Sensors Laboratory

Lab 3: Flow Sensors

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1 General Theory

1.1 Laminar vs. Turbulent Flow

Flow is generally classified into two types; laminar and turbulent, see figure 1. Laminar flow is characterized by parallel layers of streamlines usually flowing in the same direction, while turbulent flow is characterized by disordered changes in pressure and flow velocity [1].

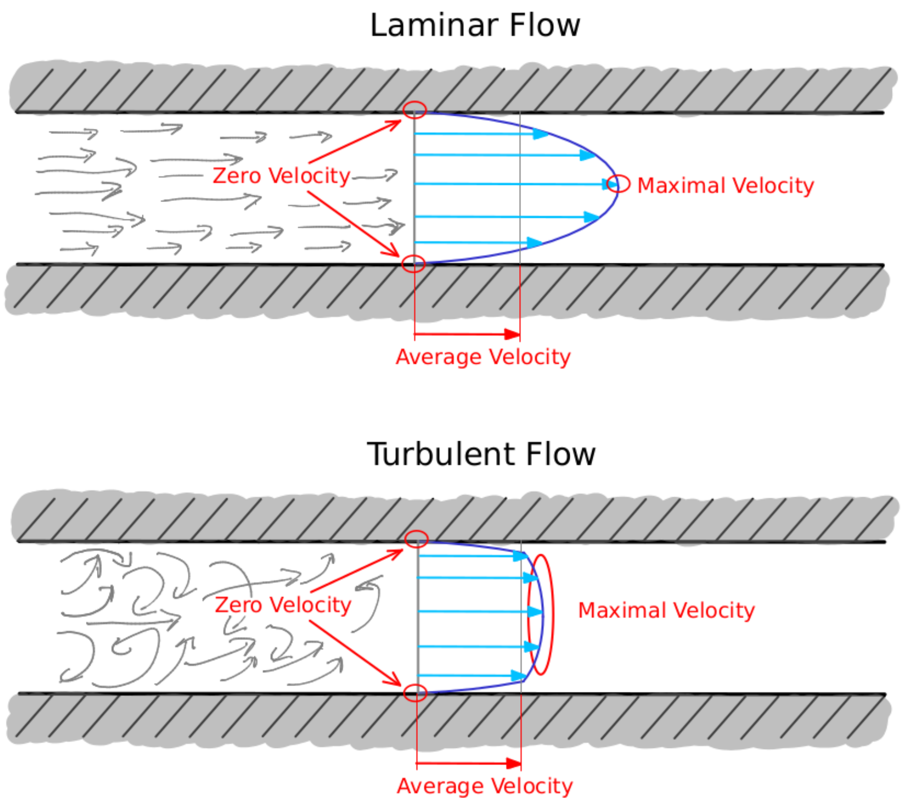

Figure 1: A visualization of laminar and turbulent flow in a channel. Note that the velocity at the edges of the channel is zero and the maximal velocity can be found in the center of the channel. In the case of the turbulent flow, the maximal velocity is spread across a wide area, while the maximal velocity only occurs at a single point in the laminar scenario [2].

1.2 Reynolds Number

The Reynolds number is a dimensionless number the ratio of the velocity and diameter of a flow channel with respect to its viscosity. This number helps to judge whether the flow of a fluid is laminar or turbulent. Typically a fluid is considered to be flowing turbulently when its Reynolds number $Re > 2300$. Reynolds number is given by

$$Re = \frac{\upsilon \cdot l}{\nu} = \frac{\upsilon \cdot l \cdot \rho}{\eta}, \tag{1}$$

where υ is denotes velocity, l denotes the diameter of the channel, ν viscosity, ρ denotes density and η denotes dynamic viscosity [2].

1.3 Continuity Equation

The continuity equation expresses that mass is conserved in a fluid. When net mass is added to a volume element, the mass of the volume element increases. The continuity equation is expressed one dimensionally by

$$\dot{m} = \rho \cdot A \cdot v = \text{constant}, \tag{2}$$

where $\dot{m}$ denotes the change in mass, ρ denotes density, A denotes the cross sectional area that the mass is added or removed from and v denotes velocity [2].

The continuity equation is commonly used to explain why a stream of water flowing out of of a tap gets thinner as it accelerates under the effect of gravity. The velocity of the water increases, while its density remains constant, thus the cross sectional area of the stream must reduce in order to to satisfy equation 2 [3].

1.4 Bernoulli's Principle

Bernoulli's principle states that an increase in a fluids velocity is accompanied with a decrease in pressure or potential energy [4]. A simple form of Bernoulli's equation is given by

$$p_{\text{tot}} = p_{\text{dyn}} + p_{\text{stat}} + g \cdot dz = \rho\frac{v^2}{2} + \int_{p_1}^{p_2} \frac{dp}{\rho} + \rho g z = \text{constant}, \tag{3}$$

where p_{tot} denotes the total pressure, p_{stat} denotes the static pressure, ρ denotes density, v denotes velocity and $g \cdot dz$ denotes the hydrodynamic pressure [2].

1.5 Streamlines

Streamlines are curves that are parallel to the velocity vectors of the fluid [5]. Some (grey) streamlines have been drawn into figure 1 in order to better illustrate the fluid's flow.

2 Objectives

A pitot tube was used to characterize the flow profile in order to determine if the flow was laminar or turbulent and the following three methods for determining flow rate in the wind tunnel from figure 2 are examined:

1. Differential pressure method
2. Mechanical (rotary vane) anemometer
3. Hot-Wire anemometer

The aim of these experiments was to measure the flow velocity and a pitot tube was used to determine the flow profile within the duct. The duct has a diameter of l $= 100$ mm and a honey-comb shaped laminator at the air inlet in order to make sure that the air entering the duct was laminar [6]. The dynamic viscosity of air is $\rho = 18.2 \cdot 10^{-6}$ Pa · s and the maximum (worst case) velocity of the air was $10\ \frac{\text{m}}{\text{s}}$, thus according to

$$Re = \frac{\upsilon \cdot l}{\nu} = \frac{\upsilon \cdot l \cdot \rho}{\eta} = 71044 > 2300 \Rightarrow \text{turbulent,} \tag{4}$$

turbulent flow was to be expected. Due to the honey-comb laminator at the inlet of the duct measurements had to be made (in section 3.3) with the help of a pitot tube in order to determine if this is truly the case.

Figure 2: An image of the wind tunnel that was used in this experiment. The air enters through the honey-comb mesh on the left side of the wind tunnel and it exits through the propeller on the right side of the wind tunnel. The wind tunnel has a sliding hatch and a fixture at the top for placing sensors inside the air stream. This wind tunnel offers three different wind speeds $2.5\ \frac{\text{m}}{\text{s}}$, $5\ \frac{\text{m}}{\text{s}}$ and $10\ \frac{\text{m}}{\text{s}}$. It has a length of 610 mm and a cross sectional diameter of 100 mm. Source: datasheet [6] and lab script [2]..

3 Experiments

3.1 Differential Pressure Method

3.1.1 Introduction

The differential pressure method uses the pressure difference caused by a fluid being forced to flow through an aperture in order to judge the fluid's velocity see figure 3. The pressure difference across the aperture was used in order to determine how fast the fluid was flowing, which in turn allowed us to calculate the mass and volume flow.

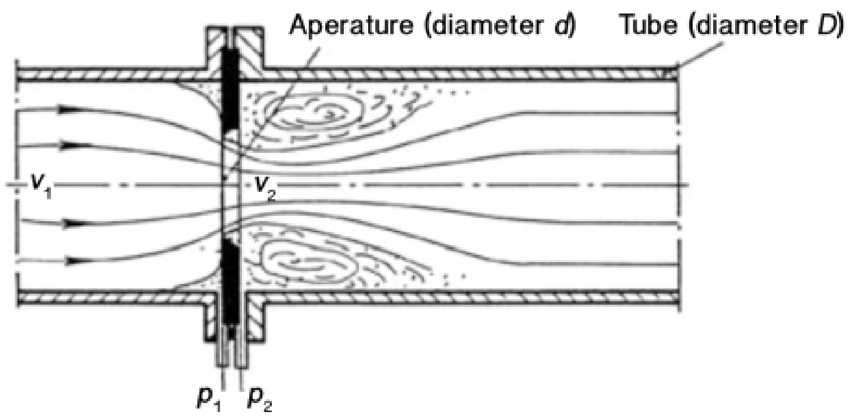

Figure 3: A graphical illustration of how the differential pressure method works. A fluid flows from left to right, when it encounters an aperture. The aperture increases the fluid's velocity (from υ_1 to υ_2) as described by the equation 2, thus causing the fluid to flow out of the aperture more quickly. The momentum from this flow results in a turbulent region around the aperture. This turbulent region does not have any net/resultant flow direction, thus it has a slightly different pressure. The pressure was measured just before and just after the aperture (at p_1 and p_2 and the pressure difference $p_1 - p_2$ was a function of the flow velocity. Source: lab script [2].

3.1.2 Theory

Equation 3 can be written as

$$0 \approx \frac{\upsilon_2^2 - \upsilon_1^2}{2} + \frac{1}{\rho}\int_{p_1}^{p_2} dp \Rightarrow \upsilon_1 \approx \sqrt{\upsilon_2^2 + 2\left(\frac{p_2 - p_1}{\rho}\right)}, \tag{5}$$

when applied to the scenario of figure 3 and equation 2 can be expressed as

$$\dot{m} = \rho \cdot A_1 \cdot \upsilon_1 = \rho \cdot A_2 \cdot \upsilon_2 \tag{6}$$

in the scenario of figure 3, thus

$$\upsilon_2 = \frac{A_1}{A_2}\upsilon_1 \tag{7}$$

holds. Equation 7 can be inserted into equation 5 to produce

$$\upsilon_1 = \sqrt{\frac{2 \cdot (p_2 - p_1)}{\rho \cdot \left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}}. \tag{8}$$

For an incompressible fluid, the rate of volume flow is given by

$$\dot{V} = v_1 \cdot A \tag{9}$$

where A is the cross sectional area of the wind tunnel and v_1 is the velocity of the fluid. A correction factor of

$$\dot{V} = \alpha \cdot \epsilon \cdot v_1 \cdot A = 0.6 \cdot v_1 \cdot A \tag{10}$$

was used in this experiment in order to take into account the geometry (α) of the wind tunnel and the compressibility (ϵ) of the air [2]. By the definition of density, the mass flow is given by

$$\dot{m} = \alpha \cdot \epsilon \cdot v_1 \cdot A \cdot \rho. \tag{11}$$

3.1.3 Experimental Methods

The freescale MPXV7002 pressure sensor [7] was used in order to determine the pressure difference across the aperture. First the pressure sensor had to be calibrated by measuring its analog output voltage[1] when both terminals were exposed to the atmospheric pressure in order to determine if there is any offset (zero setting error) and the drift of the sensor reading was observed. The supply voltage was also measured in order to take into account any errors that might be caused by the voltage source. After having noted the offset (for calibration), the aperture from figure 4 was inserted into the wind tunnel and two rubber tubes were used to attach the pressure sensor to 2 mm holes at the side of the wind tunnel (next to the aperture) as illustrated in figure 3. The pressure across the aperture was measured three times at three different air velocities, namely $2.5\ \frac{\text{m}}{\text{s}}$, $5\ \frac{\text{m}}{\text{s}}$ and $10\ \frac{\text{m}}{\text{s}}$.

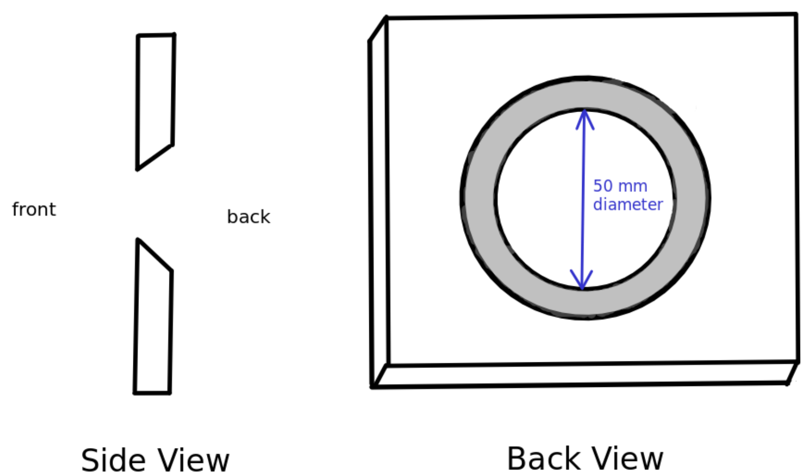

Figure 4: The aperture that was used. Note that the hole in the center has a “conical” profile (orifice) and a cross sectional diameter of 50 mm. The aperture is placed in the wind tunnel such that the fluid flows from the front to the back of the aperture as defined in the image, thus minimizing the effect of air compression.

[1] Note that the multimeter was set to take a moving average of the last 100 samples in order to stabilize the voltage readings (in all voltage measurements), but this has the side-effect that the true variance in the measurements can no longer be determined and the moving average contributes to the voltage drift.

3.1.4 Results and Discussion

First the supply voltage was measured and it was found to be 4.996 V rather than 5.0 V and the voltage adjustment knob moved in discrete steps so it was not possible to get any closer to 5.0 V. The offset voltage was measured and found to be 2.604 V right after turning on the voltage source, but it soon stabilized at 2.5905 V. The voltage at the analog output was measured at all the velocities that the fan velocities that the wind tunnel supports and noted in table 1.

Table 1: **Analog Output Voltage of the MPXV7002 at Various Fan Speeds**

Fan Velocities	$0\ \frac{\text{m}}{\text{s}}$	$2.5\ \frac{\text{m}}{\text{s}}$	$5\ \frac{\text{m}}{\text{s}}$	$10\ \frac{\text{m}}{\text{s}}$
Absolute Voltage: run 1	2595 mV	2604 mV	2622 mV	2690 mV
Absolute Voltage: run 2	2594 mV	2604 mV	2625 mV	2697 mV
Absolute Voltage: run 3	2595 mV	2605 mV	2625 mV	2697 mV
Mean Voltage Difference	2595 mV	2604 mV	2624 mV	2695 mV

The drift in the sensors output voltage right after switching on the device could have multiple causes including a voltage spike due to a slow feedback loop in the voltage source, but it is most probably due to the sensor because the datasheet addresses this problem (warm-up time) in point number 9 under ”operating characteristics”.

The low pass filter at the output of the sensor is rather small in order to ensure that the sensor is highly responsive, this allows the sensor to have a relatively short warm up time of 20 ms [7], but the voltage drift was still visible due to the moving average in the over the last 100 samples in the voltmeter. Unfortunately the sample rate of the voltmeter is unknown, but the low pass effect from the moving average was clearly sufficient to make the warm up time visible. Infact this moving average was probably carefully chosen by the tutors in order to simultaneously ensure that sufficient samples are taken during the warm up time and the drift is still visible. Depending on how much fluid must flow into the sensor in order to create a voltage swing at the output, it is possible that the rubber tubes connecting the sensor to the wind tunnel are too thin, thus resulting in a lower response time due to the mechanical equivalent of a low pass filter, but this is probably not a significant problem because air is not so viscous and not much fluid is needed to stimulate the sensor.

The sensor's datasheet states that the device is ”ratiometric within this specified excitation range” and the datasheet also states that the supply voltage must be $4.75\text{ V} \leq V_S \leq 5.25\text{ V}$ [7], thus it is safe to say that this error can be corrected by scaling up the measurements by a factor of $\frac{5.0\text{ V}}{4.996\text{ V}}$.

The absolute mean voltage at $0\ \frac{\text{m}}{\text{s}}$ is taken from table 1 and subtracted from all the values in the table in order to obtain the measured voltage relative to the mean voltage at rest. This information is illustrated in table 2. The sensors datasheet states that it has a sensitivity of $1.0\ \frac{\text{V}}{\text{kPa}}$, thus the pressure across the sensor is given by

$$\text{Pressure across the sensor} = \frac{\text{Mean Voltage Difference}}{1.0\ \frac{\text{V}}{\text{kPa}} \cdot 1000} = \frac{\text{Mean Voltage Difference}}{1.0\ \frac{\text{V}}{\text{Pa}}}. \tag{12}$$

So the pressure across the sensor is proportional to the voltage swing of the sensors output with a proportionality factor of 1. Thus the only differences between table 2 and table 3 are the units and the dimensions. These voltage and pressure values are plotted against velocity in figure 5.

Table 2: **Change in Analog Output Voltage of the MPXV7002 at Various Fan Speeds**

Fan Velocities	$0\ \frac{m}{s}$	$2.5\ \frac{m}{s}$	$5\ \frac{m}{s}$	$10\ \frac{m}{s}$
Voltage Difference: run 1	0 mV	9 mV	27 mV	95 mV
Voltage Difference: run 2	-1 mV	9 mV	30 mV	102 mV
Voltage Difference: run 3	0 mV	10 mV	30 mV	102 mV
Mean Voltage Difference	0 mV	10 mV	29 mV	100 mV

Table 3: **Change in Pressure Across the MPXV7002 at Various Fan Speeds**

Fan Velocities	$0\ \frac{m}{s}$	$2.5\ \frac{m}{s}$	$5\ \frac{m}{s}$	$10\ \frac{m}{s}$
Pressure Difference: run 1	0 Pa	9 Pa	27 Pa	95 Pa
Pressure Difference: run 2	-1 Pa	9 Pa	30 Pa	102 Pa
Pressure Difference: run 3	0 Pa	10 Pa	30 Pa	102 Pa
Mean Pressure Difference	0 Pa	10 Pa	29 Pa	100 Pa

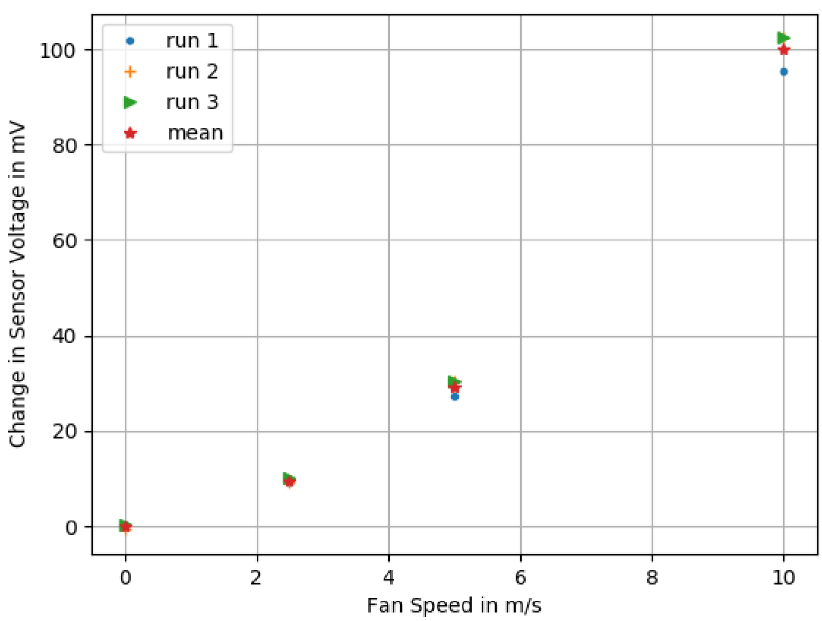

Figure 5: This plot illustrates how the output voltage of the sensor increases as the fan speed increases. Notice that the variance between the measurements increases with fan speed. This could be explained by the filters, because large voltage swings are affected more by low pass filters than small voltage swings, thus the time dependence of the measurements is not the same for all fan speeds. Another interesting thing is that the voltage across the sensor and thus also the pressure across the aperture do not increase linearly. This could be because the kinetic energy of the air increases quadratically with velocity $Ke = \frac{1}{2}mv^2$.

Equation 8 has been used in order to calculate the expected velocity (v_1) assuming that the air is incompressible and the correction factor $\alpha \cdot \epsilon \cdot v_1 = 0.6 \cdot v_1$ was used in order to determine the actual velocity. The calculation results can be seen in table 4 and figure 6, notice that the displayed precision has now been reduced to 2 significant figures because the sensitivity of the sensor is only accurate to 2 significant figures.

Table 4: **Fan Velocity and Calculated Velocities**

Fan Velocities	$0\ \frac{m}{s}$	$2.5\ \frac{m}{s}$	$5\ \frac{m}{s}$	$10\ \frac{m}{s}$
v_1	$0.0\ \frac{m}{s}$	$4.0\ \frac{m}{s}$	$7.0\ \frac{m}{s}$	$12.8\ \frac{m}{s}$
$\alpha \cdot \epsilon \cdot v_1$	$0.0\ \frac{m}{s}$	$2.4\ \frac{m}{s}$	$4.2\ \frac{m}{s}$	$7.7\ \frac{m}{s}$

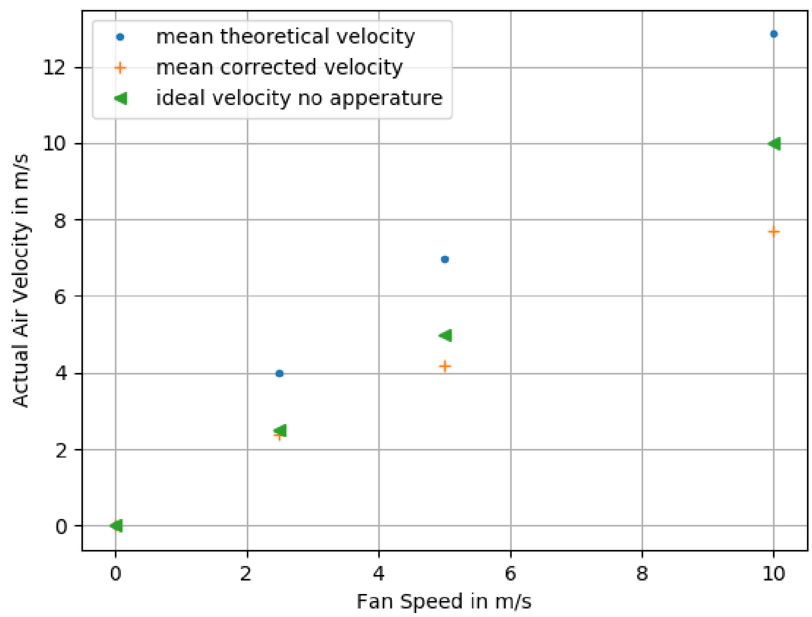

Figure 6: This plot illustrates the calculated velocity with respect to the fan speed. Note that the corrected velocity $0.6 \cdot v_1$ is lower than the fan speed, which is to be expected as the air flow is hindered by the aperture and thus the fan must do more work in order to achieve the expected velocity. Also notice that the corrected velocity doesn't increase linearly, which indicates that the aperture hinders the airflow increasingly as the velocity increases, this could again be related to the fact that the kinetic energy of the air increases quadratically.

Table 5 contains the result of executing equations 10 and equation 11 on the corrected velocity from table 4. There is no need to plot this as the plot is linearly proportional to the plot in figure 6.

Table 5: **Mass and Volume Flow Against Velocity**

Fan Velocities	$0\ \frac{m}{s}$	$2.5\ \frac{m}{s}$	$5\ \frac{m}{s}$	$10\ \frac{m}{s}$
Mean Volume Flow	$0.0\ \frac{dm^3}{s}$	$19.0\ \frac{dm^3}{s}$	$33.0\ \frac{dm^3}{s}$	$61.0\ \frac{dm^3}{s}$
Mean Mass Flow	$0.0\ \frac{g}{s}$	$24.0\ \frac{g}{s}$	$42.0\ \frac{g}{s}$	$78.0\ \frac{g}{s}$

3.1.5 Summary

Well understood obstructions such as apertures create pressure differences in the flow of a fluid, which can be used in order to accurately measure the velocity of the fluid far away from the obstruction. Given the cross sectional area, this information can be used to obtain the volume that is flowing through the channel and the density can be used to obtain the mass of the fluid that is flowing through the channel.

3.2 Mechanical (Rotary Vane) and Hot Wire Anemometer

3.2.1 Introduction

At this stage the aperture is removed from the wind tunnel and two unrelated mechanisms are used in order to measure the air velocity at the center of the wind tunnel. The velocities measured using these two methods are compared with each other and the velocity obtained using the differential pressure method. Any unexpected findings are discussed.

3.2.2 Theory

Two anemometers are used:

1. Rotary vane anemometer.
2. Hot wire anemometer.

The rotary vane anemometer has a small rotary fan blade that spins with an angular velocity that is proportional to the rate at which the fluid is flowing. Note that changes in air velocity don't instantaneously translate into proportional changes in angular velocity, the fan blades have a certain inertia, which yet again has a low pass/averaging effect on the measurement information.

There are two kinds of hot wire anemometers, namely passive and active anemometers. The passive ones simply dissipate a constant amount of power across a wire and the (temperature dependent) resistance of the wire is measured. The wire is cooled as the air flows over it and thus a change in resistance proportional to the rate at which the air flows is measured.

An active anemometer uses a feedback loop in order to adjust the power such that the wires temperature remains constant, this has the advantage that the resistance doesn't become too small to measure, but this method is limited by the maximum power that the feedback loop is able to provide and the responsiveness of the feedback loop.

3.2.3 Experimental Methods

In this experiment it is important to place the anemometers at the center of the wind tunnel such that the maximum flow can be measured regardless of whether the flow is laminar or turbulent. The anemometers are inserted into the wind tunnel through the hatch at the top one at a time. The orientation and position of the anemometer is adjusted while the wind tunnel is operational in order to find the point at which the flow rate is maximal. Note that the hot wire anemometer has a notch indicating the direction, the notch must be facing the away from the fan/towards the honey comb structure.

Once the maximal point has been found the mean flow velocity is measured over ten seconds. This was repeated once for each velocity and for each probe and the measurement results are evaluated taking into account the pressure and geometry dependent correction factors.

The hot wire anemometer in this experiment was a passive anemometer, thus the precision of the measurements depends on the velocity of the air.

3.2.4 Results and Discussion

On the time of the experiment $(2018-12-06, 17:00$ UTC) there was an air pressure of $p \approx 102.2$ kPa at the weather station of our University [8]. Probe geometry dependent correction factors α and a table that maps the air pressure to an appropriate correction factor ϵ were provided.

The highest pressure in the provided table is 101.3 kPa though, thus the data from the table must be extrapolated in order to obtain a correction factor for 102.2 kPa. The gradient is calculated using

$$\text{gradient} = \frac{\epsilon_{\text{data max}} - \epsilon_{\text{data second last}}}{p_{\text{data max}} - p_{\text{data second last}}} = \frac{1-1.006}{101.3-100.7}\,\frac{1}{\text{kPa}} = \frac{-0.006}{0.6}\,\frac{1}{\text{kPa}} = -0.01\,\frac{1}{\text{kPa}}, \tag{13}$$

and multiplied with the local pressure

$$\epsilon_{local} = (p_{\text{local}} - p_{\text{data max}}) \cdot \text{gradient} + 1 = \left((102.2-101.3)\ \text{kPa} \cdot (-0.01)\,\frac{1}{\text{kPa}}\right) + 1 = 0.991 \tag{14}$$

to obtain a local correction factor. The geometry dependent factor α is 1.00 for the rotary vane anemometer and 0.97 for the hot wire anemometer according to the script [2]. The measurement results can be found in figure 7 and table 6. As already suggested in figure 6, the measured velocities without an aperture are higher than the velocities that were measured using the differential pressure method because the air velocity $\alpha\epsilon v_1$ is lower when the aperture is obstructing the air flow in the wind tunnel. The mass and volume flow are again proportional to the velocity.

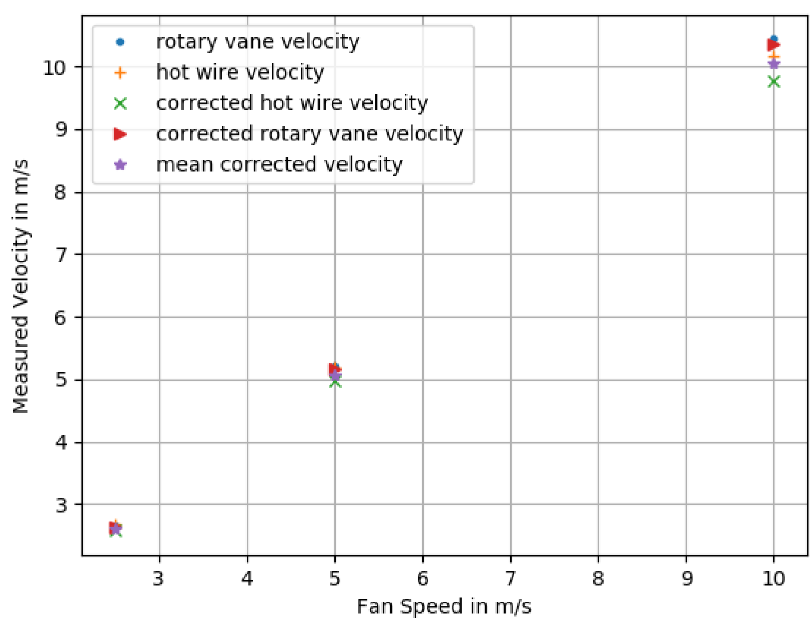

Figure 7: This figure illustrates the measured velocity data, the corrected velocity data and the mean corrected velocity data. Notice that the scatter across various technologies is rather low, thus indicating that the velocity measurements are reliable with respect to systematic errors.

3.2.5 Summary

Clearly both anemometers obstruct the airflow in the wind tunnel less than the aperture and thus there are higher flow velocities in the wind tunnel.

Table 6: **Measured Velocity Against Fan Speed**

Fan Speed	$2.5\ \frac{\text{m}}{\text{s}}$	$5\ \frac{\text{m}}{\text{s}}$	$10\ \frac{\text{m}}{\text{s}}$
Rotary Vane Velocity	$2.6\ \frac{\text{m}}{\text{s}}$	$5.2\ \frac{\text{m}}{\text{s}}$	$10.4\ \frac{\text{m}}{\text{s}}$
Hot Wire Velocity	$2.7\ \frac{\text{m}}{\text{s}}$	$5.2\ \frac{\text{m}}{\text{s}}$	$10.2\ \frac{\text{m}}{\text{s}}$
Corrected Hot Wire Velocity	$2.6\ \frac{\text{m}}{\text{s}}$	$5.0\ \frac{\text{m}}{\text{s}}$	$9.8\ \frac{\text{m}}{\text{s}}$
Corrected Rotary Vane Velocity	$2.6\ \frac{\text{m}}{\text{s}}$	$5.2\ \frac{\text{m}}{\text{s}}$	$10.3\ \frac{\text{m}}{\text{s}}$
Mean Corrected Velocity	$2.6\ \frac{\text{m}}{\text{s}}$	$5.1\ \frac{\text{m}}{\text{s}}$	$10.1\ \frac{\text{m}}{\text{s}}$

3.3 Pitot Tube

3.3.1 Introduction and Theory

Dynamic pressure is the pressure due to the flow of a fluid, this can be measured with a pitot tube as illustrated in figure 8. The goal of this experiment is to determine the flow profile of the wind tunnel at $5 \frac{\mathsf{m}}{\mathsf{s}}$ and $10 \frac{\mathsf{m}}{\mathsf{s}}$. As illustrated in figure 1, the shape of the flow profile determines if the flow in the wind tunnel is laminar or turbulent.

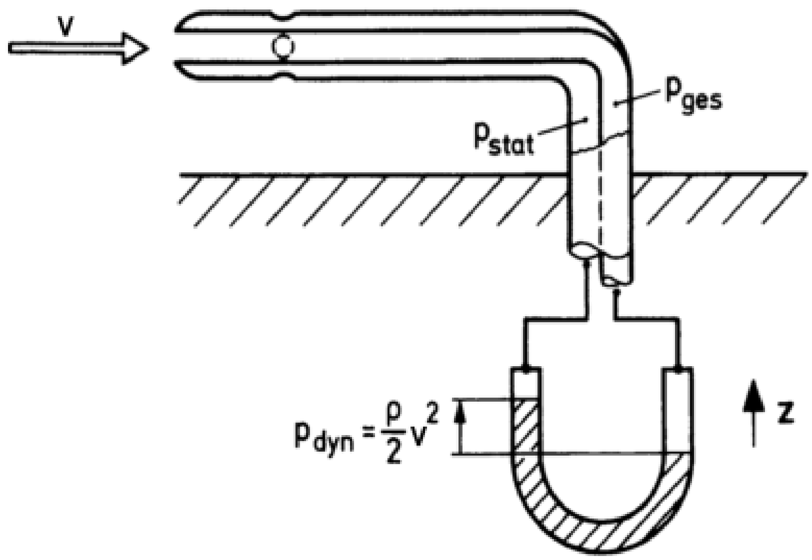

Figure 8: This figure illustrates how a pitot tube works. The dynamic and static pressure enter the front of the pitot tube, but the static pressure is canceled by the static pressure that enters the pitot tube from the side, so the pressure difference between the two sections of the pitot tube is the dynamic pressure. Source: [2].

As illustrated in figure 8, the dynamic pressure is given by

$$p_{\mathsf{dyn}} = \frac{\rho}{2} v^2. \tag{15}$$

3.3.2 Experimental Methods

The pitot tube is combined with the MPVXV6002DP pressure sensor from freescale semiconductor to measure the dynamic pressure at $5 \frac{\mathsf{m}}{\mathsf{s}}$ and $10 \frac{\mathsf{m}}{\mathsf{s}}$. Ten samples are taken at various heights for each velocity in order to create a pressure profile inside the wind tunnel. Then the whole process is repeated with the aperture inside and the pressures are compared.

3.3.3 Results and Discussion

According to equation , the pressure across the sensor in Pa has the same value as the sensors voltage swing in mV, thus table 7 and table 8 have the same values. When visualized in figure 9 one can clearly see that the pressure profile resembles the turbulent behaviour from figure 1 at $10 \frac{\mathsf{m}}{\mathsf{s}}$ without an aperture. The pressure profile at $5 \frac{\mathsf{m}}{\mathsf{s}}$ also looks turbulent, but the variance is too high to make a conclusive statement.

Anyhow it is not correct to compare pressures with velocities, equation 15 must be rearranged

$$v = \sqrt{p_{\text{dyn}} \cdot \frac{2}{\rho}} \tag{16}$$

and applied to the data in order to obtain the velocity. The result of applying this formula to the data in table 8 can be found in table 9 and figure 10.

Table 7: **Measured Voltage of MPVXV6002DP Against Height No Aperture**

height	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
10 $\frac{m}{s}$ fan	43 mV	73 mV	70 mV	70 mV	70 mV	69 mV	70 mV	70 mV	68 mV	53
5 $\frac{m}{s}$ fan	14 mV	18 mV	19 mV	17 mV	18 mV	18 mV	18 mV	17 mV	14 mV	13

Table 8: **Measured Voltage of MPVXV6002DP Against Height No Apparatus**

height	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
10 $\frac{m}{s}$ fan	43 Pa	73 Pa	70 Pa	70 Pa	70 Pa	69 Pa	70 Pa	70 Pa	68 Pa	53
5 $\frac{m}{s}$ fan	14 Pa	18 Pa	19 Pa	17 Pa	18 Pa	18 Pa	18 Pa	17 Pa	14 Pa	13

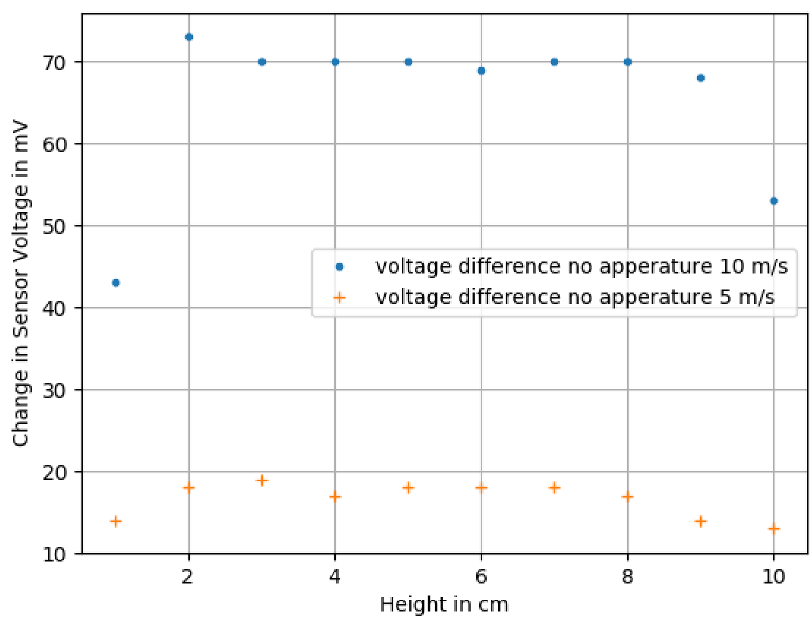

Figure 9: A plot of the measured voltage at the output of the pressure sensor against the height of the pitot tube in the wind tunnel.

Table 9: **Measured Velocity Against Height No Aperture**

height	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
10 $\frac{m}{s}$ fan	8 $\frac{m}{s}$	11 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	10 $\frac{m}{s}$	9 $\frac{m}{s}$
5 $\frac{m}{s}$ fan	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	5 $\frac{m}{s}$	4 $\frac{m}{s}$

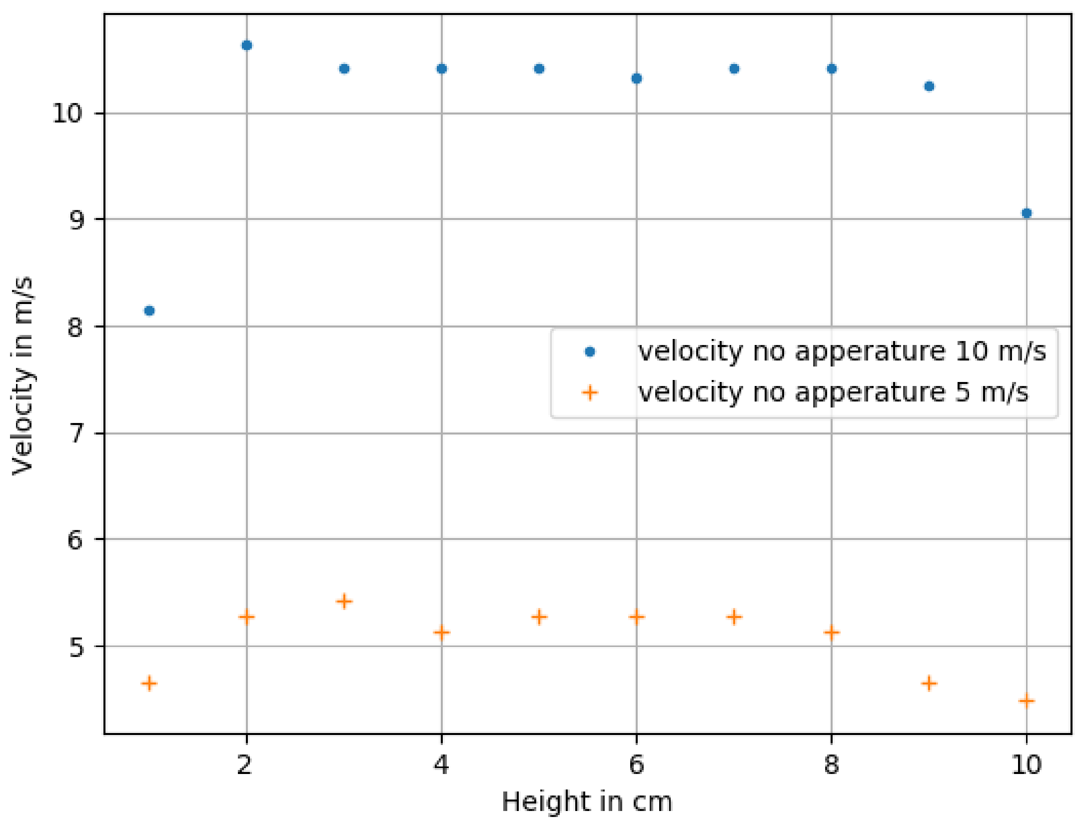

Figure 10: This figure illustrates the flow velocity with respect to the height of the flow sensor, derived from pressure measurements that were made with a pitot tube. Even though some data points are significantly higher than the fan speed, the mean value of the data points is closer to the desired velocity ($10\ \frac{\text{m}}{\text{s}}$ and $5\ \frac{\text{m}}{\text{s}}$), this resembles the patterns in figure 1. Note that even the stream lines near the edge of the wind tunnel have non zero velocities, which is a strong indicator that the air flow is turbulent.

The pressure measurement results in table 10 and figure 11 were taken from Kaaviya Vanaraj's protocol. The velocities in table 11 and figure 12 are also derived from Kaaviya's voltage/pressure measurements [9]. This was suggested by the tutor due to a lack of time to complete the measurements during the lab.

Upon comparing figure 10 with figure 12, it is clear to see that the air flow is more laminar when an aperture is used, possibly because the "jet" of air is in contact with a low pressure region rather than the solid wall of the wind tunnel. There is an increased flow near the top of the wind tunnel, possibly because the of stream lines that flow in or out of the opening that is used to insert the pitot tube into the wind tunnel.

Table 10: **Measured Pressure Against Height With Aperture [9]**

height	0 cm	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
10 $\frac{m}{s}$ fan	7 Pa	8 Pa	7 Pa	42 Pa	107 Pa	106 Pa	107 Pa	62 Pa	0 Pa	21 Pa	32 Pa
5 $\frac{m}{s}$ fan	3 Pa	4 Pa	2 Pa	26 Pa	30 Pa	29 Pa	29 Pa	8 Pa	3 Pa	4 Pa	8 Pa

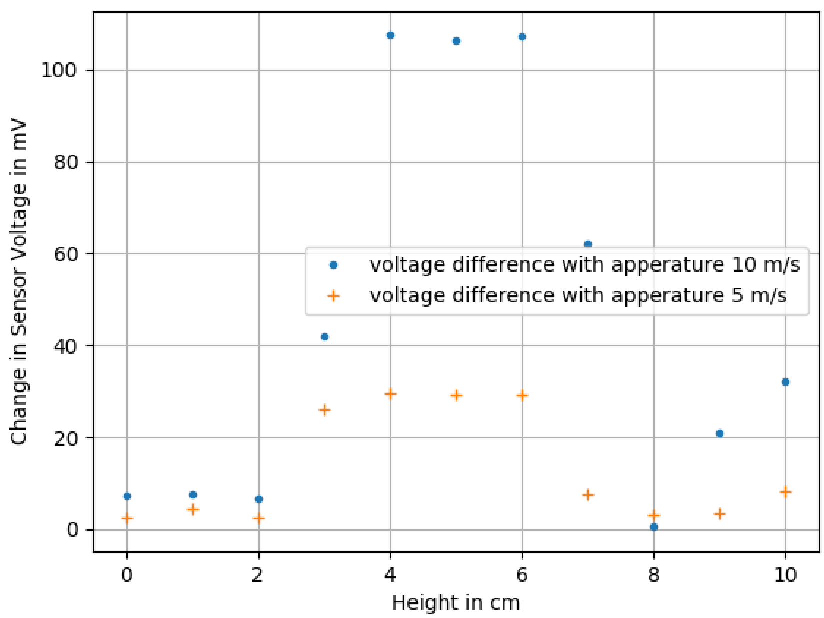

Figure 11: This figure illustrates the voltage swing at the output of the pressure sensor with respect to height at $10\ \frac{m}{s}$ and $5\ \frac{m}{s}$, when the aperture is installed. The effect of the aperture can be seen clearly when comparing these results with the results in figure 9. The aperture causes an increased pressure at the center of the wind tunnel and a drop in pressure along the sides. Interestingly the pressure rises again at the upper edge of the wind tunnel, this could be due to turbulence. [9]

Table 11: **Measured Velocity Against Height With Aperture [9]**

height	0 cm	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm	9 cm	10 cm
10 $\frac{m}{s}$ fan	3 Pa	3 Pa	3 Pa	8 Pa	13 Pa	13 Pa	13 Pa	10 Pa	1 Pa	6 Pa	7 Pa
5 $\frac{m}{s}$ fan	2 Pa	3 Pa	2 Pa	6 Pa	7 Pa	7 Pa	7 Pa	3 Pa	2 Pa	2 Pa	4 Pa

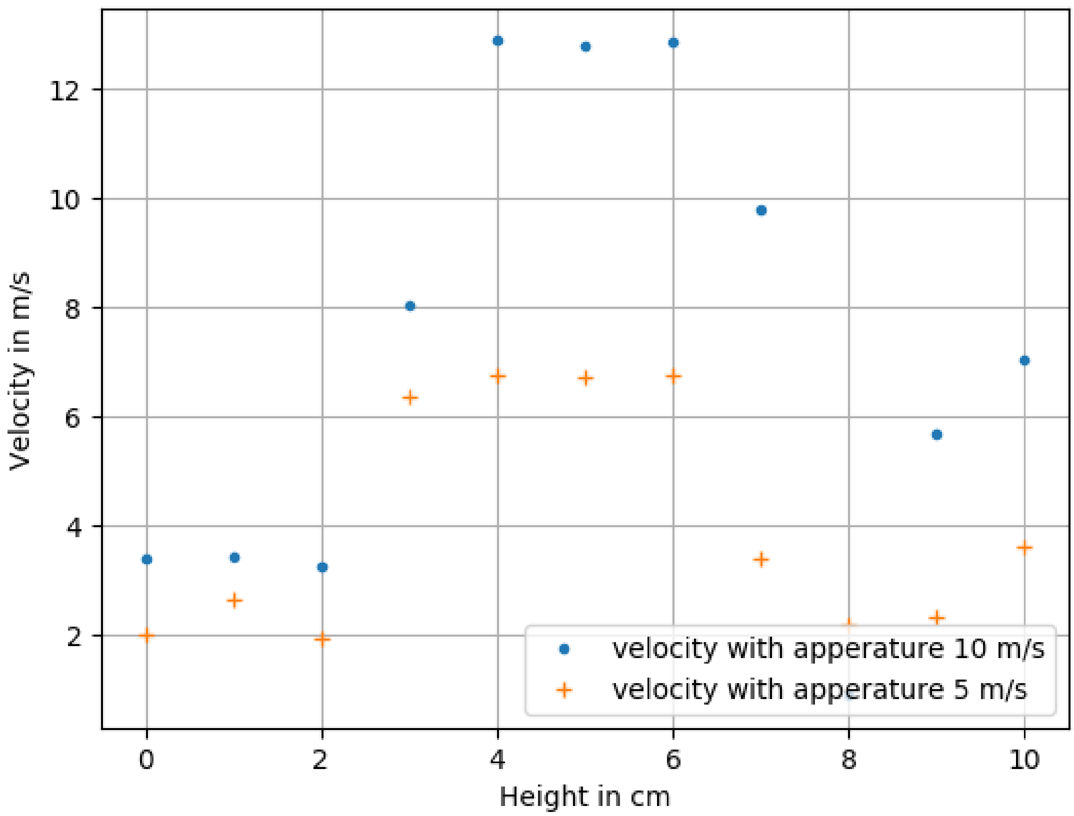

Figure 12: This figure illustrates the air velocity in the wind tunnel with the aperture installed with respect to height at $10\ \frac{\mathrm{m}}{\mathrm{s}}$ and $5\ \frac{\mathrm{m}}{\mathrm{s}}$. The effect of the aperture can be seen clearly when comparing these results with the results in figure 10. The aperture causes an increased velocity at the center of the wind tunnel and a drop in velocity along the sides. Interestingly the velocity rises again at the upper edge of the wind tunnel, this could be due to turbulence [9].

3.3.4 Summary

The pitot tube can be used to measure the dynamic pressure and air velocity, but it requires a very precise pressure sensor and a stable mechanism for holding the sensor. Perhaps the motion of the experimenters hand is the most significant source of error in this experiment. Upon comparing the velocity profile with and without the aperture, the flow in the wind tunnel with an aperture seems more laminar. This could be deceiving because the measurement is taken close to the aperture and the aperture ensures that there is no net velocity near the walls of the wind tunnel regardless of how turbulent the air flow is.

All in all the measurement results agree with equation 4, which states that the air flow is turbulent.

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