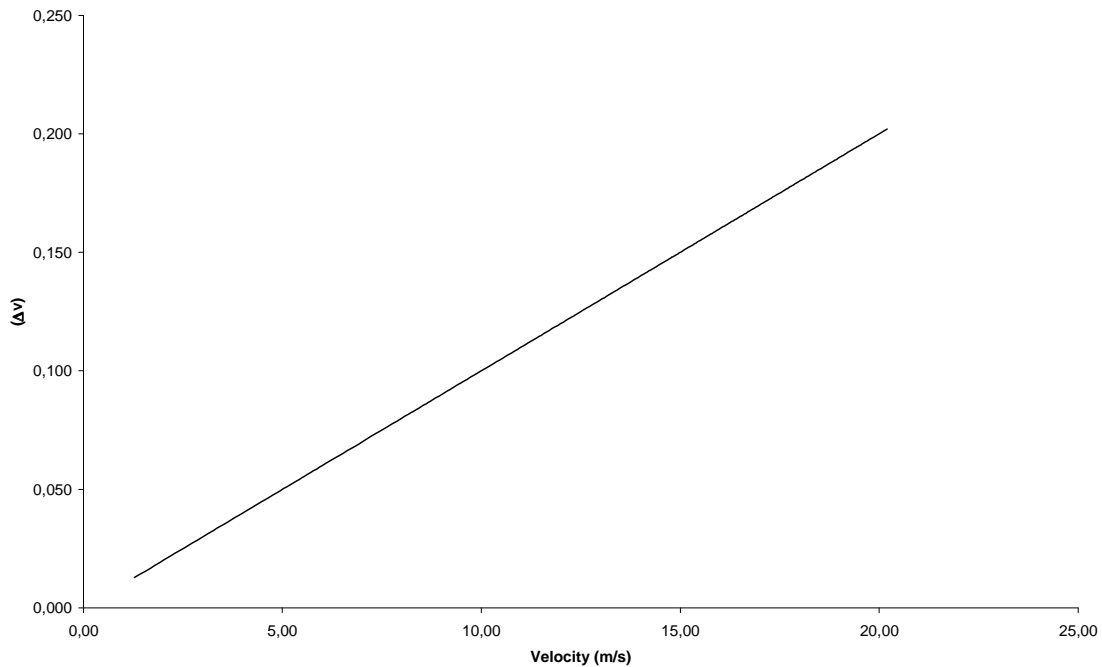


Figure 12: limits of variation

If we pay attention to the graphic, we will see that the maximum possible variation is the 1% of the value of the air velocity. In other words, its accuracy is $\pm 1\%$.

4.3 Hardware implementation

Summarizing, the pitot tube gets two different pressures (static pressure and total pressure). Using two plastic tubes, we connect the pitot tube to the transmitter, which is able to measure a differential pressure. The transmitter gives a current value depending on the value of the differential pressure. This current runs through an electric circuit. This electrical circuit has a load. Due to the current that runs through the electric circuit, there is a voltage drop in the load. This voltage drop is taken to an Analog digital converter. This device, which receives the analog signal (voltage), is able to give a digital signal. This digital signal is carried to a computer using a USB connection.

Finally, programming software reads this digital signal and gives us numeric values of pressure and velocity.

4.3.1 Hardware scheme

The hardware scheme (fig. 13) is detailed below.

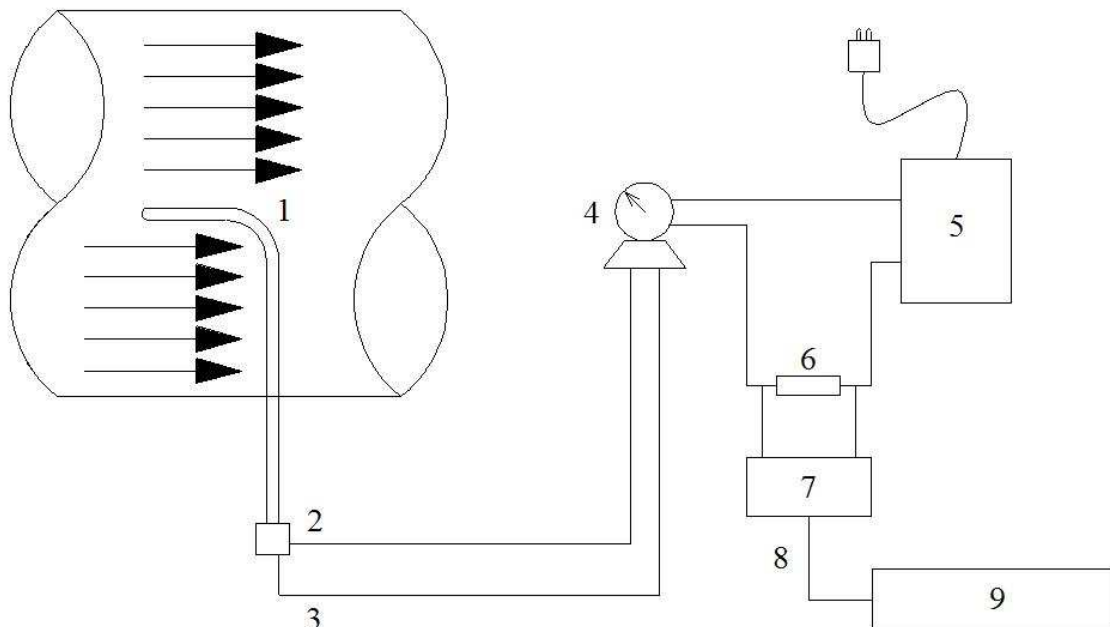


Figure 13: hardware scheme

1. Pitot tube
2. Static pressure connection
3. Total pressure connection
4. Transmitter
5. Power supply
6. Load
7. Analog digital converter
8. USB connection
9. Computer

4.3.2 Previous calculations

Before the installation, we must take into account the operating limits of the transmitter to choose the correct power supply, the correct load and the correct device.

According to the manufacturer, the output signal range is 4 mA to 20 mA, and the power supply must deliver 10 to 35 VDC with a minimum current capability of 40 mA. The manufacturer also provides a formula and a graph (fig. 14) to make the calculations faster. In the graph we can see the operating region. [17]

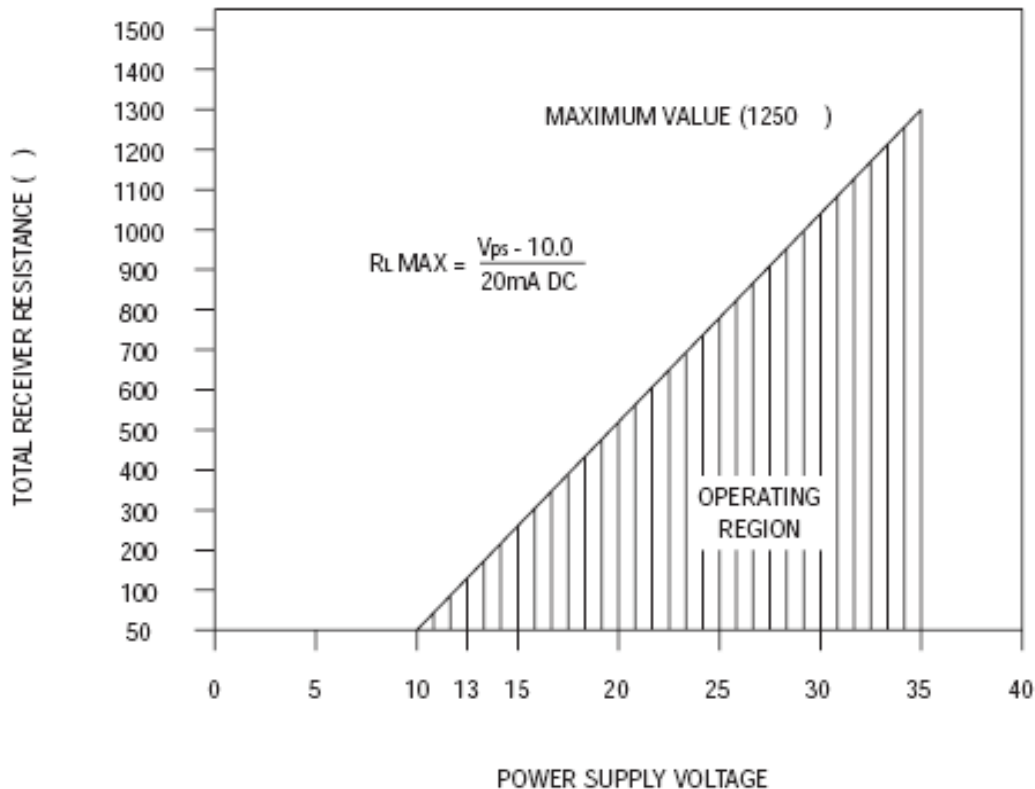


Figure 14: operating region [26]

Now, assuming that the power supply delivers 24 VDC (this power supply is very common and easy to use), we calculate the value of R_L max. This value should never be exceeded. [17]

$$R_L \text{ MAX} = \frac{V_{ps} - 10}{20\text{mA DC}}$$

$$\frac{24 - 10}{20\text{mA DC}} = 700\Omega$$

The limit for the load is 700 Ohms. Now, we do the calculations using the Ohm's law with different values of resistance, using the 4 mA to calculate the minimum voltage drop and 20 mA to calculate the maximum voltage drop in the load [17]:

- 700 Ohms

$$V = I \times R$$

$$4 \text{ mA} \times 700 \Omega = 2,8 \text{ V}$$

$$20 \text{ mA} \times 700 \Omega = 14 \text{ V}$$

- 350 Ohms

$$V = I \times R$$

$$4 \text{ mA} \times 350 \Omega = 1,4 \text{ V}$$

$$20 \text{ mA} \times 350 \Omega = 7 \text{ V}$$

- 250 Ohms

$$V = I \times R$$

$$4 \text{ mA} \times 250 \Omega = 1 \text{ V}$$

$$20 \text{ mA} \times 250 \Omega = 5 \text{ V}$$

The best voltage range seems to be from 1V to 5V. The difference is not too big and many analog digital converters can work in this range with good results.

4.3.3 Analog digital converter NI USB-9006

Once the value of the load has been chosen, we need an analog digital converter to obtain a digital signal from the analog signal.

The best device for this purpose is the NI USB-9006 (*fig. 15*) manufactured by National Instruments. It provides basic data acquisition functionality for applications such as simple data logging, portable measurements, and academic lab experiments. It is affordable for student use and powerful enough for more sophisticated measurement applications. [12]



Figure 15: NI USB-9006 [27]

The main features are [12]:

- 8 analog inputs (14-bit, 48 kS/s)
- 2 analog outputs (12-bit, 150 S/s); 12 digital I/O; 32-bit counter
- Bus-powered for high mobility; built-in signal connectivity
- OEM version available
- Compatible with Labview, LabWindows/CVI, and Measurement Studio for Visual Studio .NET
- NI-DAQmx driver software and NI Labview SignalExpress LE interactive data-logging software

4.3.4 *Installation pitot tube*

First of all, we should install the pitot tube in the wind tunnel, but due to the testing zone is not installed yet, we must calibrate the pitot tube and make measurements manually.

We have to install two plastic tubes. We connect the first one to the static pressure connection and the second one to the total pressure connection. We must ensure that there is no leakage (*fig. 16*).

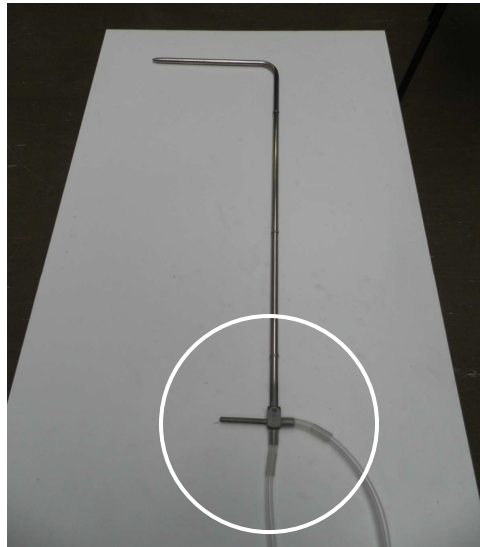


Figure 16: pitot tube connections

To calibrate the pitot tube and take measurements, we should put the tip of the pitot tube near the centre of the wind tunnel and parallel to the sidewall. The insertion tube must be perpendicular to the base of the wind tunnel. The tip must be looking to the fan (fig. 17).



Figure 17: pitot tube positioning

4.3.5 Installation transmitter

The installation of the transmitter is more complicated. The transmitter should be mounted on a vertical surface with the connections directed down to prevent moisture from entering either the pressure ports or the electrical cable entry. To mount the transmitter we have to use #8 x 1/2" metal screws in the mounting flanges. [17]

4.3.6 Transmitter's electrical connection

Our connection is a 2 wire connection. The connections to the transmitter (*fig. 18*) are made through a two circuit European style terminal block located at the bottom of the main PCB board. Polarity is indicated by + (positive) and – (negative) signs on the PCB board. The other end of the wire connected to the positive terminal must be connected also to the positive terminal of the power supply. The other end of the wire connected to the negative terminal must be connected to the load. [17]

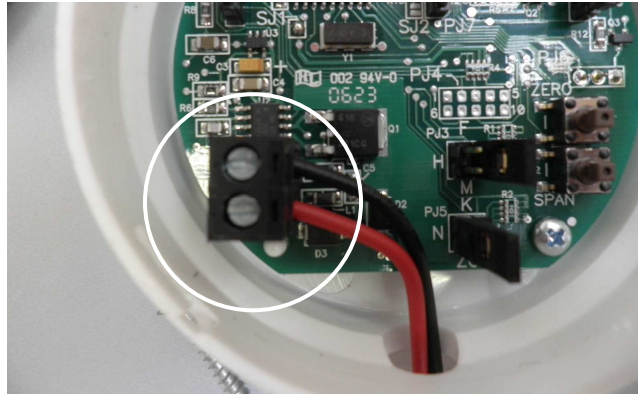


Figure 18: connections to the transmitter

4.3.7 Installation Load

The load must be installed between the transmitter (negative terminal) and the power supply (negative terminal).

4.3.8 Installation Analog digital converter

Once the main circuit is installed, we must install the device. We connect two wires at the ends of the load (*fig. 19*).

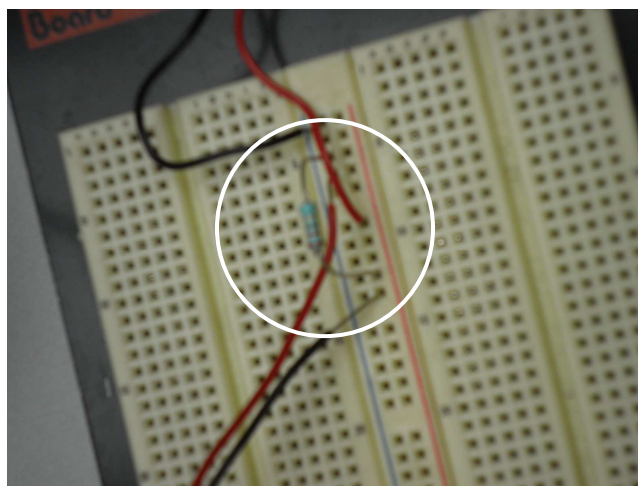


Figure 19: device connections 1

These two wires are also connected to the device, in two analog inputs. In this case, the inputs are *AI6* and *AI2* (fig. 20).

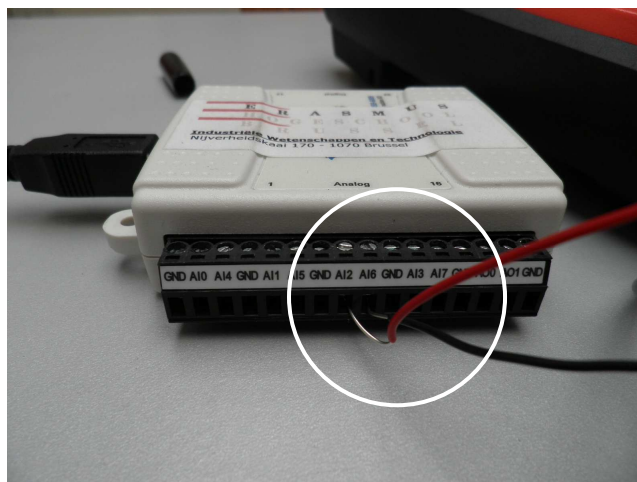


Figure 20: device connections 2

Afterwards, we connect the USB cable to the computer.

4.4 Software implementation

4.4.1 Labview 8.5

There is several programming software compatible with the device NI USB-9006. In this case, we use Labview because it is the easiest to use and the manufacturer is the same as the device, which means the performance is suppose to be better. Labview is a graphical programming environment used by millions of engineers and scientists to develop sophisticated measurement, test, and control systems using intuitive graphical icons and wires that resemble a flowchart. [12]

4.4.2 How to read digital data

To first step is to read the data we receive from the device. To achieve this, there is an application in Labview called DAQ Assistant (fig. 21). [18]

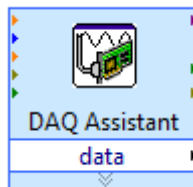


Figure 21: DAQ Assistant

We must open the properties window and set up the acquisition mode, the number of samples we want to read and the rate in Hz. In this case, we want continuous samples and we operate with 1000 samples and 1000 Hz (1000 samples in 1 second) (fig. 22). [16]

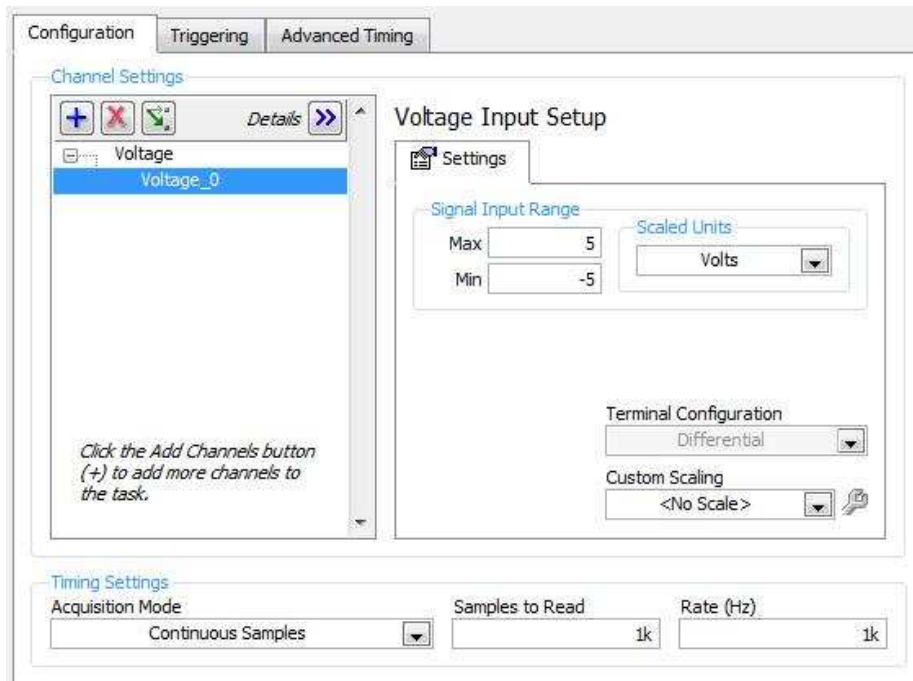


Figure 22: DAQ Assistant set up

4.4.3 Obtain a mean value

When we are measuring the voltage, the data we acquire is not a value, is a graphic. We need to obtain average values to be able to read the voltage easily. To get this, there is an application called Statistics (*fig. 23*). [18]

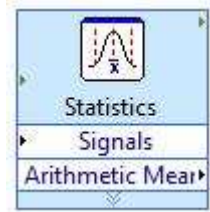


Figure 23: Statistics

Now we open the properties window (*fig. 24*) and we select the Arithmetic mean. Now, we have a value of voltage every second. [18]

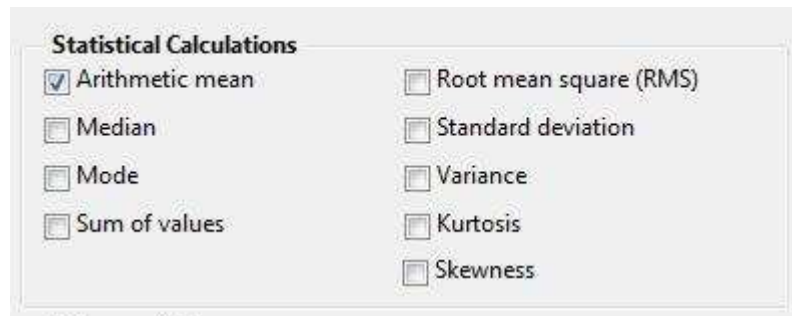


Figure 24: Statistics properties window

4.4.4 Voltage to pressure

According to the calculations we did before, when the pressure is zero, the voltage drop in the load is 1 V, and when the pressure is 250, the voltage drop in the load is 5 V. Now, using this info we need to convert voltage to pressure for all values between 1 V and 5 V. To do this conversion from voltage to pressure there are several ways, but the easiest one is to use an application called polynomial interpolation (*fig. 25*). This way, we will be able to obtain the pressure directly interpolating.



Figure 25: Polynomial interpolation

During the calibration, we will measure the voltage when the pressure is zero, and when the pressure is maximum. We will measure intermediate points too to obtain a better graph.

4.4.5 Pressure to velocity

The last step is to convert pressure to velocity. This step is very easy. We just need an application called Formula (fig. 26) to convert pressure to velocity using the Bernoulli equation.

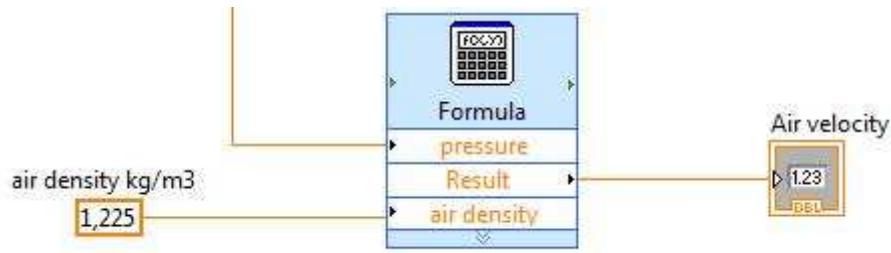


Figure 26: Formula, pressure to velocity

We only need the value of the air density. In this case, we want to obtain the air velocity in m/s, so the air density is in kg/m^3 . The pressure is supposed to be in Pa.

4.4.6 Block diagram

This is the Block diagram (fig. 27), in Labview.

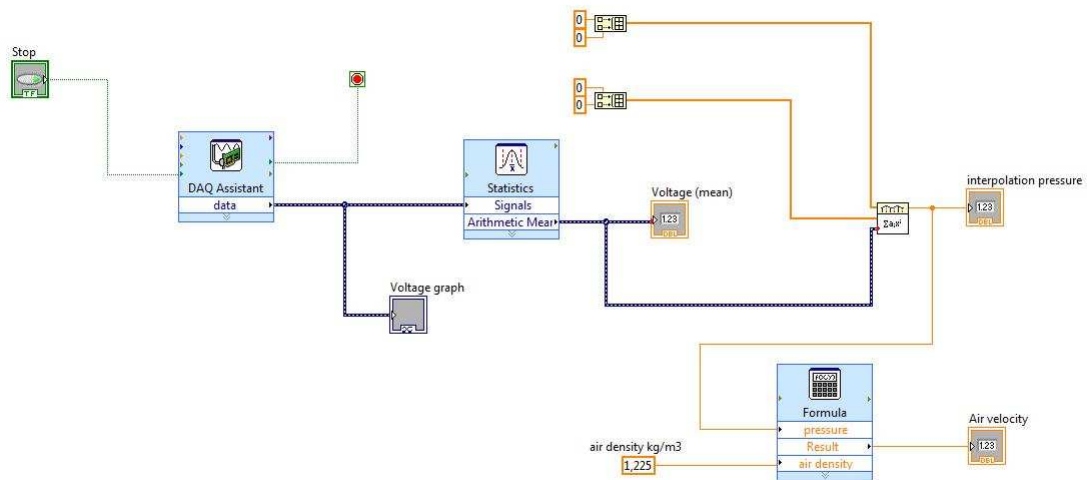


Figure 27: block diagram

4.4.7 Front Panel

This is the Front panel (fig. 28), where we can see the graphic and the values.

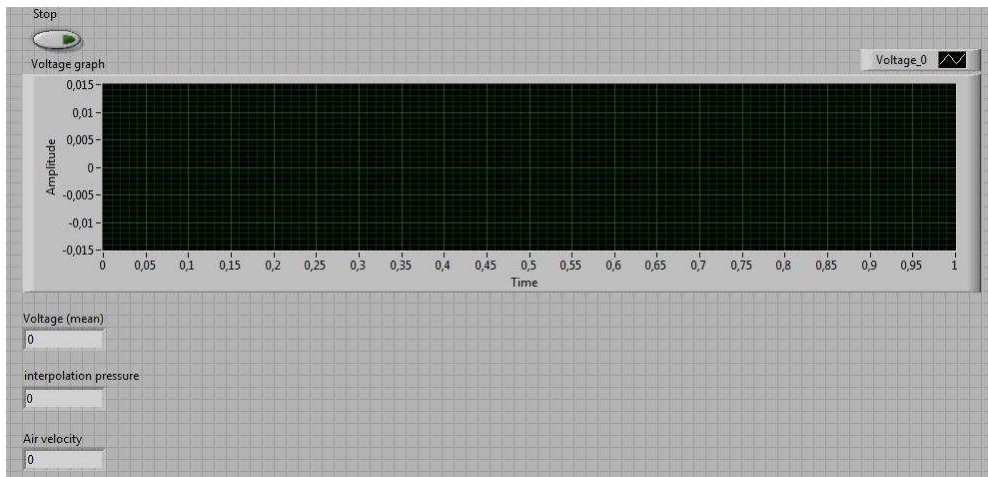


Figure 28: front panel

4.5 Transmitter set up

4.5.1 Select range

The operating range is controlled by a shorting jumper on jumper block PJ3. Its primary function is to control when the unit is in the high (“H”), medium (“M”) or low (“L”) range. To select one of the ranges above, we have to short together using the supplied shorting jumper the two pins next to the letter which corresponds to the range we are interested in. We are going to use the transmitter in the low range, so we put the shorting jumper next to the letter “L” (the right side, *fig. 29*). [17]

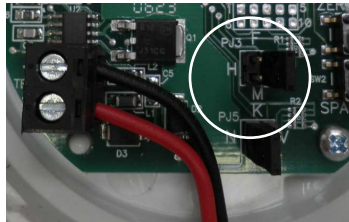


Figure 29: select range

4.5.2 Select operation mode

The operating mode is controlled by a shorting jumper on jumper block PJ5 (*fig. 30*). [17]

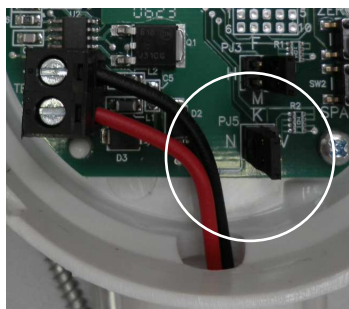


Figure 30: operation mode

There are two operating modes, Normal and Velocity. The Normal operating mode provides for zero pressure to correspond to 0 V or 4 mA output. This mode is selected by placing the supplied shorting jumper for PJ5 on the pins next to the letter “N”. The Velocity mode provides the ability for the unit in conjunction with a pitot tube or similar flow sensor with known K factor to give a direct output in air velocity. This mode is selected by placing the supplied shorting jumper for PJ5 on the pins next to the letter “V”. [17]

We want to measure pressure, so we place the supplied shorting jumper next to the letter “N”.

4.5.3 Set measurements units

The transmitter can be easily set to operate in either English or metric units. The programming jumper is PJ7 (fig. 31). [17]

English units are selected by placing the provided shorting jumper on the lower two pins of the block. Metric units are selected by placing the provided shorting jumper on the upper two pins of the block. We want to operate in metric units. So we place the shorting jumper on the upper two pins of the block. [17]

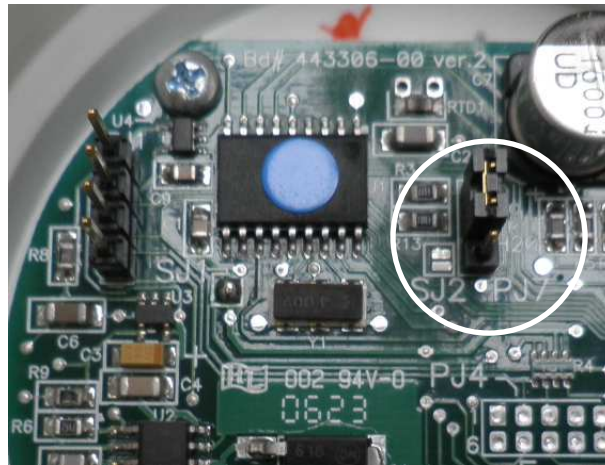


Figure 31: set measurement units

4.5.4 Zero and Span calibration

To set up the zero, we have to leave the hose barbs vented and press and hold the “Zero/Up” switch for about 4-5 seconds (fig. 32). We use an amperemeter to be sure the zero is set up. When the current is 4mA, the zero point is calibrated. [17]

To calibrate the span, we need a calibrated pressure source capable of generating a stable pressure value of 250 Pa. We also need a manometer or gage capable of validating the calibration and a voltmeter or milliammeter to calibrate the output. In this case, we don't have the source capable of generating a stable pressure value of 250 Pa, so we will try to calibrate the transmitter as well as we can using another procedure, forgetting the span. [17]

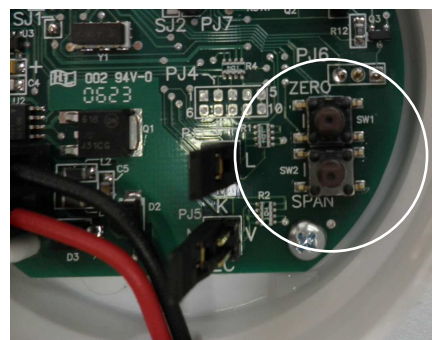


Figure 32: zero calibration

4.6 Calibration procedure

This is the calibration procedure:

- First, we measure the speed of the air using the anemometer AIRFLOW (*fig. 33*). This anemometer is easy to use and suitable for we want to do.

We take 3 measurements, and we calculate the average value of the air speed using these 3 measurements.

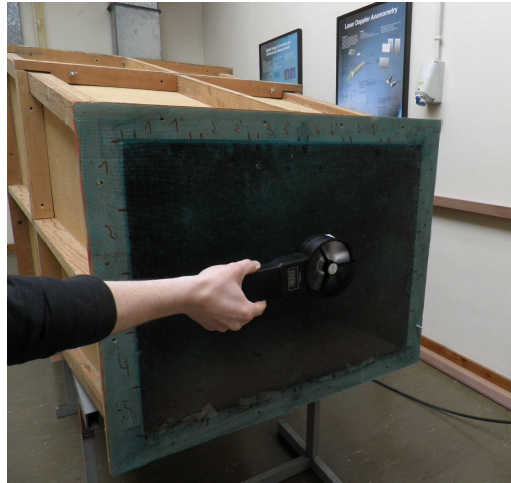


Figure 33: anemometer AIRFLOW

- Then, we use the pitot tube and the transmitter to measure the speed of the air (*fig. 34*). The value is constantly changing because the flow is not laminar and we are measuring the speed manually. We take an average value. In addition, we also measure the value of the voltage drop in the load. The value is constantly changing also, so we take an average too.

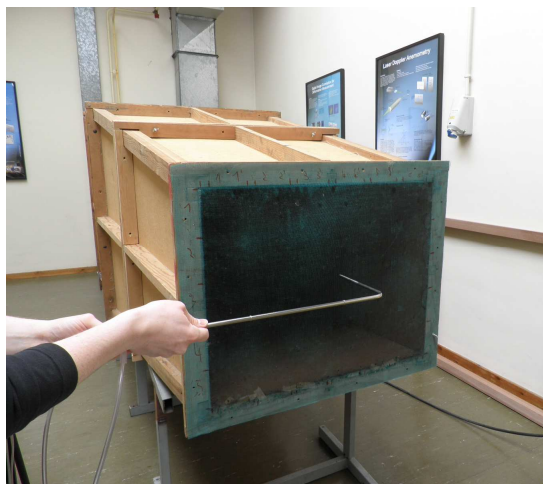


Figure 34: pitot tube and transmitter

- Now, we take 14 measures more following the same two steps detailed above. To achieve this, we decrease the power of the wind tunnel progressively until the speed of the air is almost zero.

- Once all the measures are made, we make a table with all data collected (table 6). We calculate the pressure from the average speed of the anemometer, using the Bernoulli equation.

Speed anemometer (m/s)				Pressure (Pa)	Voltage (v)	Speed pitot tube (m/s)
1 st measure	2 nd measure	3 rd measure	average			
0,68	0,93	0,86	0,82	0,42	0,88	1,6
1,84	2,04	2,17	2,02	2,49	0,93	2,9
2,72	2,63	3,06	2,80	4,81	0,98	3,8
3,52	4,03	3,85	3,80	8,84	1,05	4,8
4,58	4,64	4,64	4,62	13,07	1,13	5,7
5,47	5,69	5,59	5,58	19,09	1,23	6,7
6,58	6,6	6,58	6,59	26,57	1,39	7,8
7,17	7,25	7,39	7,27	32,37	1,5	8,5
8,03	8,46	8,28	8,26	41,76	1,67	9,92
8,86	9,06	9,2	9,04	50,05	1,85	10,6
9,88	9,64	9,85	9,79	58,70	2,01	11,65
10,42	10,15	10,48	10,35	65,61	2,14	12,17
10,68	10,83	10,9	10,80	71,49	2,22	12,85
11,76	11,88	11,65	11,76	84,76	2,5	13,8
13,13	12,78	12,77	12,89	101,82	2,82	15,01

Table 6: measurements

- Now, we make a graph (fig. 35) representing the average of the anemometer and the speed of the pitot tube.

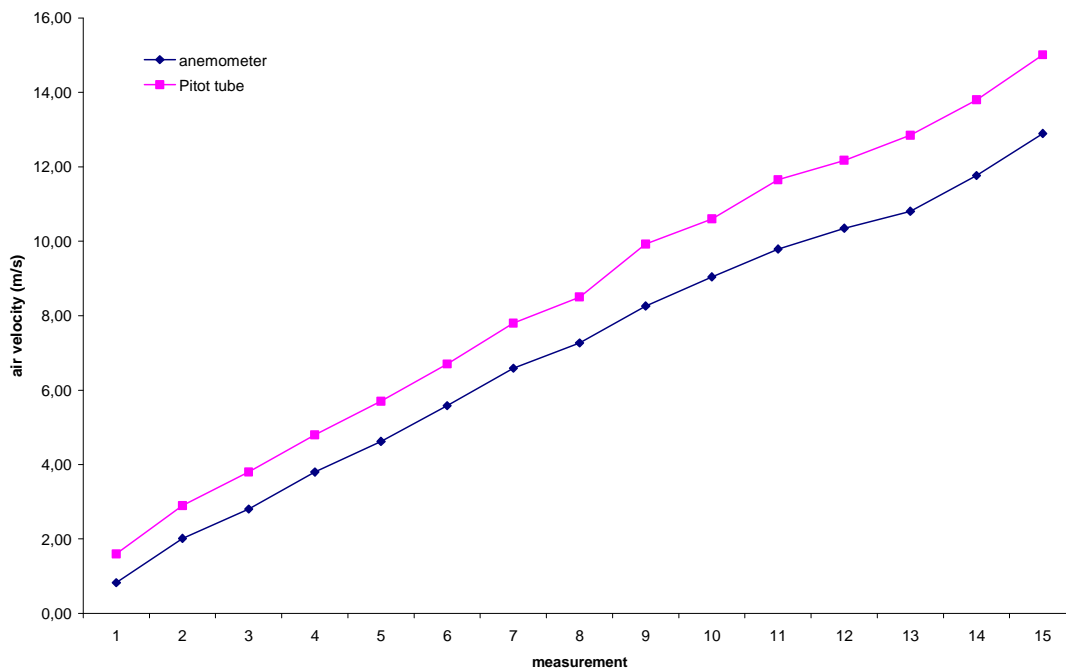


Figure 35: average of the anemometer and the speed of the pitot tube

We can see that the values measured by the pitot tube are higher than the average of the anemometer. Taking into account that the pitot tube and the transmitter are not calibrated as they should be, we can do something to calibrate them using the anemometer.

- Now, we change some parameters in the Labview application. When we measured the speed using the anemometer and the pitot tube together with the transmitter, we also measured the voltage drop in the load. Using this data (*table 7*) and the relationship between the voltage drop and the pressure, we can create a graph (*fig. 36*) to interpolate and obtain a best value for the speed, measuring the voltage drop.

Pressure (Pa)	Voltage (v)
0,42	0,88
2,49	0,93
4,81	0,98
8,84	1,05
13,07	1,13
19,09	1,23
26,57	1,39
32,37	1,5
41,76	1,67
50,05	1,85
58,70	2,01
65,61	2,14
71,49	2,22
84,76	2,5
101,82	2,82

Table 7: pressure and voltage

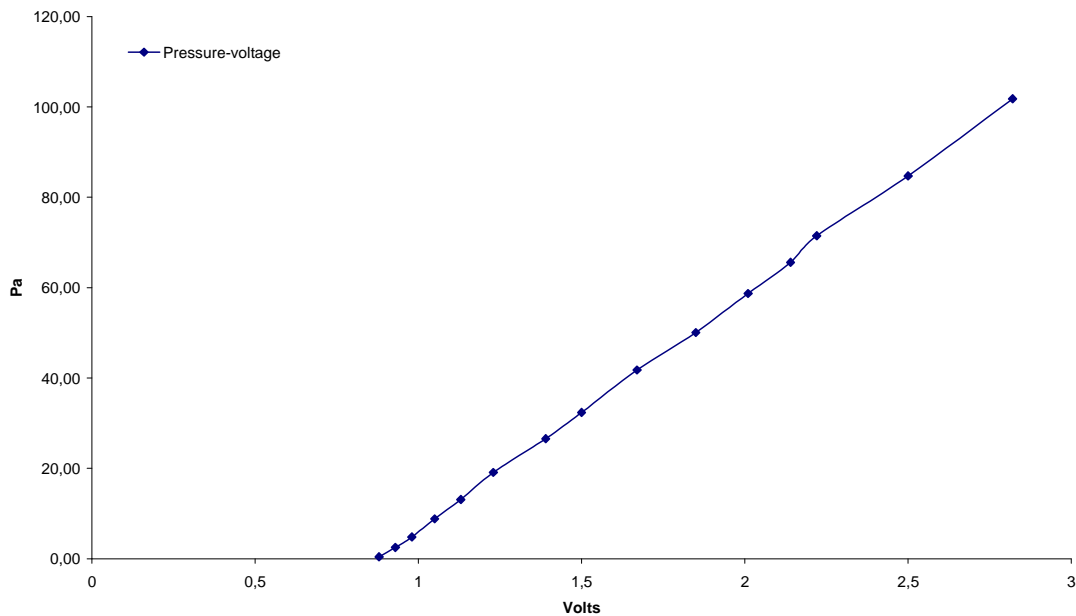


Figure 36: pressure (Pa) and voltage (volts)

Then the block diagram calibrated (fig. 37) is:

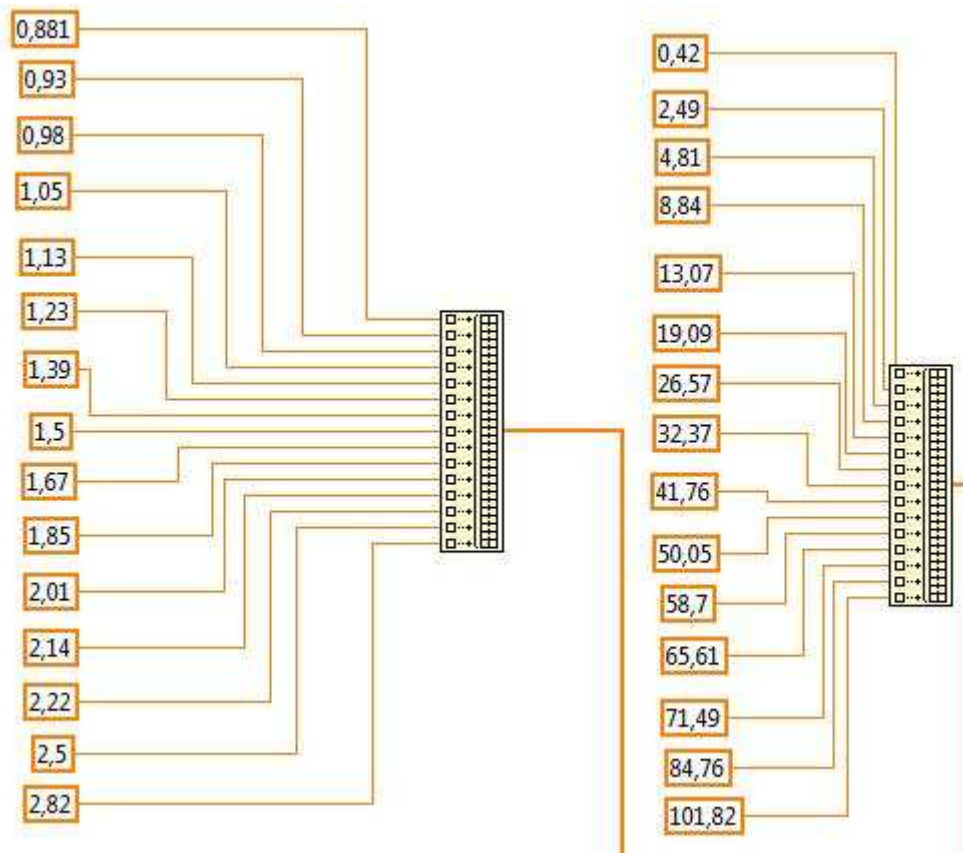


Figure 37: Block diagram calibrated after test 1

Now, what we should do is to do new measurements to check if this works.

4.7 Test 1

After the first calibration, we measure again the same way we did the first test. We obtain now the following table (table 8):

Speed anemometer (m/s)				Speed pitot tube (m/s) - calibrated-
1 st measure	2 nd measure	3 rd measure	average	
1,36	1,24	1,641	1,41	1,5
2,97	2,83	2,92	2,91	3,2
3,44	3,27	3,72	3,48	3,7
4,1	3,62	3,57	3,76	4
4,6	4,9	4,7	4,73	4,9
5,7	6,04	5,69	5,81	5,9
6,2	6,11	6,21	6,17	6,3
7,21	7,31	7,13	7,22	7
7,63	7,33	7,13	7,36	7,4
9,43	9,62	9,55	9,53	9,01
11,06	10,98	11,17	11,07	10,8
12,34	12,53	12,2	12,36	Not good

Table 8: measures test 1

Now, we represent the table in a graph (fig. 38):

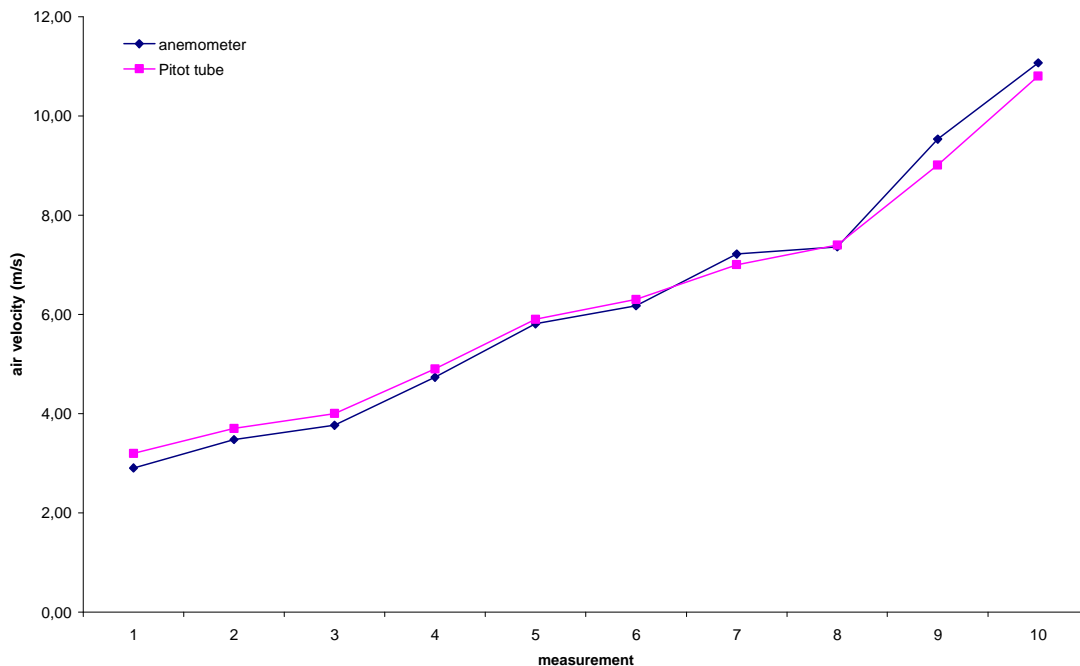


Figure 38: average of the anemometer and the speed of the pitot tube, test 2

We can see that the values are not the same, but they are closer than before the first calibration. The problem is that using the actual application of Labview, we cannot measure the speed of the air at maximum power. That's why we need to reconsider the Labview application and the procedure used to calibrate the pitot tube and the transmitter.

4.8 Second calibration: changes in the Labview application and procedure of calibration

Now, we need to solve the problem with the Labview application and the procedure of calibration. To achieve this, we do the following changes:

- Now, we are going to use a support for the pitot tube (fig. 39), to get more reliable values because the pitot tube will measure always the velocity of the air in the same area.



Figure 39: pitot tube and support

- We also do changes in the Labview application. We change the application polynomial interpolation for the application linear fit (fig. 40). With this application and using the new data acquired in this second calibration, we will create a regression line. The values of slope and intercept will be used in a formula afterwards, where the “X” value is the mean of the voltage drop and the “Y” value is the pressure. This way, we try to get a better calibration. [18]

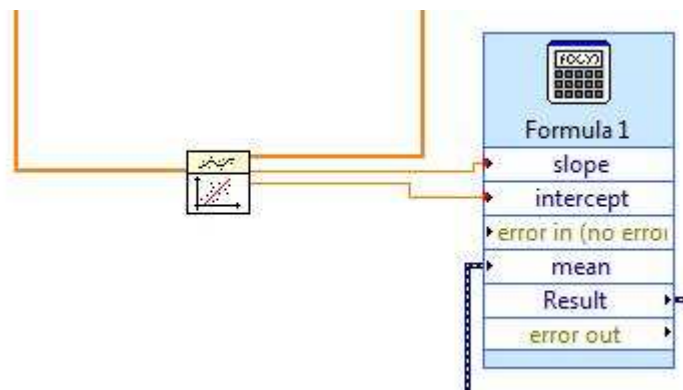


Figure 40: linear fit and formula

We do measurements again, obtaining the next table (table 9):

Speed anemometer (m/s)				Pressure (Pa)	Voltage (v)	Speed pitot tube (m/s)
1 st measure	2 nd measure	3 rd measure	average			
1,44	1,56	1,65	1,55	1,47	0,9	1,7
2,97	3,06	3,02	3,02	5,57	0,96	3,2
4,18	4,27	4,18	4,21	10,86	1,05	4,4
4,97	5,28	5,2	5,15	16,25	1,15	5,6
6,12	6,29	6,2	6,20	23,57	1,29	6,9
7,27	7,3	7,2	7,26	32,25	1,43	8
8,36	8,31	8,23	8,30	42,20	1,64	9,4
9,16	9,46	9,65	9,42	54,39	1,85	10,5
11,07	10,93	10,87	10,96	73,53	2,15	12,1
12,24	12,42	12,42	12,36	93,57	2,45	13,5
13,09	13,15	13,2	13,15	105,86	2,7	14,4

Table 9: measures second calibration

Now, we use the pressure and the voltage in the Labview application to create the following graph (fig. 41) and regression line:

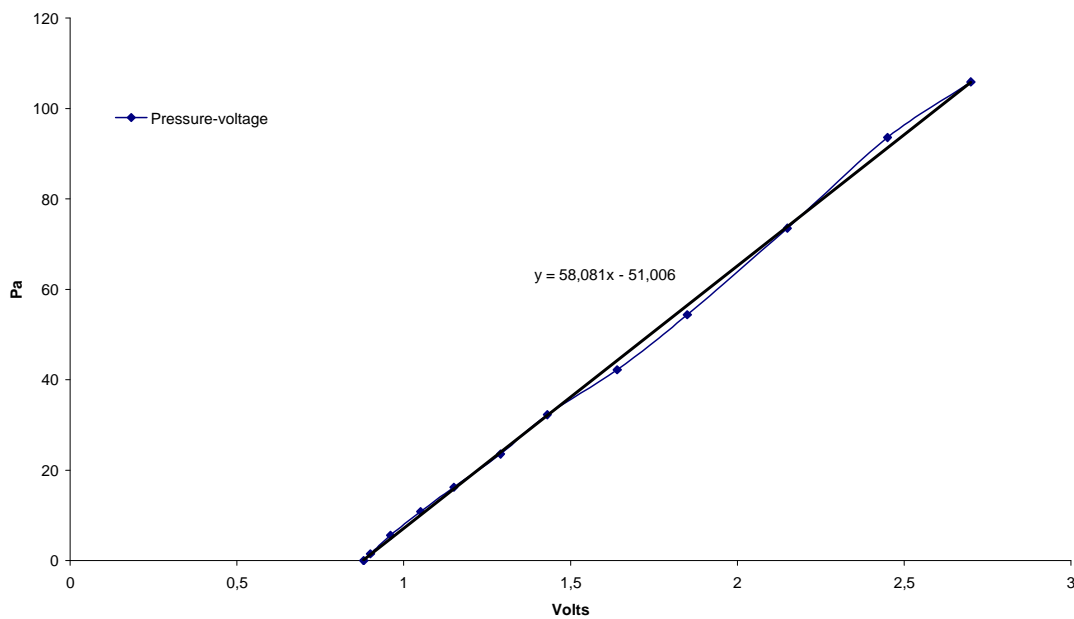


Figure 41: regression line

Slope: 58.081

Intercept: 51.006

Regression line $\rightarrow y = 58.081 \times x - 51.006$

This is the regression line that we will use in the following test.

4.9 Test 2

After the second calibration, we measure again the same way we did the first test. We obtain now the following table (table 10):

Speed anemometer (m/s)				Speed pitot tube (m/s) - calibrated-
1 st measure	2 nd measure	3 rd measure	average	
1,66	1,64	1,61	1,64	1,7
2,84	2,77	2,82	2,81	2,9
4,03	3,96	3,97	3,99	4
4,9	4,96	4,96	4,94	5,1
6,17	6,16	6,19	6,17	6,3
7	7,03	7,12	7,05	7,3
7,94	7,93	7,93	7,93	8,1
8,66	8,73	8,86	8,75	8,9
9,89	9,94	9,88	9,90	10
10,83	10,96	10,8	10,86	11
12,45	12,54	12,29	12,43	12,6
13,35	13,01	13,08	13,15	13,13

Table 10: measures test 2

Now, we represent the table in a graph (fig. 42):

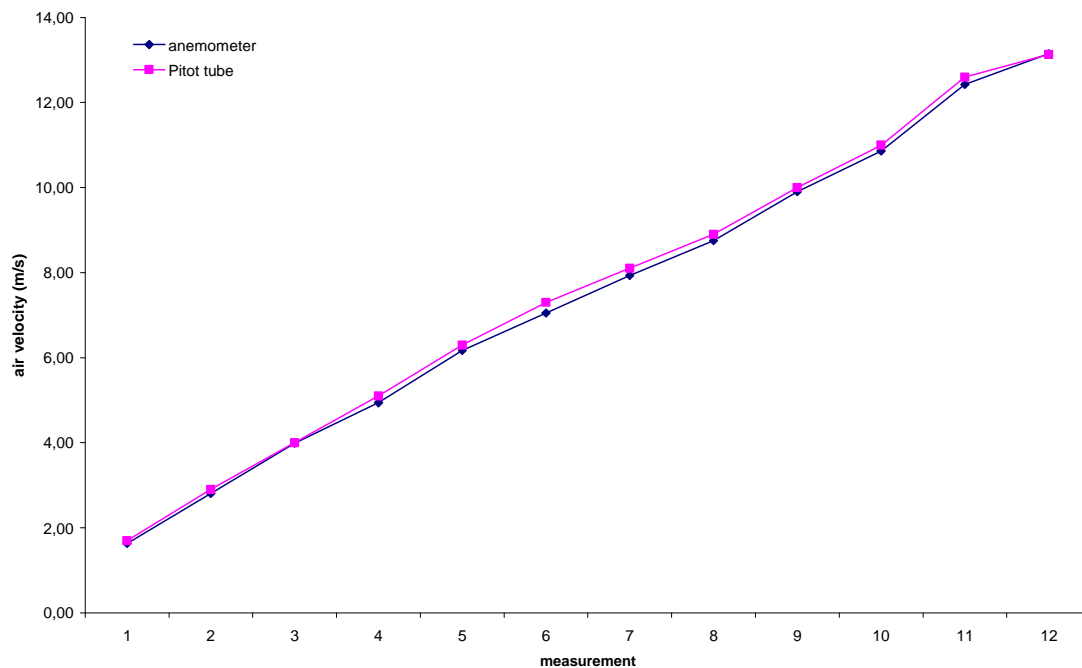


Figure 42: average of the anemometer and the speed of the pitot tube, test 2

4.10 Conclusion

We can see that the values in test 2 are quite similar, and the problem we had when we were measuring the speed of the air at maximum power is solved. The pitot tube and the transmitter are calibrated using the anemometer.

Chapter 5. MEANS TO VISUALIZE THE AIRFLOW

5 Means to visualize the air flow

As a second step, we have to find a good system to visualize the air flow and see how it changes when it finds an obstacle on its way. To do this, there is more than one option. We can introduce smoke streams inside the wind tunnel, using a smoke generator and a nozzle or technical jets to create them. We can also use aerosols and laser beams for the same goal. In the following lines, there are some explanations of how they work and some of the most important features of the elements analyzed in the market research.

5.1 Smoke generator

There are many ways to obtain smoke. One of the most used techniques by amateurs is dry ice in warm water. Other techniques are combining ammonia gas and hydrochloric gas (both gases separately are poisonous, but the reaction between them is relatively innocuous) or mixing sugar, saltpeter (potassium nitrate) and baking soda as a retarder. Commercial smoke generators use a mixture of propylene glycol glycerine and water (*fig. 43*). These machines should be called “fog machines” because they don’t burn anything, so you cannot obtain “smoke”. Despite this, they are commonly known as smoke generators.

We won’t have a problem to obtain good quality of fog. We will be in trouble if we try to create the streamlines. Compressing the fog stream (actually tiny drops of water and glycerine) tends to make the fog sublimate back out. The trick is to use a correct needle or nozzle to avoid this fact.



Figure 43: smoke generator

All these smoke generators can be used with or without a fog nozzle to create the streamline inside the wind tunnel.

A market research of smoke generators and different accessories (*table 11, table 12*) is detailed in the next table.

Company	model	Height-width-length (mm)	Weight (kg)	Power supply	Power consumption	Warm-up time (min)	Fogging power (m ³ /min)
SMOKEMAKE R	F-100	209 x 298 x 686	14,5	120 VAC/60 Hz/14 A 240 VAC/50 Hz/7 A	1680 W	--	--
DANTEC	195 SG-D	255 x 215 x 540	11	230 VAC/50 Hz/12,5 A	2200 W	9	1100
DANTEC	FOG 2010	145 x 170 x 340	6,1	230 VAC/50 Hz/10 A	1650 W	5	470
E-BAY	METAL SMOKE MACHINE	280 x 190 x 160	3,1	230 VAC	500 W	4	60
E-BAY CISCOSHOP	METAL SMOKE MACHINE	130 x 160 x 315	4,5	230 VAC	700 W	5	90
E-BAY SOUND-7	ANTARI Z-80	330 x 160 x 240	3,7	230 VAC	700 W	4	90
SAFEX	FOG 2005	145 x 170 x 340	6,1	230 VAC/50 Hz/10 A	1650 W	5	325
SAFEX	FOG 2010	145 x 170 x 340	6,1	230 VAC/50 Hz/10 A	1650 W	5	470
E-BAY HQ POWER	VDL1200SM	260 x 280 x 530	7,5	230 VAC/50 Hz/10 A	1200 W	9	450

Table 11: smoke generators

Company	accessory	shape	Dimensions (mm)
DANTEC	Fog injection nozzle	bow	6 x 200
DANTEC	Fog injection nozzle	hook	6 x 100 x 100
DANTEC	Flexible tube	tube	2000 x 80
DANTEC	Tube adapter	--	--
DANTEC	Remote quantity control for 110 VAC	--	--

table 12: accessories

The price of each element is:

- Smoke generators:
 - SMOKEMAKER F-100: 1084 \$
 - DANTEC 195 SG-D: 2867 €
 - DANTEC FOG 2010: 2284 €
 - E-BAY METAL SMOKE MACHINE: 46,90 €
 - E-BAY CISCOSHOP METAL SMOKE MACHINE: 49,99 €
 - E-BAY SOUND-7 ANTARI Z-80: 49 €
 - SAFEX FOG 2005: 999 €
 - SAFEX FOG 2010: 1100 €
 - E-BAY HQ POWER VDL1200SM: 108,70 €

- Accessories:
 - DANTEC Fog injection nozzle bow: 163 €
 - DANTEC Fog injection nozzle hook: 170 €
 - DANTEC Flexible tube: 65 €
 - DANTEC Tube adapter: 137 €
 - DANTEC Remote quantity control for 110 VAC: 253 €

5.2 Aerosol generators

For our purposes, we need particles that can be disturbed by an obstacle and can be visualized. Technically, an aerosol is a suspension of fine particles or droplets in a gas. By definition, aerosol generators are suitable to visualize the air flow. We can use either aerosols for industrial purposes or aerosols for pharmaceutical purposes or aerosols for cooking purposes.

5.2.1 Industrial aerosols

Industrial aerosol generators are recommended for testing systems with air flows, for work stations, negative pressure filtration units, biosafety cabinets, ceiling modules, small or portable cleanrooms, HEPA filter units in installations where an adequate supply of clean, etc. The wind tunnel is not one of the recommended applications, but we can take into account industrial aerosol generators when we decide what to use to see the airflow.

Industrial aerosol generators produce the smallest droplets in the size range from 0.2 to around 2 μm . Industrial generators can obtain an aerosol from solid particles or from liquid particles. For example, as solid particles they can use latex particles, NaCl, and other salt solutions. On the other hand, as liquid particles they can use paraffin (generally not toxic), DOP (dioctyl phthalate) and PAO (polyalphaolefin). Industrial aerosol generators (*fig. 44*) produce primary droplets in the size range from 20 to 200 μm combining a good orifice size, liquid flow rate, and breakup frequency. Afterwards, submicrometer particles are produced by evaporating away the volatile solvent from the primary droplets. [13] [21]



Figure 44: Industrial aerosol generator [28]

The aerosol generators also can be of two types, depending on the power supply. Some generators need electrical power supply, but other need only compressed air.

A small market research of industrial aerosols is detailed below (*table 13*).

Company	model	Height-width- length (mm)	Weight (kg)	Power supply	Flow rate (l/min)
TSI	3079	175 x 200 x 280	4,5	230 VAC 110 VAC	1 – 4,2
TOPAS	ATM 226	175 x 200 x 280	4,2	240 VAC	0,8 - 5
ATI	TDA-4B	230 x 280 x 250	7,3	compressed air	85 - 500
ATI	TDA-4B lite	230 x 200 x 250	5,5	compressed air	85 - 250

Table 13: industrial aerosol generators

The price of each element is:

- TSI 3079: 4950 €
- TOPAS ATM 226: 3208,8 €
- ATI TDA-4B: 2801,6 €
- ATI TDA-4B lite: 2117,2 €

5.2.2 *Pharmaceutical aerosols*

Most aerosols for pharmaceutical purposes generate larger droplets than industrial aerosol generators. Nasal inhalators (*fig. 45*) produce the large droplets in the size range from 20 to around 120 μm . [14]



Figure 45: nasal inhalator [29]

Nebulizers (*fig. 46*) produce smaller droplets in the size range from 0.5 to around 20 μm . [19]



Figure 46: nebulizer [30]

There are also painkilling sprays (*fig. 47*), which could be useful for our purposes. The droplets size is bigger in this case. [19]



Figure 47: painkilling spray [31]

5.2.3 Cooking aerosols

We can also use aerosols designed for cooking (*fig. 48*). They are uncommon, but they can be useful. They are really cheap and the droplets are not harmful, because the liquid is oil.



Figure 48: cooking aerosol [32]

5.3 Laser beam

A laser beam (*fig. 49*) could be a good option to visualize the air flow combined with smoke generators or aerosol generators. We can create a laser sheet which can make the perturbations in the airflow easier to see.



Figure 49: laser beams [33]

A laser is a device that controls the way that energized atoms release photons. "Laser" is an acronym for light amplification by stimulated emission of radiation, which describes very succinctly how a laser works. [15]

Although there are many types of lasers, all have certain essential features. In a laser, the lasing medium is “pumped” to get the atoms into an excited state. Typically, very intense flashes of light or electrical discharges pump the lasing medium and create a large collection of excited-state atoms (atoms with higher-energy electrons). It is necessary to have a large collection of atoms in the excited state for the laser to work efficiently. In general, the atoms are excited to a level that is two or three levels above the ground state. This increases the degree of population inversion. The population inversion is the number of atoms in the excited state versus the number in ground state. Once the lasing medium is pumped, it contains a collection of atoms with some electrons sitting in excited levels. The excited electrons have energies greater than the more relaxed electrons. Just as the electron absorbed some amount of energy to reach this excited level, it can also release this energy. As the figure below illustrates (*fig. 50*), the electron can simply relax, and in turn rid itself of some energy. This emitted energy comes in the form of photons (light energy). [15]

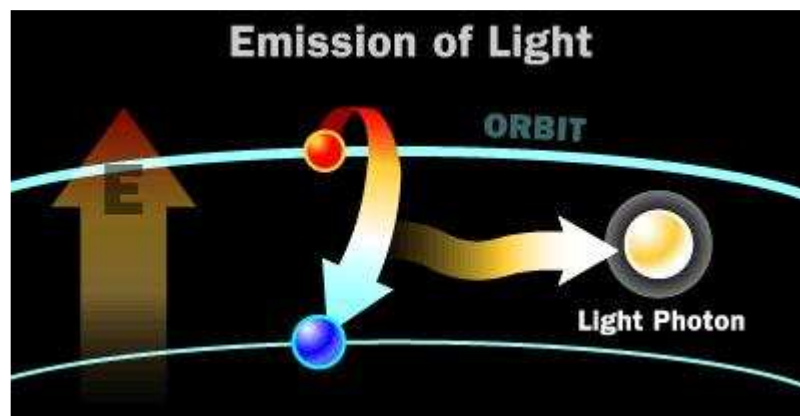


Figure 50: emission of photon (light energy) [34]

The photon emitted has a very specific wavelength (color) that depends on the state of the electron's energy when the photon is released. Two identical atoms with electrons in identical states will release photons with identical wavelengths. [15]

The easiest example to explain how a laser works is the ruby laser. A ruby laser consists of a flash tube, a ruby rod and two mirrors (one half-silvered). The ruby rod is the lasing medium and the flash tube pumps it. [15]

Firstly, the laser in its non-lasing state is like that (*fig. 51*). The flash tube doesn't emit light. [15]

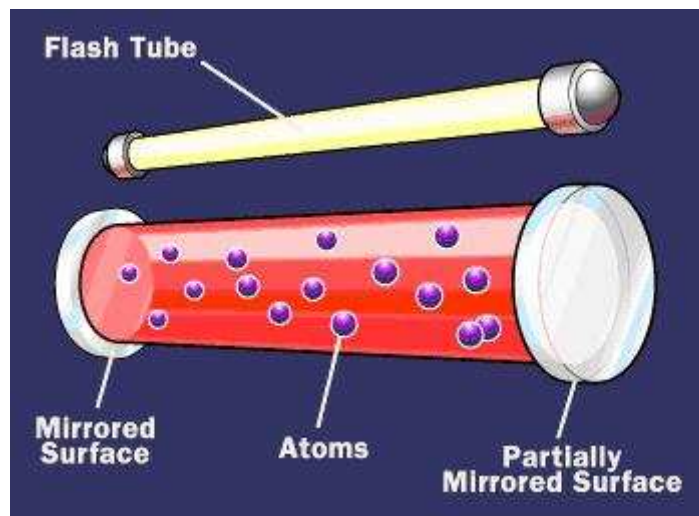


Figure 51: non-lasing state [36]

Now, we turn on the flash tube and inject light into the ruby rod. The light excites atoms in the ruby (*fig. 52*). [15]

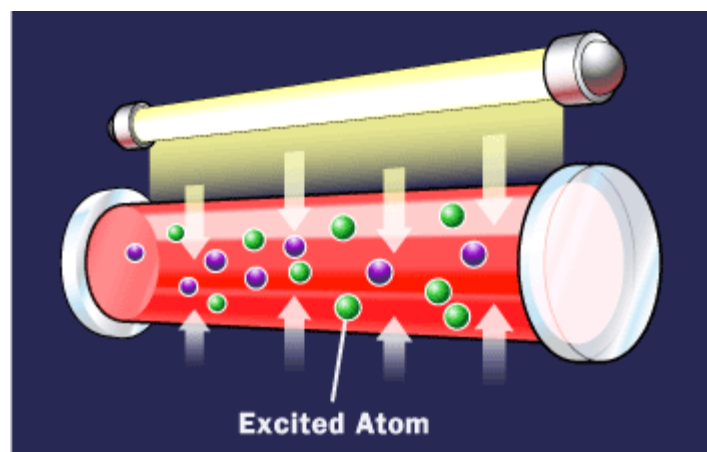


Figure 52: flash tube injects light [37]

Because of the light, some of these atoms emit photons (*fig. 53*). [15]

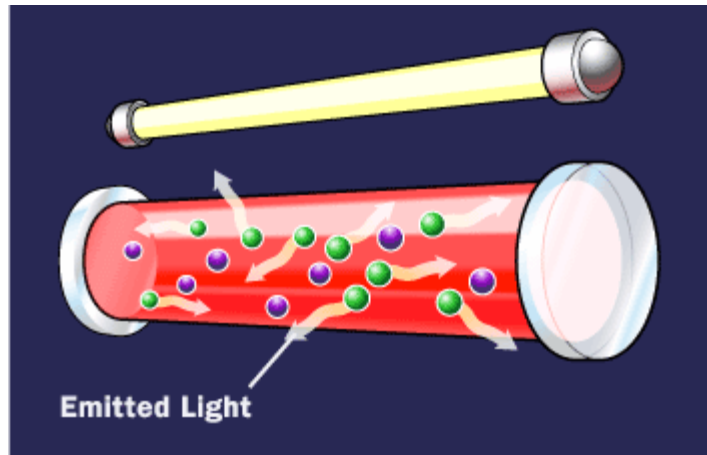


Figure 53: Emitted light [38]

Some of these photons run in a direction parallel to the ruby's axis, so they bounce back and forth off the mirrors. As they pass through the crystal, they stimulate emission in other atoms (*fig. 54*). [15]

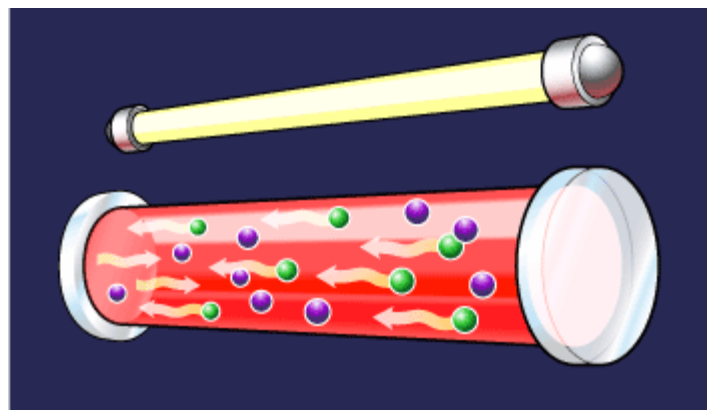


Figure 54: more emitted light [39]

Finally, a monochromatic, single-phase, columnated Light leaves the ruby through the half-silvered mirror. Now we have the laser beam (*fig. 55*). [15]

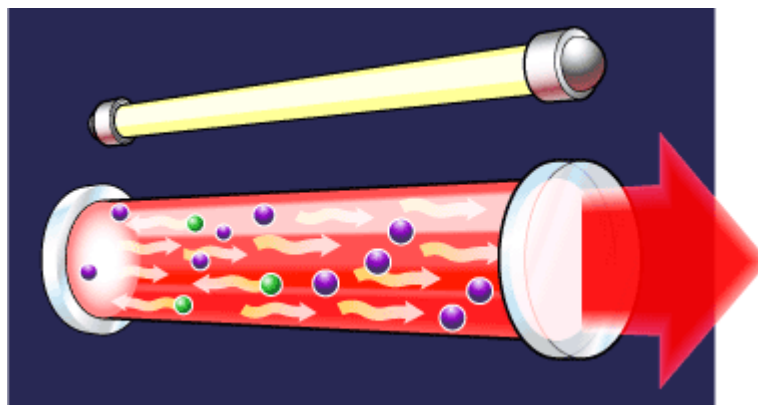


Figure 55: laser beam [40]

5.3.1 Laser market research

We are interested in the visible spectrum, because we want to see the light when it goes through the smoke or the aerosol particles. The visible spectrum range is from 415 nm to 695 nm approximately. Depending on the particular lasing material being used, we can find red lasers, which wavelength range is from 630 to 695 nm, orange lasers (from 612 nm to 630 nm), yellow lasers (from 568 nm to 612 nm), green lasers (from 511 nm to 568 nm), blue lasers (from 457 nm to 511 nm) and violet lasers (from 415 nm to 457 nm). There are too many colours, because each colour has different shades. The most used are red, green and blue. [16]

A market research of lasers is detailed below in the following table (*table 14*).

Company	model	Wavelength (nm)	Power	colour	Lifetime (hours)	Power supply
Dragon laser	Red diode laser	655±10	1 W	red	10000	90-264 VAC
Dragon laser	Green diode laser	532±1	1 W	green	10000	90-264 VAC
Dragon laser	Green laser module	532±1	20 mW	green	10000	90-264 VAC
Dragon laser	Green pointer	532±1	160 mW	green	>5000	2 x AAA batteries
Dragon laser	Red pointer	640±10	100 mW	red	>5000	2 x CR 123 Lithium batteries
Wicked laser	Executive pro	532±1	125 mW	green	>5000	2 x AAA batteries
Wicked laser	Evolution pro	532±1	130 mW	green	>5000	2 x AA batteries
Wicked laser	Spider I pro	532±1	200 mW	green	>5000	Rechargeable lithium battery type 18650
E-BAY Barlock	Red pointer	650±10	5 mW	red	>5000	3 x LR41 button cell

Table 14: laser beams

The price of each element is:

- Dragon laser red diode laser: 392,2 €
- Dragon laser green diode laser: 1628 €
- Dragon laser green laser module: 73,26 €
- Dragon laser green pointer: 369,9 €
- Dragon laser red pointer: 332,9 €
- Wicked laser executive pro: 97,97 €
- Wicked laser evolution pro: 117,9 \$

- Wicked laser spider I pro: 997,9 \$
- E-BAY Barlock red pointer: 5,9 €

5.4 *Different combinations to visualize the air flow*

We have many options to consider seeing the airflow. For example, we can buy a smoke generator and use it alone, without laser, we can use accessories for the smoke generator, we can buy an aerosol generator instead of a smoke generator and use it in conjunction with the laser beam, etc.

Now we will see in detail the most important options with their advantages and disadvantages and afterwards we will decide which one is the best for our aim.

5.4.1 *Smoke generator only*

The first option is to buy only the smoke generator, and using a plastic tube, carrying the smoke into the wind tunnel. If we do this, the advantages and disadvantages would be:

- Advantages:
 - The smoke is easy to see, so we would have no problem to notice how the air flows.
 - The smoke doesn't stain.
 - This option would be easier to install.
 - It would be cheap, because we only need the smoke generator and a plastic tube.
- Disadvantages:
 - There are no streamlines, so it would be more difficult to see how the airflow is disturbed if we put an obstacle.

5.4.2 *Smoke generator and fog nozzle*

The second option is to buy the smoke generator, a fog injection nozzle and a plastic tube with two tube adapters. The advantages and disadvantages would be:

- Advantages:
 - The smoke is easy to see, so we would have no problem to notice how the air flows.
 - The smoke doesn't stain.
 - Now, we can create streamlines, and we are able to see how the airflow is disturbed.

- Disadvantages:
 - The installation would be more complex.
 - The price increases because it is necessary to buy more specialized equipment.
 - This option is intended to create streamlines, so maybe we are not able to see other phenomena.

5.4.3 *Smoke generator and laser sheet*

The third option is to buy a smoke generator and create a laser sheet. Like in the first option, we would use a plastic tube to carry the smoke inside the wind tunnel. These are the possible advantages and disadvantages:

- Advantages:
 - The smoke is easy to see, so we would have no problem to notice how the air flows.
 - The smoke doesn't stain.
 - We will be able to notice how the smoke density changes when it finds and obstacle and goes through the laser sheet afterwards.
- Disadvantages:
 - We need to create a laser sheet.
 - The price could increase significantly, depending on what we use to create the laser sheet.

5.4.4 *Industrial aerosol generator and laser sheet*

The fourth option is to buy an industrial aerosol generator and combine it with a laser sheet. The advantages and disadvantages could be:

- Advantages:
 - The particles created by the industrial aerosol generator don't stain.
 - We can see how the distribution of aerosol particles changes downstream using the laser sheet if we put an objet inside the wind tunnel.
- Disadvantages:
 - The price is really expensive.

- We need to create a laser sheet.
- We won't be able to see streamlines.

5.4.5 *Pharmaceutical aerosol generator and laser sheet*

The fifth option is to buy a pharmaceutical aerosol generator and combine it with a laser sheet. The advantages and disadvantages might be:

- Advantages:
 - Pharmaceutical aerosol generators are cheap, so we can make several tests with different aerosols.
 - We can see how the distribution of aerosol particles changes downstream using the laser sheet if we put an object inside the wind tunnel, as the industrial aerosol generators.
- Disadvantages:
 - Some pharmaceutical aerosol generators stain, so we would have to clean the wind tunnel after every test.
 - We need to create a laser sheet.
 - There is no streamlines.

5.4.6 *Cooking aerosol generator and laser sheet*

The last option is to use a spray designed to spread oil on a grill and combine it with a laser sheet. The advantages and disadvantages are the same as the fifth option, but adding one more disadvantage; this spray is not easy to find at the stores, and the only way to buy is on-line.

5.5 Conclusion

I think the most important points to consider when making this decision are the price and the possibility to see the streamlines.

I would discard the option of the smoke generator only and the option of the industrial aerosol generator and laser sheet, because only smoke is useless and the price of the industrial aerosol generators are very expensive.

I would also discard the possibility of using the cooking aerosol generator because is difficult to get, there are no streamlines and we would need to clean the wind tunnel many times.

Among the other possibilities (Smoke generator and fog nozzle, Smoke generator and laser sheet and Pharmaceutical aerosol generator and laser sheet) some are better than others. I think the best option is to combine these, but introducing some changes:

- We should buy a cheap smoke generator. If the smoke generator is not a good option, we can use it for other purposes.
- We should try to create a laser sheet. The components should be cheap, easy to install and easy to use.
- We should try to create streamlines, but first we must try to do it on our own. If we cannot do this, we will consider buying specialized equipment.
- We should buy different pharmaceutical aerosols and test them. They are not expensive and the results can be really good.

Chapter 6. SELECTION OF THE MEANS TO VISUALIZE THE AIRFLOW

6 Selection of the means to visualize the air flow

6.1 Selection of the Smoke generator

After assessing and evaluating all the smoke generators, we have reached the following points:

- The smoke generator SMOKEMAKER F-100 is only available in the USA, so we cannot buy it.
- The smoke generators of DANTEC (195 SG-D and FOG 2010) and SAFEX (FOG 2005 and FOG 2010) seem perfect for our purposes, because according to the manufacturer (DANTEC is just a seller, the distributor in The Netherlands, SAFEX is the manufacturer) is suitable to use it for research purposes in a wind tunnel. The problem is the price. These smoke generators have many features which we don't really need, and this increases the price.
- The smoke generators found on EBAY are really cheap compared to the others. The smoke generators of 500 W (METAL SMOKE MACHINE and METAL SMOKE MACHINE CISCOSHOP) and 700 W (ANTARI Z-80) seem to have insufficient power, because their fogging power is poor. In contrast, the smoke generator HQ POWER VDL1200SM is cheaper than the most powerful smoke generators (SAFEX, DANTEC) and the fogging power is more or less the same. The only problem is that it needs more time for the warm-up.

As a conclusion, our choice is HQ POWER VDL1200M, because although the warming-up is long, the features and the price are perfect.

6.2 Selection of the Fog nozzle, experiment 1

First of all, we should try to build a fog nozzle, doing experiments. To do the first one, we need the following components:

- Plastic tube 21 mm diameter, 1 m length
- Manual pump to inflate bicycle tires, balls...
- Plastic elbow, 80 mm diameter, 45 degrees
- Needle to inflate balls
- Tape
- Plastic bags, 130 l of capacity
- Teflon tape

6.2.1 Installation prior to the experiment 1

To do the experiment, we need to put the plastic elbow on the smoke output of the smoke generator. The problem is that the diameter of the plastic elbow is 75 mm and the diameter of the smoke output is 80 mm. We use tape and Teflon tape to solve this problem and to prevent leakage (*fig. 56*).



Figure 56: leakage prevention

Afterwards, we introduce the elbow and make sure that it doesn't move. Now, we put a plastic bag in the other extreme of the elbow and we fix it using the tape. On the other extreme of the plastic bag, we put the plastic tube of 1 m and we fix it using also the tape (*fig. 57*).



Figure 57: plastic bag and plastic tube

In the other extreme of the plastic tube, we put the tip of the manual pump and the needle (fig. 58). We take advantage of the small hole of the needle to try to create a thin line of smoke. We use the tip of the manual pump to mount on it the needle.

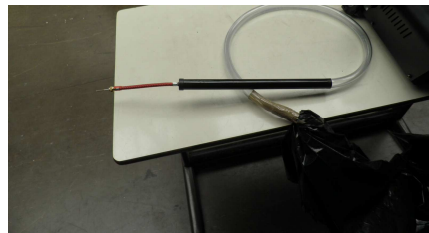


Figure 58: tip of the manual pump and the needle

6.2.2 Experiment 1 without the tip of the manual pump and the needle

We do the experiment outside, because of the smoke. We remove the tip of the manual pump and the needle to check if the pressure of the smoke is too much for the plastic bag (fig. 59).



Figure 59: without the tip of the manual pump and needle

The plastic bag is not full of smoke. Instead, the plastic bag melts and smoke leaks. The smoke doesn't reach the plastic tube (*fig. 60*).



Figure 60: plastic bag melts

As a conclusion, we can say that the plastic bag cannot stand the heat and the smoke sublimates.

6.2.3 *Experiment 1 with the tip of the manual pump and the needle but without the plastic bag.*

In this case, we remove the plastic bag and we connect directly the plastic tube to the smoke output (*fig. 61*).



Figure 61: without the plastic bag

Now, the smoke doesn't come out the tube. The tube cannot stand the high temperature (it deforms) and the smoke sublimates inside. We have the same problem as the previous experiment. Also the tip of the manual pump deforms because it is made of plastic too.

6.2.4 *Experiment 1 with the tip of manual pump but without the plastic bag and the needle*

Now, we try the same thing as before but removing the needle (*fig. 62*). We need a bigger hole, and the hole in the tip of manual pump where the needle was mounted is perfect, because it is bigger but not too much.



Figure 62: without the plastic bag and needle

Now, we finally obtain streamline, but the plastic tube deforms again and the pump also. The smoke sublimates inside the plastic tube.

6.2.5 Experiment 1: conclusion

As a conclusion, we can say we are in the right direction, but we need something that will not deform and stand the temperature. Something that deforms less could be another option. That's why we do a second experiment.

6.3 Selection of the Fog nozzle, experiment 2

Now, to do the second experiment to select the fog nozzle, we need the following components:

- Plastic tube 21 mm diameter, 2 m length
- Manual pumps to inflate bicycle tires, balls...
- Tape
- Teflon tape
- 1 x wooden board 1220 mm x 610 mm x 9 mm with nine holes
- 3 x wooden board 1220 mm x 610 mm x 9 mm
- 1 x wooden board 610 mm x 628 mm x 9 mm
- 1 x wooden board 610 mm x 628 mm x 9 mm with a hole
- 8 x wooden block
- nails

6.3.1 Installation prior to the experiment 2

What we want to do now is to fill a box made of wood to fill with smoke. This way, we try to avoid the massive smoke condensation in the bag, giving more space to the smoke to expand. We will do this box using wooden boards, following the dimensions above.

One wall has 9 holes (*fig. 63*).

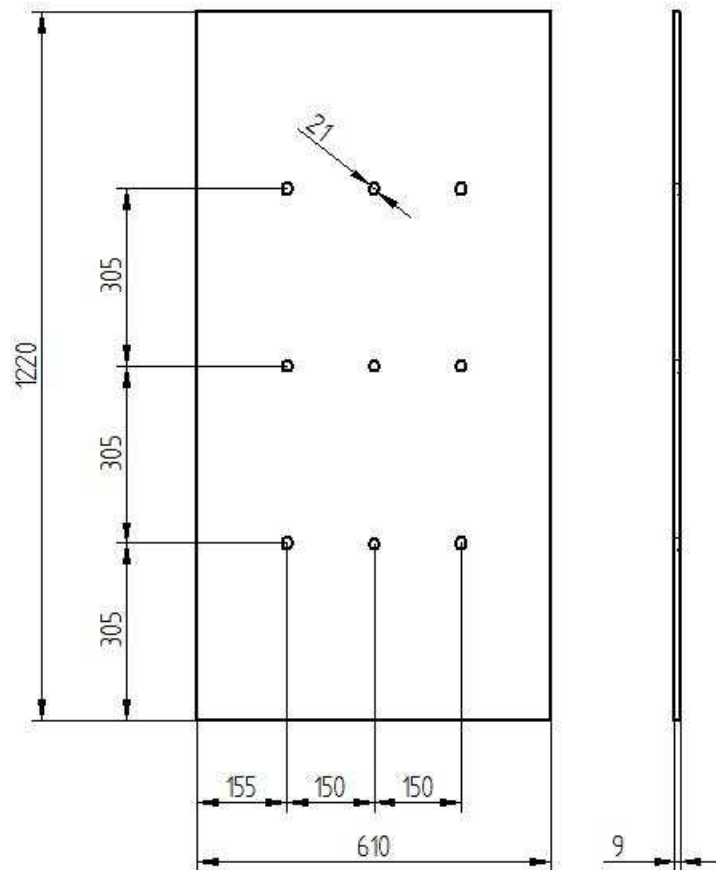


Figure 63: wooden board with 9 holes

This wall is to be on the top, and the holes are made to place plastic tubes. In the other end of each plastic tube, we put the tip of manual pump to create the streamline. Doing this, we create 9 streamlines. We don't need them all working at the same time, but this way we have streamline in different places of the cross-section. If we want only one streamline, we can cover the remaining holes using tape or allowing the smoke coming out to reduce the smoke pressure inside the box.

We have also 3 wooden walls without holes (*fig. 64*). The purpose of those walls is to create the box.

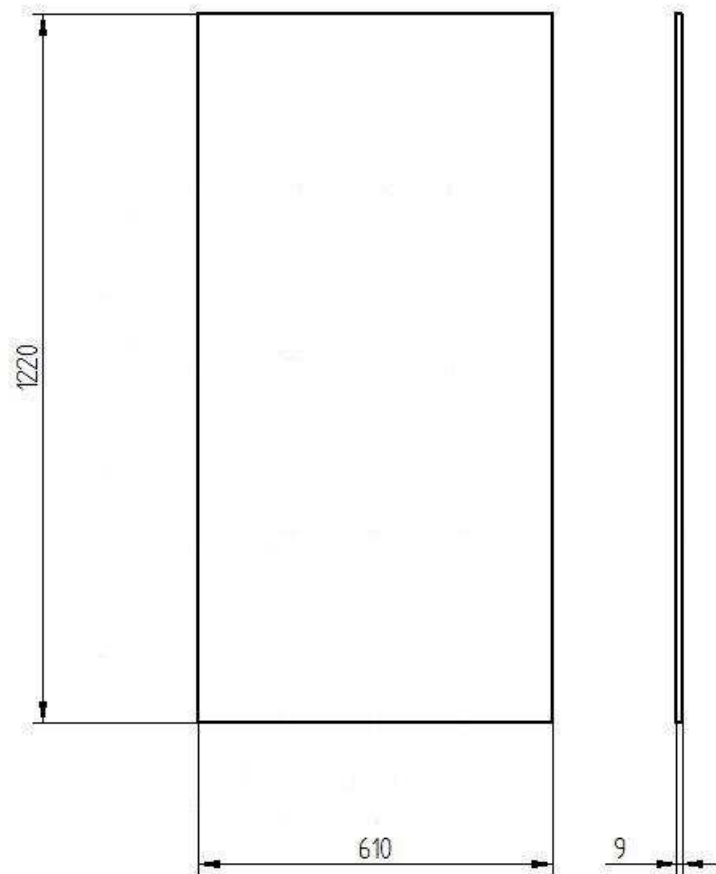


Figure 64: wooden board without holes

There is also a wooden wall with a bigger hole (fig. 65). This hole is to put the smoke output of the smoke generator. That is how we will fill the box with smoke.

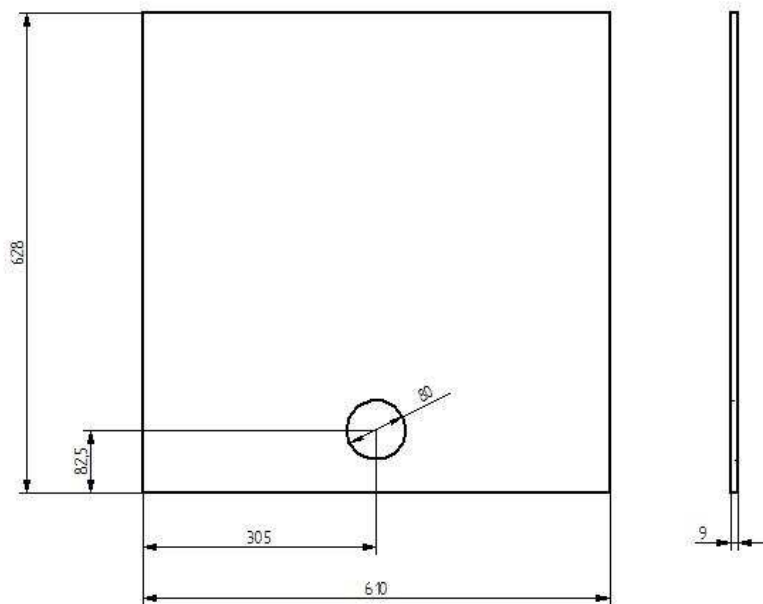


Figure 65: wooden board with one big hole

The last wall is like the previous one, but this time without the hole.

All these dimensions are not the real ones, they are only approximations. Now, we have to cut larger boards to get what we want. Due to the procedure of cutting the larger boards, the dimensions may change, but purpose is still the same.

Finally, we use 8 wooden blocks to build the box. These are necessary because the wood is too weak and it could break when we put the nails.

We put one block in each corner of the box (*fig.66*). In this case the dimensions are not important.



Figure 66: wooden blocks

Now, we put tape on the joints to prevent leakage, because there are small spaces between the walls and the smoke could come out decreasing the pressure inside the box.

Finally, the box is like this (*fig. 67*):



Figure 67: wooden box with sealed joints

Now, we have to put the smoke inside the box. To get this, we place the smoke output of the smoke generator inside the biggest hole. It is a fact that the hole is bigger than the smoke output. To avoid the leaks, we use tape and Teflon tape to increase the diameter of the smoke output (*fig. 68*).



Figure 68: Teflon tape

Now, we cover eight holes of the wall which is on the top using the tape, and in the remaining hole we place one plastic tube with the tip of manual pump (one streamline is enough for now). We use a support and a clamp to grab the tip of the manual pump and place in the middle of the cross section. We put them with the help of small wooden boards (*fig. 69, 70*), trying to disturb the airflow as less as possible.



Figure 69: support and clamp, side view



Figure 70: support and clamp, front view

6.3.2 Experiment 2 using all

We do this experiment in the wind tunnel.

We turn on the wind tunnel and the smoke generator to see what happens (*fig. 71*).

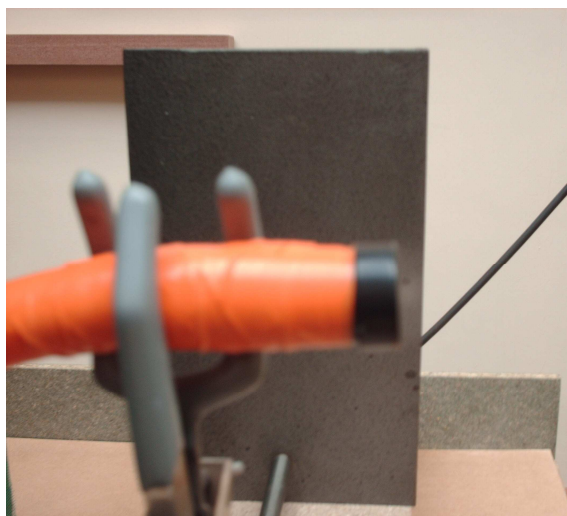


Figure 71: only one hole opened

There is no leakage, but the pressure inside is too low and the smoke doesn't come out of the tip of the manual pump. We have to solve this problem.

6.3.3 Experiment 2 with less space inside the box

Now, we use two wooden walls to reduce the space inside the wooden box (*fig. 72*). This way, we want to increase the pressure and check if the smoke comes out of the tip of the manual pump. We turn on the wind tunnel and the smoke generator again to check if the changes are correct.



Figure 72: two wooden boards

Reducing the space inside the problem is not solved. We have to find another solution.

6.3.4 Experiment 2 connecting the plastic tube directly to the smoke output

Experiment 1 has shown that the plastic tube deforms when it is connected directly to the smoke output. On the other hand, that is the only way we can achieve the streamline.

This time, using a longer plastic tube (2 meters, *fig. 73*) we want to check if the plastic tube deforms less when it is longer. We know the smoke sublimates inside the plastic tube, increasing the pressure. We make two small incisions in the plastic tube to let the sublimated smoke go out and to reduce the pressure. We also put a flange (*fig. 74*) in the smoke output to make this joint more stable. We turn on the wind tunnel and the smoke generator again to check if the changes are correct.

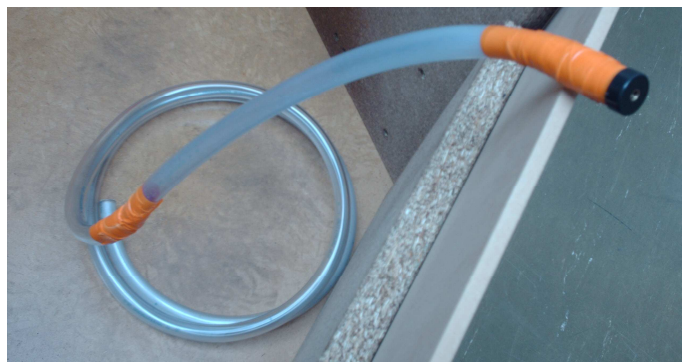


Figure 73: 2 meters plastic tube



Figure 74: flange

Now, we have the streamline but the shape is not clear (*fig. 75*).

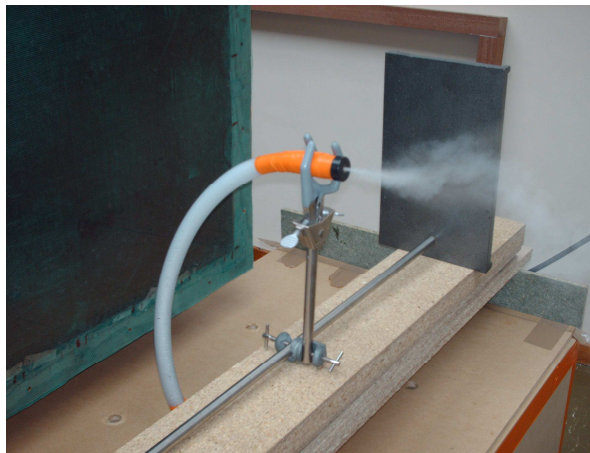


Figure 75: streamline

6.3.5 *Experiment 2: conclusion*

As a conclusion, we can say we are in the right direction like in the experiment 1. The wooden box is useless to get the streamlines, but we can use it to keep the leftover smoke controlled during the tests. Using the longer plastic tube, the deformation is less so we can do longer tests, but we still need something that will not deform and stand the temperature.

6.4 Selection of the laser sheet components

To do a laser sheet, what we need is a laser beam and a rotating mirror to reflect the light.

After evaluating all the laser beams we have reached the following points:

- We have green lasers and red lasers. The color is not important (we want a laser sheet, no matter what color) and red lasers are cheaper than green lasers. We can discard green lasers.
- Between red lasers, the DRAGON LASER RED DIODE LASER is the most powerful (1 Watt) but it is also the most expensive.
- The DRAGON LASER RED POINTER is also expensive and its power (100 mW) is much lower than the Dragon laser red diode laser (1 W).
- The E-BAY BARLOCK RED POINTER is really cheap and is the least powerful (1 mW).

As a conclusion, our choice is E-BAY BARLOCK RED POINTER, because although the power is low, it is very cheap. If we finally need a powerful laser, we can borrow one from the physics laboratory first and do the experiments, and if it finally works, then we can buy DRAGON LASER RED DIODE LASER.

6.4.1 The rotating mirror

To do the rotating mirror, we use:

- Three small mirrors
- A Plastic bar
- Glue
- Tape
- Electric motor

What we do is to put the three small mirrors on the plastic bar forming an equilateral triangle. We use the tape to increase the diameter of the plastic bar and to fix the mirrors on the plastic bar to prevent the triangle from breaking when the bar starts to spin. We use the glue to fix the bar to the electric motor. Finally, we have this (*fig. 76*).

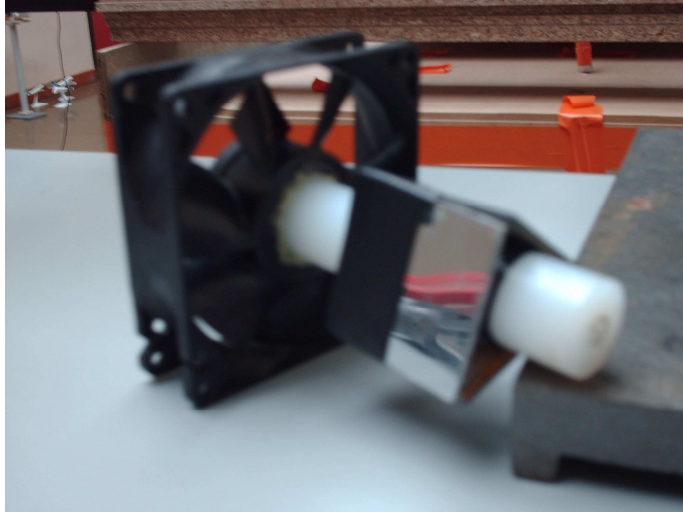


Figure 76: rotating mirror

Chapter 7. EXPERIMENTS USING THE SELECTED MEANS TO VISUALIZE THE AIR FLOW

7 Experiments using the selected means to visualize the air flow

After the selection process explained in the previous chapter, we do some experiments using all of them in different combinations. We have chosen:

- Smoke generator: HQ POWER VDL1200M.
- Fog nozzle: Experiment 2 connecting the plastic tube directly to the smoke output.
- Laser sheet: E-BAY BARLOCK RED POINTER and rotating mirror.

The elements above have been selected to use in the following experiments, but it doesn't mean that we use only this stuff. In some cases, we use some laboratory stuff which was property of the University already. We use also the wing profile provided by Vincent de Frenne (*fig. 77*).

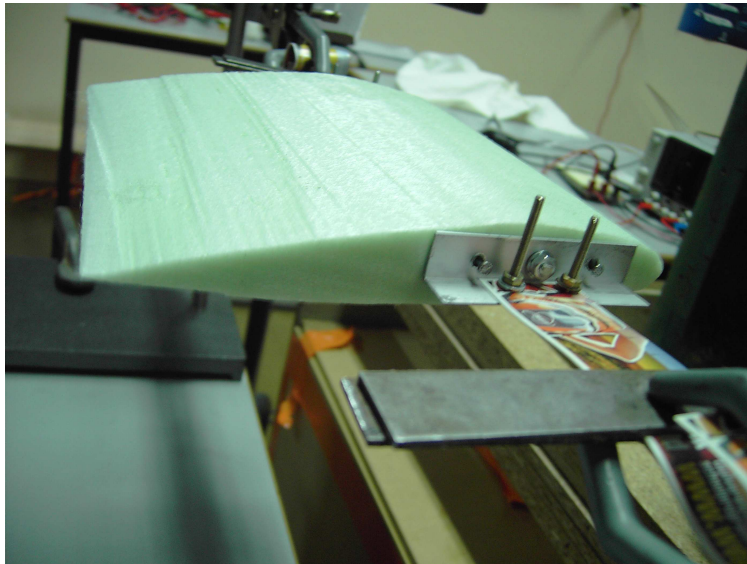


Figure 77: wing profile

7.1 Experiment 1 using the smoke generator, the fog nozzle and the laser sheet

In this experiment we use all the elements above (smoke generator, fog nozzle and laser sheet). We do this experiment also in the dark, because this way the laser is easier to see when it goes through the smoke.

We use this wing profile to check if we are able to visualize how the streamline surrounds it above and below (with light) and if we can see any phenomena downstream using the laser sheet (in the dark). We place the wing profile in front of the fog nozzle at a range of 20 cm approximately.

7.1.1 Experiment 1 with light

Wind tunnel speed set at 7 m/s approximately. We turn on the smoke generator and we see what happens (*fig. 78*). We change the air velocity every few seconds. We don't use the laser sheet now.

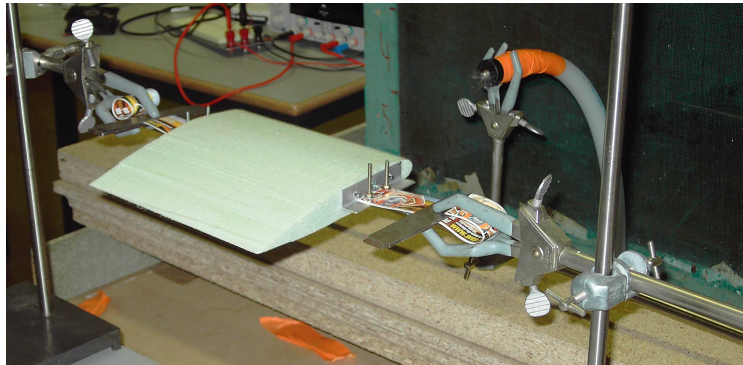


Figure 78: experiment 1 with light

7.1.2 Experiment 1 with light: conclusion

We can see that it doesn't work. The streamline doesn't reach the wing profile because it spreads very fast. The reasons for this could be that the density of the smoke is not enough and the turbulence of the airflow is too high for all air velocities.

7.1.3 Experiment 1 in the dark

Now, behind the wing profile, we put the rotating mirror at a range of 15 cm approximately. We turn on the wind tunnel and we select an average speed, around 7 m/s. We put the laser in front of the rotating mirror at a range of 60 cm. We turn on the smoke generator, the rotating mirror and the laser. We turn off the lights to see what happens.

7.1.4 Experiment 1 in the dark: conclusion

We are not able to see anything downstream the wing profile using the laser sheet. The reasons seem to be the same as the experiment 1 with light.

7.2 Experiment 2 using the smoke generator and the laser sheet

In this experiment we use only the smoke generator and the laser sheet. We do this experiment also in the dark, because this way the laser is supposed to be easier to see when it goes through the smoke. In this case we place the smoke output in front of a small hole in the left side of the duct upstream (*fig. 79*).

Firstly, we turn on the smoke generator few seconds to fill the duct with smoke. Then, we place the rotating mirror and the laser as before. Finally, we turn off the lights and turn on the wind tunnel at maximum speed to see what happens.



Figure 79: experiment 2

7.2.1 Experiment 2: conclusion

We are not able to see any phenomena downstream the wing profile. In the dark we don't notice any laser beam or laser sheet. This may be because the smoke is not dense enough and the laser beam is not powerful enough.

7.3 Experiment 3 using the smoke generator and the fog nozzle without the tip of the manual pump

In this experiment we use the smoke generator and the fog nozzle, but without the tip of the manual pump (fig. 80). We do this because we want to increase the quantity of smoke that comes out the fog nozzle.

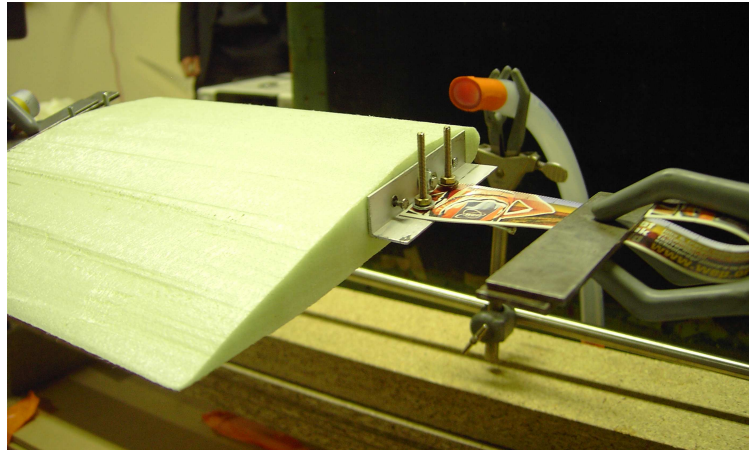


Figure 80: experiment 3

We turn on the wind tunnel and we select an average speed, around 7 m/s. Afterwards we turn on the smoke generator. We change the air velocity every few seconds.

7.3.1 Experiment 3: conclusion

In this case, we are able to see how the smoke surrounds the wing profile above and below (fig. 81), and some phenomena may occur downstream the wing profile. We don't know it for sure because it is undetectable by the human eye; the movement of smoke carried by the air flow is very fast. Perhaps using a special video camera we could see the smoke movement in slow motion and check what really happens.

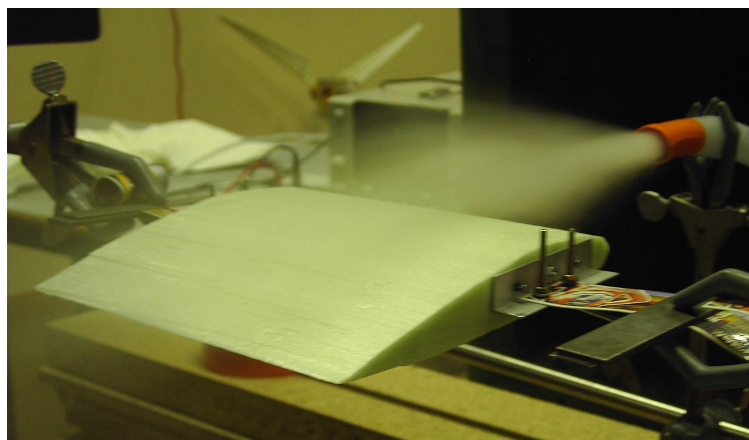


Figure 81: smoke above and below

Chapter 8. CONCLUSIONS AND RECOMMENDATIONS

8 Conclusions and Recommendations

8.1 *Measurements instruments: conclusion*

The first goal is to install and test a device to measure air speed during test are being executed in the wind tunnel. A pitot tube and transmitter are commonly used for this purpose and the results are good. In this case, using a Labview application we are able to know the speed of the air up to a precision of 15 m/s.

The measurement system is not calibrated as recommended by the manufacturer, but using an available anemometer and a linear interpolation in our software application we get an air velocity reading sufficiently reliable.

8.2 *Measurements instruments: recommendations*

There are some recommendations to improve the accuracy of the measurement system:

- The pitot tube should be installed permanently in a mobile support. This way, we would be able to measure the air velocity in the test section and measure other variables in other places.
- The transmitter should be calibrated as the manufacturer recommended.
- The transmitter and all the components of the electric circuit should be also installed permanently too. This way, we don't need to set up the zero point every time we use the measurement system and the components would be better protected.
- The airflow in the wind tunnel needs to be relatively turbulence-free and laminar. In this case, the different systems to make the airflow less turbulent (air vanes, honeycomb...) are not installed yet. Because of this, the airflow is turbulent and the total pressure and the static pressure measured by the pitot tube are not constant values. They go up and down constantly, and this variation makes the measurement more difficult. We need to install some systems to make the airflow less turbulent.

8.3 *Means to visualize the airflow: conclusion*

The visualization is also very important. In this case, we try to visualize the air flow using a smoke generator, a fog nozzle built by ourselves and a laser sheet.

After all the experiments and tests, we are able to create a streamline (using the plastic tube and the tip of a manual pump) but this is not as good as it should be to affirm that we have reached our goal because the smoke spreads and the streamline disappears very fast. We can also create a current of smoke inside the duct of the smoke generator placing the smoke output in front of a hole in the left side of the duct, but this seems to be not enough for our goal. The laser sheet works (using a laser beam and a rotating mirror), but the device created is not accuracy and the laser is not powerful

enough. Despite not having reached our goal as we should, all devices created to see the airflow could be the base for better systems.

8.4 Means to visualize the airflow: recommendations

There are some recommendations to improve the means to visualize the airflow:

- We can create the streamline but it breaks very easy. Due to the systems to make the airflow less turbulent are not installed yet, the air inside the wind tunnel is not turbulence-free. When the smoke from the fog nozzle comes into contact with the turbulent flow, it gets also turbulent. We could try to reduce the turbulence of the airflow to see if doing this the streamline doesn't disappear. Another option to avoid this fact could be increasing the pressure of the smoke.
- We can use other materials instead of plastic tube. It deforms because of the heat of the smoke and makes the system less efficient. For example, we can use stronger plastic tubes (they are more resistant, but also more expensive and more rigid), we can use also metal tubes (they stand the smoke temperature but they are more expensive and it is more difficult to cut and make elbows or joints). The best choice would be to use tubes made of special fabric that stands high temperatures which are designed for this purpose (this tubes are included in the market research, but it is the most expensive option).
- We can use another liquid to create the smoke. Maybe this way we can increase the density of the smoke and make the laser easier to see when it goes through the smoke.
- We can use a fog nozzle designed for this purpose.
- We need a more powerful laser beam to see it when it goes through the smoke.
- We could use a special video camera to be able to see the aerodynamic phenomena in slow motion.
- In the future, we can test pharmaceutical aerosols instead of the smoke generator to create small droplets.

Chapter 9. BIBLIOGRAPHY

9 Bibliography

9.1 Books

- [1] Pedro María Diéguez. Transmisión de calor. Pamplona. Spain. 2009. UPNA
- [2] King L. V. On the convection of heat from small cylinders in a stream of fluid. 1914 Phil. Trans. R. Soc.
- [3] Collis D. C. & Williams M. J. Two-dimensional convection from heated wires at low Reynolds number. 1959. J. Fluid Mech.
- [4] Bruun H. H. et al. Velocity calibration relationships for hot wire anemometry. 1988. J. Phys. E: Sci Instrum.

9.2 Web pages

- [5] Wikipedia. < http://en.wikipedia.org/wiki/Wind_tunnel >
- [6] Princeton University. < http://www.princeton.edu/~asmits/Bicycle_web/Bernoulli.html >
- [7] Engineering toolbox. < http://www.engineeringtoolbox.com/pitot-tubes-d_612.html >
- [8] Dantec Dynamics. < <http://www.dantecdynamics.com/Default.aspx?ID=824> >
- [9] JLC international. < http://www.jlcinternational.com/air_velocity.htm >
- [10] Wikipedia. < http://en.wikipedia.org/wiki/Delta_method >
- [11] Stata. < <http://www.stata.com/support/faqs/stat/deltam.html> >
- [12] National Instruments. < <http://sine.ni.com/nips/cds/view/p/lang/en/nid/14605> >
- [13] Reference answers. < <http://www.answers.com/topic/aerosol> >
- [14] Pharmaceutical-Int. < <http://www.pharmaceutical-int.com/article/pharmaceutical-aerosols.html> >
- [15] Howstuffworks. < <http://science.howstuffworks.com/laser5.htm> >
- [16] Lexel Laser. < http://www.lexellaser.com/techinfo_wavelengths.htm >

9.3 Manuals

- [17] Dwyer. Series MS Magnesense® Differential Pressure Transmitter. Specifications - Installation and Operating Instructions.

[18] National instruments. Labview® fundamentals.

9.4 Articles

[19] Calibración de tubos de pitot tipo S en el LABINTHAP. Mexico. 2010

[20] Marcus Hultmark & Erik Sällström. Can King's law be numerically verified? A report in MTF112, Convective Heat Transfer. Sweden. 2006. Chalmers.

[21] Ranade, M. B., Woods, M. C., Chen, F-L., Purdue, L. J. and Rehme, K. A. 'Wind Tunnel Evaluation of PM10 Samplers', Aerosol Science and Technology, 13: 1, 54 — 71. 1990

9.5 Images

[22] < <http://www.flowkinetics.com/images/fig1.png> >

[23] < http://www.efunda.com/designstandards/sensors/hot_wires/hot_wires_intro.cfm >

[24] < <http://www.dantecdynamics.com/Default.aspx?ID=824> >

[25] < <http://www.directindustry.com/prod/e-e-elektronik/air-velocity-transmitter-13965-44877.html> >

[26] < http://www.dwyer-inst.com/PDF_files/MS-HIGH_iom.pdf >

[27] < <http://sine.ni.com/nips/cds/view/p/lang/en/nid/14605> >

[28] < http://www.topas-gmbh.de/_220_en.htm >

[29] < <http://allergyasthma.wordpress.com/2008/05/15/albuterol-switching-to-new-hfa-formulation/> >

[30] < <http://gentecmedical.com/ultrasonic-nebulizer.html> >

[31] < <http://ticotica.wordpress.com/2009/10/12/lunes-de-fiesta-y-de-humor/> >

[32] < <http://www.veloxgrills.com/flourishoilspray.html> >

[33] < http://es.warnlaser.com/Laser_Beam.html >

[34] < <http://science.howstuffworks.com/laser3.htm> >

[35] < <http://science.howstuffworks.com/laser5.htm> >

[36] < <http://science.howstuffworks.com/laser5.htm> >

[37] < <http://science.howstuffworks.com/laser5.htm> >

[38] < <http://science.howstuffworks.com/laser5.htm> >

[39] < <http://science.howstuffworks.com/laser5.htm> >

[40] < <http://science.howstuffworks.com/laser5.htm> >

APPENDIX A

10 Appendix A

This appendix includes the measurement systems and instruments evaluated during the project. Pitot tubes, manometers, hot wire anemometers and air velocity transmitters

10.1 Pitot tubes

Company: KIMO

Model: TPL-XX-XXXX



Some features:

- L-shaped
- Constructed of stainless steel
- Ellipsoidal tip design
- According to ISO 3966 regulation
- From 0 °C to 600 °C
- Able to measure static, dynamic and total pressure.
- Different insertion lengths (from 3 mm to 3000 mm)
- Various diameters (from 3 mm to 14 mm)

Company: KIMO

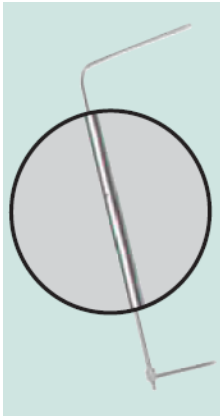
Model: TPL-XX-XXXX-T



Some features:

- L-shaped
- Constructed of stainless steel
- Ellipsoidal tip design
- According to ISO 3966 regulation
- From 0 °C to 600 °C, able to measure static, dynamic and total pressure
- Thermocouple thermometer integrated
- Various insertion lengths (from 3 mm to 3000 mm)
- Various diameters (from 3 mm to 14 mm)

Company: DWYER
Model: 160-XX



Some features:

- L-shaped
- Resistant stainless steel
- Hemispherical tip design
- ASME design, meets AMCA and ASHRAE specifications
- No correction factors required
- No calibrated needed
- Low sensitivity to misalignment
- Silver soldered connections for leak-proof operations
- Various insertion lengths (from 8-5/8'' to 60-5/8'')
- Standard diameter (5/16'')

Company: DWYER
Model: 160e-XX



Some features:

- L-shaped
- Resistant stainless steel
- Ellipsoidal tip design
- Widely used in U.K. and Europe
- Designed to meet British Standard 1042
- Silver soldered connections for leak-proof operations
- Chart with air velocity calculations included
- Various insertion lengths (from 0.2 meters to 1.52 meters)
- Standard diameter (6 mm) for total and static pressure

Company: DWYER
Model: 160S-XX, 160S-XXPM (permanent mounting)



Some features:

- 0.84 flow coefficient
- Long lasting
- Welded stainless steel construction
- Designed specifically for flow measurement of dirty
- Total and static pressure tubes precisely aligned.
- Various insertion lengths (from 18'' to 72'')
- Standard diameter (5/16'')

Company: FURNESS CONTROLS
Model: FCO65



Some features:

- Constructed of stainless steel
- Optional version with thermocouple embedded
- Suitable for temperatures up to 500 °C
- Various insertion lengths (customer specifications)
- Various diameters (from 2.1 mm to 25 mm)

10.2 Manometers

Company: KIMO

Model: MP200



Some features:

- Easy to use
- Large blue screen
- Wireless connections to personal computers
- Suitable to measure pressure, air velocity, temperature, volume air flow and humidity
- Weight: 340 grams
- Four 1.5V battery-operated
- Three optional languages (English, French and the third one can be downloaded)

Company: DWYER

Model: MS-XXX with optional display



Some features:

- Versatile transmitter for monitoring pressure and air velocity
- Selectable English or Metric ranges
- Good accuracy and stability
- Four digit LCD
- Weight: 230 grams
- Easy to install (permanent mounting)

10.3 Hot wire anemometers

Company: KIMO

Model: CTV 200



Most important features:

- Speed range: from 0-1 m/s to 0-20 m/s
- Accuracy: $\pm 3\%$
- Response time: 4 sec.
- Type of fluid: air and neutral filtered gas
- Working temperature: 0°C to 50°C
- Hot wire made of stainless steel
- Hot wire dimensions: diameter 8 mm, length 150 or 300 mm
- Cable dimensions: diameter 8 mm, length 2 m
- Display: alphanumeric, 2 lines of 16 digits
- Weight: 800 g
- Power supply: 24 VAC/VDC $\pm 10\%$
- Output: 2 x 4-20 mA or 2 x 0.10 V (4-wire)
- Consumption: 5 VA
- Electrical connection: screw terminal block for cable $\varnothing 1.5 \text{ mm}^2 \text{ max}$
- Interface to personal computers (optional)
- Price: 495 €

10.4 Air velocity transmitters

Company: KIMO

Model: CTV 100



Some features:

- Various velocity ranges: 0 m/s to 5, 10, 15, 20, 30 m/s
- Accuracy: $\pm 3\%$
- Response time: 2 sec
- Type of fluid: air and neutral filtered gas
- Working temperature: 0°C to 50°C
- Display: LCD, 5 digits
- Power supply: 24 VAC/VDC $\pm 10\%$
- Output: 4-20 mA or 0.10 V (3-wire)
- Consumption: 40 mA (0-10 V) or 80 mA (4-20 mA)
- Electrical connection: screw terminal block for cable $\varnothing 1.5 \text{ mm}^2$ max
- Interface to personal computers (optional)
- Cable probe (optional)
- Price: 239 €

Company: ALNOR

Model: 8455



Some features:

- Protected probe tip
- Rugged ceramic sensor
- Critical environment installations
- Various velocity ranges: 0.125 m/s to 1.0, 1.25, 1.50, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10.0, 12.5, 15.0, 20.0, 25.0, 30.0, 40.0, 50.0 m/s
- Accuracy: $\pm 2\%$
- Response time: 0.2 sec
- Various probe length: 7.5 cm, 15 cm, 22.5 cm, or 30 cm
- Working temperature: 0°C to 93°C
- Power supply: 11 to 30 VDC (2-wire), 18 to 38 VAC (3-wire), 350 mA maximum
- Output: field selectable (0 to 5V, 0 to 10V, 0 to 20V, 2 to 10 mA, 4 to 20 mA)
- Price: 950 \$ (buy on-line)

Company: ALNOR
Model: 8465



Some features:

- Less flow blockage
- Ideal for measuring in confined spaces
- Various velocity ranges: 0.125 m/s to 1.0, 1.25, 1.50, 2.0, 2.5, 3.0, 4.0, 5.0, 7.5, 10.0, 12.5, 15.0, 20.0, 25.0, 30.0, 40.0, 50.0 m/s
- Accuracy: $\pm 2\%$
- Response time: 0.2 sec
- Various probe length: 7.5 cm, 15 cm, 22.5 cm, or 30 cm
- Working temperature: 0°C to 93°C
- Power supply: 11 to 30 VDC (2-wire), 18 to 38 VAC (3-wire), 350 mA maximum
- Output: field selectable (0 to 5V, 0 to 10V, 0 to 20V, 2 to 10 mA, 4 to 20 mA)
- Price: 1329 \$ (buy on-line)

Company: ALNOR
Model: 8475



Some features:

- Omni directional probe tip
- Ideal for unknown or varying flow direction
- Accurate at very low velocities (0.05 to 0.5 m/s)
- Various velocity ranges: 0.05 m/s to 0.5, 0.75, 1.0, 1.25, 1.50, 2.0, 2.5 m/s
- Accuracy: $\pm 3\%$
- Response time: 5 sec
- Various probe length: 7.5 cm, 15 cm, 22.5 cm, or 30 cm
- Working temperature: 0°C to 93°C
- Power supply: 11 to 30 VDC (2-wire), 18 to 38 VAC (3-wire), 350 mA maximum
- Output: field selectable (0 to 5V, 0 to 10V, 0 to 20V, 2 to 10 mA, 4 to 20 mA)
- Price: 1660 \$ (buy on-line)

APPENDIX B

11 Appendix B

This appendix includes the different means to visualize the airflow evaluated during the project. There are smoke generators, accessories for the smoke generators as fog nozzles and technical jets, industrial aerosols, and laser beams. The dimensions (when available) are in this order: height, width, length.

11.1 Smoke generators

Company: SMOKEMAKER

Model: F-100



Some features:

- Designed for wind tunnel studies
- Very low noise levels
- Remote controller (optional)
- LED status indicators
- Fluid level sight gauge
- User replaceable fluid filter
- Continuously variable output with full timing controls on 0-10 V
- Power supply: 120 VAC/60 Hz./14A or 240 VAC./50 Hz./7A
- Thermocouple over temperature protection
- Dimensions: 209 mm x 298 mm x 686 mm
- Weight: 14.5 Kg.
- Price: 1084 \$, shipping cost included (buy on-line)

Company: DANTEC
Model: 195 SG-D



Some features:

- Designed for applications in clean-room environments
- Small, powerful device that generate a dense white fog
- The fog is non-irritant and non-flammable
- Mean droplet size around 1 μm
- Fog Fluid consumption: 15 ml/min - 115 ml/min
- Power supply: 220 VAC
- Price: 2867 € (buy on-line)

Company: DANTEC
Model: FOG 2010



Some features:

- Designed for applications in clean-room environments
- Small, powerful device that generate a dense white fog
- The fog is non-irritant and non-flammable
- Mean droplet size around 1 μm
- Fog Fluid consumption: 10 ml/min - 85 ml/min
- Power supply: 110 VAC
- Price: 2284 € (buy on-line)

Company: E-BAY (Belgium)
Model: METAL SMOKE MACHINE 500W



Some features:

- 2-year guarantee
- Ideal for use on stage, discos and theatres
- Remote control with on/off switch
- Warm up: ± 4 min
- Fogging power: 60 m^3/min
- Power supply: 230 VAC
- Power consumption: 500 W max.
- Tank capacity: 0.8 l
- Various smoke liquids (standard, high density, pro high density)
- Dimensions: 280 mm x 190 mm x 160 mm
- Weight: 3.1 kg
- Price: 46.90 €, shipping costs 8.90 € (buy on-line)

Company: E-BAY, CISCOSHOP (Belgium)
 Model: METAL SMOKE MACHINE 700W



Some features:

- Ideal for use on stage, discos and theatres
- Remote control with on/off switch
- Warm up: ± 5 min
- Power supply: 230 VAC
- Power consumption: 700 W max.
- Tank capacity: 0.8 l
- Dimensions: 130 mm x 160 mm x 315 mm
- Weight: 4.5 kg
- Price: 49.99 €, shipping costs 8 € (buy on-line)

Company: E-BAY, SOUND-7 (Belgium)
 Model: ANTARI Z-80



Some features:

- 2-year guarantee
- Warm up: ± 4 min
- Fog Fluid consumption: 25 ml/min
- Fogging power: 90 m³/min
- Power supply: 230 VAC
- Power consumption: 700 W max.
- Tank capacity: 0.8 l
- Dimensions: 330 mm x 160 mm x 240 mm
- Weight: 3.7 kg
- Price: 49 €, shipping costs 9.80 € (buy on-line)

Company: SAFEX
 Model: FOG 2005



Some features:

- Equipped with an external tank holder
- 8 pole remote control socket
- Warm up: ± 5 min
- Fog Fluid consumption: 80 ml/min max.
- Fogging power: 325 m³/min
- Power supply: 230 VAC/ 50 Hz/ 10 mA
- Power consumption: 1650 W max.
- Tank capacity: 0.3 l
- Dimensions: 145 mm x 170 mm x 340 mm
- Weight: 6.1 kg
- Price: 795 €

Company: SAFEX
Model: FOG 2010



Some features:

- Equipped with an external tank holder
- 8 pole remote control socket
- Equipped with special hose attachment
- Output control
- Equipped with for nozzle attachment
- Warm up: ± 5 min
- Fog Fluid consumption: 85 ml/min max.
- Fogging power: 470 m³/min
- Power supply: 230 VAC/ 50 Hz/ 10 mA
- Power consumption: 1650 W max.
- Tank capacity: 0.3 l
- Dimensions: 145 mm x 170 mm x 340 mm
- Weight: 6.1 kg
- Price: 1100 €

Company: E-BAY, HQ-POWER (Belgium)
Model: VDL1200SM



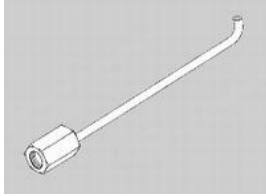
Some features:

- Equipped with an internal tank holder
- Output control
- Warm up: ± 9 min
- Fogging power: 450 m³/min
- Power supply: 230 VAC/ 50 Hz
- Power consumption: 1200 W max.
- Tank capacity: 2.5 l
- Dimensions: 530 mm x 260 mm x 280 mm
- Weight: 7.5 kg
- Price: 108,70 € (buy on-line)

11.2 Fog nozzles and other accessories

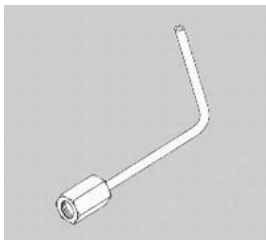
Company: DANTEC

1. Fog Injection Nozzle, bow, 6 x 200 mm



- Price: 163 € (buy on-line, shipping cost not-included)
- Can only be used with FOG 2010

2. Fog Injection Nozzle, hook, 6 x 100 x 100 mm



- Price: 170 € (buy on-line, shipping cost not-included)
- Only with FOG 2010

3. Flexible Tube, length 2 m, Ø80 mm



- Price: 65 € (buy on-line, shipping cost not-included)

4. Tube Adapter to connect the fog generator and the flexible tube



- Price: 137 € (buy on-line, shipping cost not-included)

5. Remote Quantity Control for 110 VAC generators



- Price: 253 € (buy on-line, shipping cost not-included)
- For remote activation and for variation of fog quantity

11.3 Industrial aerosol generators

Company: TSI

Model: 3079



Some features:

- Atomizer with twin-stream injection nozzle and baffle
- Particle size: 0.2-0.3 μm
- Particle concentration: $>10^7/\text{cm}^3$
- Particle liquid type: DES, DOP, PAO paraffin
- Particle solid type: Latex particles, NaCl, salt solutions
- Flow rate: 1.0-4.2 L/min
- Maximum counter-pressure: 10 kPa
- Power supply: 110/230 VAC
- Power requirements: Operates on 12 VDC
- Dimensions: 280 mm x 200 mm x 175 mm
- Weight: 4.5 Kg.
- Price: 4950 €

Company: TOPAS

Model: ATM226



Some features:

- Patented injector nozzle (GM 94 08 604)
- Particle concentration: $>10^7/\text{cm}^3$
- Aerosol materials: DEHS, DOP, paraffins, salt solutions...
- Flow rate: 0.8-5.0 L/min
- Maximum counter-pressure: 10 kPa
- Power supply: 100/240 VAC
- Power requirements: Operates on 12 VDC
- Dimensions: 280 mm x 200 mm x 175 mm
- Weight: 4.2 Kg.
- Price: 3208,8 €

Company: ATI
Model: TDA-4B



Some features:

- 6 laskin nozzle design
- Aerosol output range: 50-8100 cfm
- Aerosol concentration: 10-100 ug/l
- Aerosol type: polydispersed (cold)
- Flow rate: 85-500 L/min
- Power supply: not required
- Compressed air at 20 psi
- Dimensions: 230 mm x 280 mm x 250 mm
- Weight: 7.5 Kg.
- Price: 2801,6 €

Company: ATI
Model: TDA-4B lite



Some features:

- 3 laskin nozzle design
- Aerosol output range: 50-5000 cfm
- Aerosol concentration: 10-100 ug/l
- Aerosol type: polydispersed (cold)
- Flow rate: 85-250 L/min
- Power supply: not required
- Compressed air at 20 psi
- Dimensions: 230 mm x 200 mm x 250 mm
- Weight: 5.5 Kg.
- Price: 2117,2 €

11.4 Laser Beams

Company: DRAGON LASER

Model: Red diode laser



Some features:

- Wavelength: 655 ± 10 nm
- Output power: >1000 mW
- Power stability: $<5\%$
- Warm-up time: <5 min
- Operating temperature: $10-35$ °C
- Power supply: 90-264 VAC or 5 VDC
- Laser head dimensions: 140.8 mm x 73 mm x 46.2 mm
- Weight laser head: 0.6 Kg
- Power supply dimensions: 133 mm x 130 mm x 65 mm
- Weight power supply: 1,2 Kg
- Price: 392,2 € (buy on-line)

Company: DRAGON LASER

Model: Green diode laser



Some features:

- Wavelength: 532 ± 1 nm
- Output power: >1000 mW
- Power stability: $<5\%$
- Warm-up time: <10 min
- Operating temperature: $10-35$ °C
- Power supply: 90-264 VAC
- Laser head dimensions: 155 mm x 77 mm x 60 mm
- Weight laser head: 0.9 Kg
- Power supply dimensions: 238 mm x 146 mm x 102 mm
- Weight power supply: 2.3 Kg
- Price: 1628 € (buy on-line)

Company: DRAGON LASER

Model: Green laser module



Some features:

- Wavelength: 532 ± 1 nm
- Output power: >1000 mW
- Power stability: $<10\%$
- Warm-up time: <10 min
- Operating temperature: $10-35$ °C
- Power supply: 90-264 VAC
- Price: 73,26 € (buy on-line)

Company: DRAGON LASER

Model: Green pointer



Some features:

- Wavelength: 532 nm
- Average output power: 15-200 mW
- Dimensions: 13 mm x 150 mm
- Net weight: 55 g
- Operating temperature: 10-35 °C
- Power supply: 2 x AAA batteries
- Price: 369,9 € (buy on-line)

Company: DRAGON LASER

Model: Red pointer

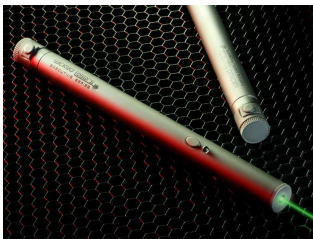


Some features:

- Wavelength: 640±2 nm
- Average output power: 100-300 mW
- Dimensions: 29 mm x 198 mm
- Net weight: 225 g
- Operating temperature: 10-35 °C
- Power supply: 2 x CR123A lithium batteries
- Price: 332,9 € (buy on-line)

Company: WICKED LASER

Model: Executive pro



Some features:

- Wavelength: 532 nm
- Average output power: 15-125 mW
- Dimensions: 13 mm x 144 mm
- Power supply: 2 x AAA 1.5 V
- Price: 97,97 \$ (buy on-line)

Company: WICKED LASER

Model: Evolution pro



Some features:

- Wavelength: 532 nm
- Average output power: 20-130 mW
- Dimensions: 20,2 mm x 182 mm
- Power supply: 2 x AA 1.5 V
- Price: 117,9 \$ (buy on-line)

Company: WICKED LASER

Model: Spider I pro



Some features:

- Wavelength: 532 nm
- Average output power: 200 mW
- Dimensions: 31,4 mm x 204 mm
- Weight: 240 g
- Power supply: Rechargeable lithium ion battery type 18650
- Price: 997,9 \$ (buy on-line)

Company: EBAY BARLOCK

Model: Red pointer



Some features:

- Wavelength: 650 ± 10 nm
- Average output power: 5 mW
- Power supply: 3 x LR41 button cell
- Price: 5,9 \$ (buy on-line)