Fluid Mechanics

Laboratory tasks specially developed by Non-conventional Ventilatory TEAM (NVT) FBME CTU for education at UHS and ITC in Cambodia in order to increase knowledge in the field of biomedical engineering:

1. Pneumatic resistance R - properties and parallel to electrical resistance
2. Flow resistance - Reynolds number, Hagen-Pouissel equation
3. Obstructive flow measurement
4. Other types of flow meters
5. Compliance
6. Automatic measurement of a compliance
7. Acoustic weight, Resonant circuits
8. Electro Acoustic analogies
9. Bernoulli equations, Losses in the pipeline
10. Static, stagnation a dynamic pressure - Pitot tube

Content

1. List of quantities

Quantity	Symbol	Unit
Volume flow rate	*Q* *q*	m^3 /s L/s L/min
Pressure	*P*	Pa cmH_2O
Volume	*V*	l L m^3
Voltage	*U*	V
Resistance	*Rp* *R* r_a	Pa・ s / m^3 Ω
Current	*I*	A
Density	*r*	kg/ m^3
Diameter	*D*	m
Radius	*r* *Rt*	m
Dynamic viscosity	η μ	(Pa・ s) / (N・ s/ m^3)
Velocity	*v* *u*	m/s
Length	*L* *l*	m
Velocity of sound	c_0	m/s
Temperature	*T* *t*	℃
Compliance	*C* c_a	m^3 /Pa L/kPa L/cmH2O m^4 ・ s^2 /kg
Cross-section area	*S*	m^2
Acoustic weight	m_a	kPa ・ s^2 / l
Height	*h*	m
Stagnation/ total pressure	P_t	Pa cmH_2O
Static pressure	P_s	Pa cmH_2O
Standard acceleration due to gravity	*g*	m/ s^2

2. PNEHYKUR

Pnehykur is a pneumatic and hydraulic kit specially developed for teaching Fluid Mechanics and Plumbing. The complete instructions for use are in attachment: *Pnehykur manual*.

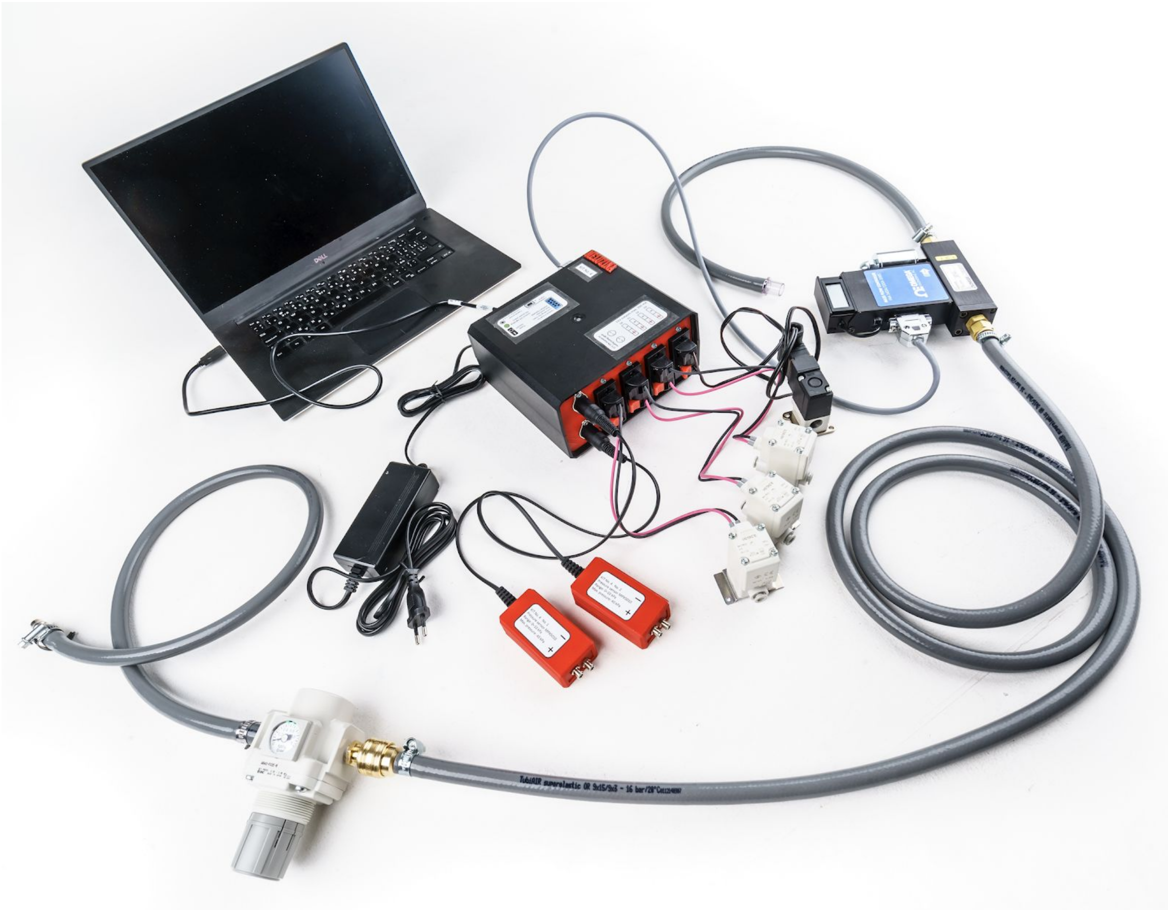

Fig. 1: Completely connected Pnehykur kit with OMEGA FMA5400 controller

2.1. Every Pnehykur kit contains:

1. Meluzína
2. 2x pressure sensor
3. Connector between Meluzína and OMEGA FMA5400 controller
4. Connector between Meluzína and PC
5. Power supply 12V
6. 3x 2/2 electromagnetic solenoid
7. 1x Pressure reducing valve
8. 1x 3/2 electromagnetic solenoid
9. Connector between air distribution system and pressure reducing valve
10. 2x connector between pressure sensor and other sampling point
11. 3x Manometer
12. 1x Pressure relief valve
13. 2x muffler
14. 3x straight internal fittings
15. 3x straight external fittings
16. 4x T-connector
17. 3x straight connector
18. 2x Y-connector
19. 1x X-connector
20. 3x throttle valve
21. 1x self closing straight fitting
22. 2x ball valve
23. 1x T-connector with internal fittings

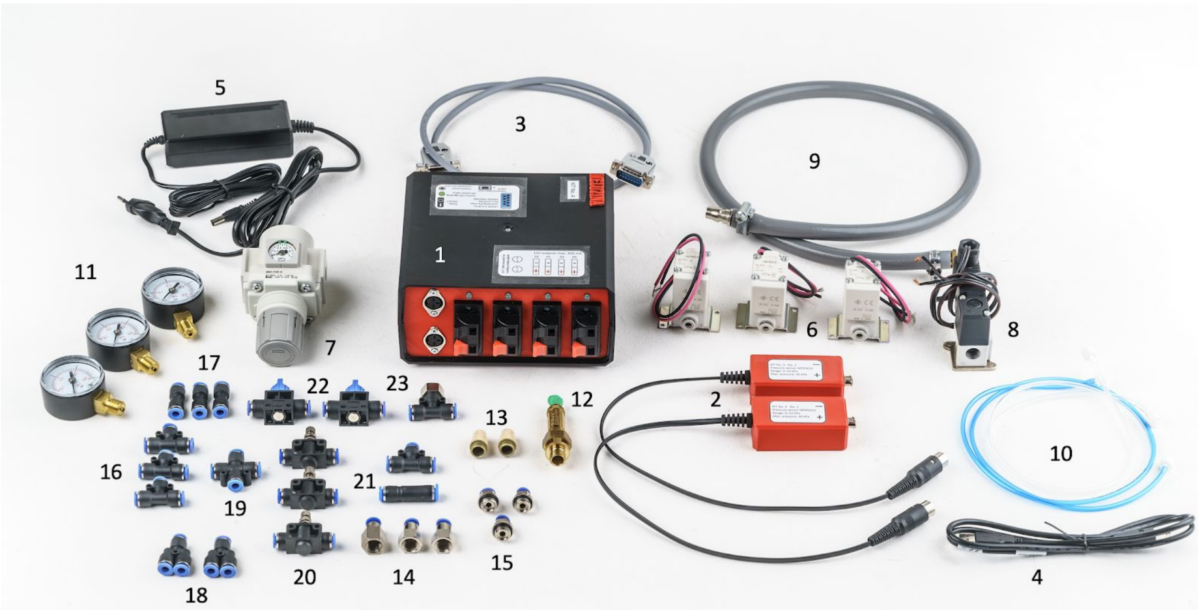

Fig. 2: Complete kit of Pnehykur

3. Software for the laboratory tasks

To be able to complete the following laboratory tasks, you will need to use the prepared software. For more information about the software, see the *Pnehykur manual*.

The needed software for laboratory tasks:

1. OMEGA control
2. Manual P–Q measurement / Automatic P–Q measurement
3. Manual P–Q measurement / Automatic P–Q measurement
4. Valve cycling
5. Pressure measurement
6. Automatic measurement of compliance
7. Oscillometer
8. Valve cycling
9. ---
10. ---

4. Fluid mechanics laboratory tasks

4.1 Pneumatic resistance R - properties and parallel to electrical resistance

Goals

a) The aim of this exercise is to acquaint students with the application of pneumatic resistance in acoustic systems.
b) Point out the similarities and differences between resistances in electrical and acoustic systems.
c) To acquaint students with individual components that are used in healthcare, their properties and their pressure-flow characteristics.

Theory

There are two basic quantities in electrical systems: voltage ***U*** and current ***I***. The relationship between these quantities measured on a lossy electrical conductor is described by Ohm's law. This law states that the voltage at the ends of a conductor is proportional to the current flowing through the conductor. The proportionality constant is resistance ***R***, as shown in Equation 1.

$$U = R \cdot I \tag{1}$$

The electric current is a longitudinal quantity that flows from one end of the conductor to the other. Voltage is a transverse quantity, measured at each end of the conductor. In order for current to flow through a conductor, the voltage at the beginning of the conductor must be different from that at the end.

Analogously to quantities in electrical systems, we can define quantities in acoustic systems. At both ends of the tube we can define the pressure ***p*** of the fluid, which is a transverse quantity, analogous to the voltages U in electrical systems. In the case of a tube, the longitudinal quantity is the flow rate ***q***. The relationship between the pressure ***p*** and the flow rate ***q*** is analogous to Ohm's law, since the pressure drop across the tube is proportional to the flow rate. The proportionality constant is a quantity analogous to the electrical resistance ***R***, which in fluidics is called the flow resistance ***Rp***. The flow resistance (analogous to the electrical resistance ***R***) is greater the longer the tube and the smaller its internal cross-section. The flow resistance ***Rp*** indicates how large the volume flow ***q*** of gas through the system is due to the application of the pressure difference Δp. This dependence can be expressed by Equation 2 assuming **laminar flow**.

$$\Delta p = Rp \cdot q \qquad (2)$$

(You will learn more about the issue of flow resistances in laboratory exercise 2: Flow resistance)

The difference in static pressures measured at different parts of the tube is generally dependent on the distance of these points downstream, the cross section of the tube downstream of the normal vector to the flow vector, tube curvature, tube smoothness, flow character, dynamic fluid viscosity, fluid density and fluid volume flow (analogy of wire resistance in electrical systems). In the case of the distance between the static pressure measuring points, their difference is directly proportional to the distance. The greater the distance in the flow direction, the longer the fluid molecules are exposed to friction, the greater the energy losses of the fluid molecules, the greater the difference in static pressures.

Experiments

1. Electrical resistance x Pneumatic resistance

a) Measure the resistance of the metal wire with a multimeter.
b) Make a knot on this wire and measure the resistance again.

Fig. 3: Digital multimeter and resistive wires

c) Do the same for the hose. You have got at your disposal the Omega FMA5400 flow controller and the Testo 512 pressure gauge, hoses, medical couplings.

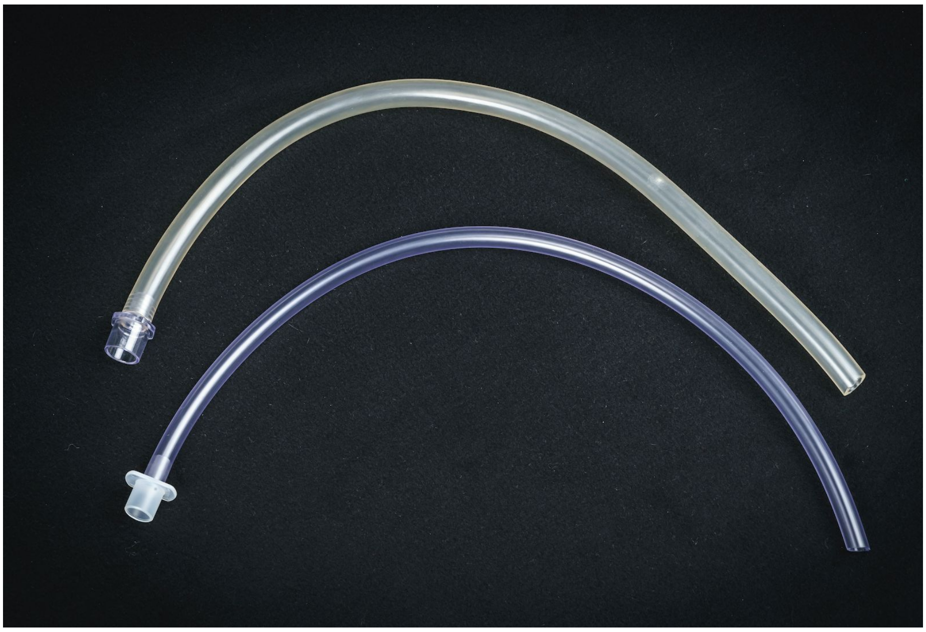

Fig. 4: Hoses of two different diameters

d) Connect the computer to Meluzína and connect Omega FMA5400 to Meluzína with connectors included in Pnehykur kit.
e) Connect the hose from Omega FMA5400 to a pressure reducing valve (**max. 2 bar**).
f) Connect the apparatus to the air distribution system.
g) Set the flow rate on the computer.
h) At a flow rate of 30 l/min and 60 l/min, measure the pressure drop across the hose (D1 = 10 mm and D2 = 5 mm) with a Testo 512 pressure gauge. Measure the pressure in front of the hose with the inlet + and the inlet to the pressure gauge - leave free in the atmosphere.
i) Calculate the resistance of the tubes based on knowledge of the flow and pressure change.
j) Make a knot on these hoses and measure the pressure drop again at the flow rates according to point d) and calculate the resistance.
k) Compare hose resistances with and without a knot.

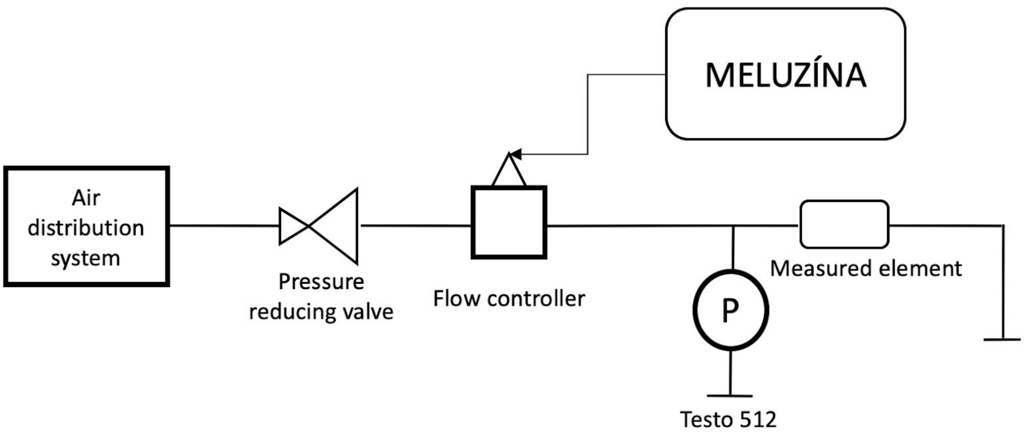

Fig. 5: A scheme of the apparatus for the measurement

2. Pressure-flow characteristics of a hose

a) Measure the pressure in front of the hoses (D1 = 10 mm, D2 = 5 mm) in the range of 10–100 l/min.

b) Plot the values in a graph and display its P-Q characteristics and R-Q characteristics.

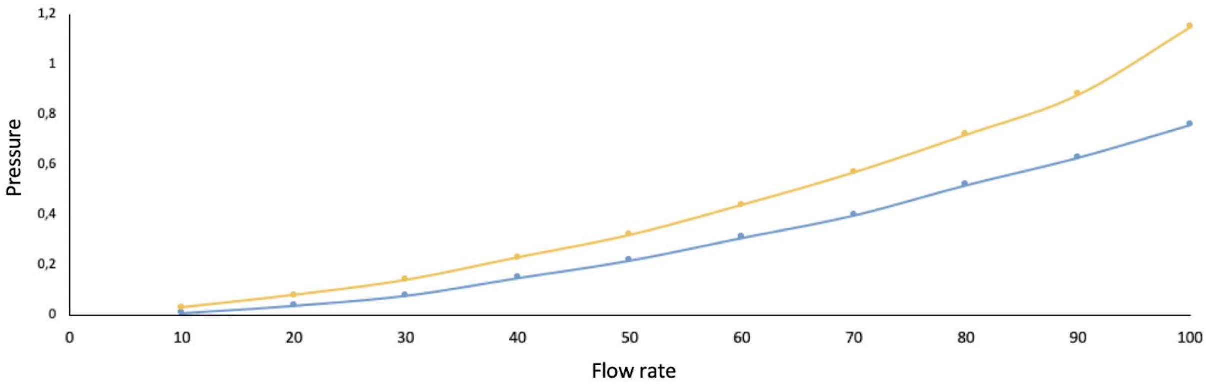

Fig. 6: An example of expected results

3. Pressure-flow characteristics of a given element

a) Measure the P-Q characteristic of the element in the range 10 l/min – 100 l/min.

b) Determine the resistance of the element depending on the flow.

c) Interpolate the curve with the trend and determine if the resistance is constant.

Fig. 7: An element with a typical resistance

4. Pressure-flow characteristics of a medical equipment

a) Measure the P-Q characteristics of the antibacterial filter, endotracheal cannula and D-lite spirometric sensor in the range of 10–100 l/min.
b) Measure the pressure using Testo 512 in front of the medical equipment with the inlet + and the inlet to the pressure gauge - leave free in the atmosphere.
c) Verify that HME antibacterial filter has similar P-Q characteristics to a given element with capillaries and D-lite spirometric sensor has similar characteristics to a hose (sampling points has to be closed on D-lite).

Fig. 8: Endotracheal cannulas

Fig. 9: HME filters

Fig. 10: Spirometric sensor D-lite

Equipment

Pnehykur kit
Omega FMA5400
Testo 512 pressure gauge
Medical couplings
Resistance wire
Multimeter
Hoses (D1 = 5 mm and D2 = 10 mm)
Endotracheal tube
HME antibacterial filter
D-lite spirometric sensor
Hoses

Questions

Why do we measure the change in pressure on the pressure gauge from the atmosphere in this laboratory task and not directly behind the element?

Reference

LUMB, A. B. Nunn's applied respiratory physiology. 7th ed. Oxford: ButterworthHeinemann, 2010. xii, 556 p. ISBN 978-0702029967.

4.2 Flow resistance - Reynolds number, Hagen-Pouissel equation

Goals

a) To understand the meaning of the term flow resistance in pneumatics.
b) To understand the influence of radius and length of a tube on its resistance.
c) To understand the difference in construction of linear and quadratic resistors and consequently to check their functioning.

Theory

The interrelation of the pressure drop between the beginning and the end of a pneumatic system and gas flow rate in the system can be described by a parameter called flow resistance or simply resistance. The flow resistance ***R*** (Pa·s/m^3) indicates how large volume flow rate ***q*** (m^3/s) of gas in a system arises due to the application of pressure difference ***Δp*** (Pa). This relation could be formulated as:

$$R = \frac{\Delta p}{q}. \qquad (1)$$

This formula for flow resistance is a pneumatic analogy for electric resistance, where the pressure and volume flow rate are replaced by voltage and electric current, respectively. In electrical circuits, we usually think over the constant value of resistance, independent of the current. On the other hand, the situation in pneumatic systems is more complicated: The value of pneumatic resistance is often affected by the gas flow rate. That complicates the system description and also creation of accurate realizations of pneumatic resistances – the resistors.

The mutual relation between the pressure drop ***Δp*** and the gas volume flow rate ***q*** depends upon the nature of the flow in the system, and it could be described by a power function in a common form

$$\Delta p = a \cdot q^b, \qquad (2)$$

where ***a*** and ***b*** are constants characterizing the pneumatic resistance.

If the gas flow is laminar, the value of the exponent ***b*** equals 1. Then the pneumatic resistance of the system does not depend on the flow rate and for a resistor with circular cross section it is determined by the formula:

$$R = a = \frac{8 \cdot L \cdot \eta}{\pi \cdot r^4}, \tag{3}$$

where ***L*** (m) is the length of the resistor, η (Pa·s) is gas dynamic viscosity and ***r*** (m) is the radius of the resistor.

In a circular cross-sectioned tube, during the turbulent flow, the value of b approximately equals 2. Therefore, the value of resistance ***R***, defined by (1), is itself directly proportional to flow rate. Then, a circle-sectioned resistor has its resistance indirectly proportional to the fifth power of its radius.

Often, the form of flow is neither laminar nor clearly turbulent. In this case we speak about a transient flow. Then the value of the exponent b is somewhere between 1 and 2. For example, in the case of the respiratory system of the normal human it was reported b = 1.3.

As the most common practical realization of flow resistance, a so-called parabolic resistor is used, where b is near to 2. The resistor is realized by a local constriction of a tube profile, made by a thin barrier with a small hole in the middle. The advantage of the parabolic resistor is especially its simple construction, cleansing, and a low cost.

The construction of a linear resistor with constant value of flow resistance for used flows is more complicated and expensive. The flow resistors are usually made from a bundle of glass capillaries, long enough and situated in a wide tube. The number of capillaries and their radius determine the maximal flow rate, when the flow is still laminar, e.g., when the value of the Reynolds's number for a single capillary is less than 2300. The Reynolds number is calculated as

$$\mathrm{Re} = \frac{\rho \cdot \bar{v} \cdot d}{\eta}, \tag{4}$$

where ρ (kg/m^3) is gas density, ***d*** (m) means the capillary radius, η (Pa·s) means dynamic viscosity of gas, and ***v*** (m/s) symbolizes the mean gas speed which could be calculated as

$$\bar{v} = \frac{Q/n}{\pi r^2}. \tag{5}$$

Q (m^3/s) is the total volume flow rate of the gas through the resistor, and ***n*** symbolizes the number of capillaries.

Note: The volume flow rate is usually not given in m^3/s, but rather in L/s or L/min in respiratory care. We will respect this fact in our further calculations. For the aforementioned respiratory system of a healthy adult human the resistance may be expressed as

$$\Delta p = 0{,}24 \cdot q^{1,3} \tag{6}$$

for the pressure drop calculated in kPa and for volume flow rate stated in l/s.

Experiments

1. Influence of tube length and diameter on resistance

a) Connect the sampling points of one of the tubes to the rail with three-way valves.
b) Connect the pressure sensor MPX5010 to the three-way valve rail with the positive port +. Port - leave freely into the atmosphere.
c) Connect the Omega FMA5400 to a pressure reducing valve (**max. 2 bar**).
d) Connect the apparatus to the air distribution system.
e) Use Meluzína to set the flow rate on the OMEGA FMA 5400 flow controller.
f) Set the flow rate to 50 l/min and measure the pressure change at each of the sampling points separately for both hoses.
g) **Let only one three-way valve open at one time**.
h) Proceed in the same way for flow 80 l/min.
i) Determine how the resistance depends on the length and diameter of the hose for both hoses.
j) Calculate the resistance at one chosen sampling point of both tubes based on the knowledge of flow and pressure.
k) Compare the calculated resistance with a theoretical resistance based on the equation 3. (If the values are not similar, try to calculate the Reynolds number based on the equation 4 and read the theory one more time).

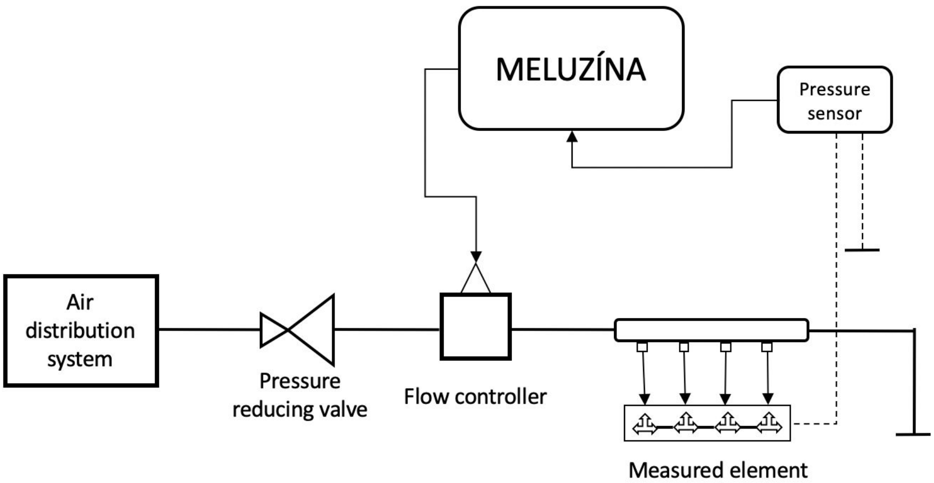

Fig. 11: A scheme of the apparatus for the measurement

Dynamic air viscosity: $\boldsymbol{\mu}$ = 1.84 · 10-5 N · s · m^{-2}

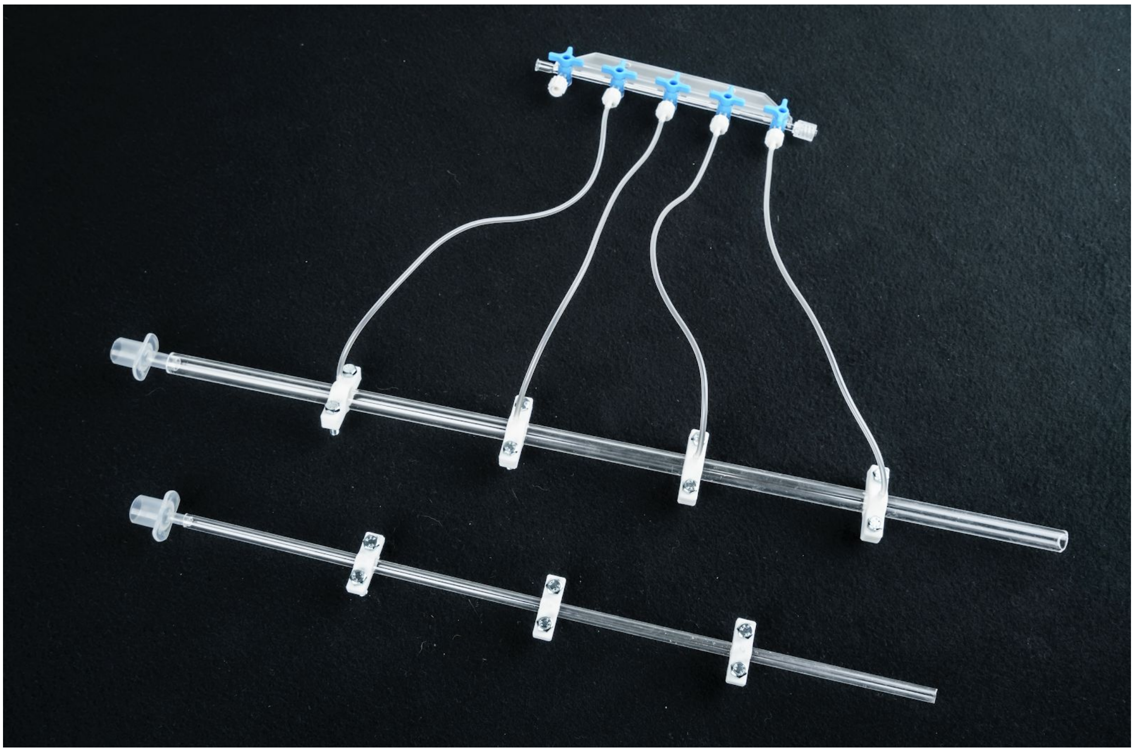

Fig. 12: Typical connecting to the tubes

2. Linear resistance

a) Measure the P-Q characteristic of a given linear resistance in the range of 10–100 l/min with step 5 l/min. Use the pressure sensor MPX5010 and the OMEGA FMA 5400 flow controller for the measurement (you can use the data from task No. 1).

b) Measure the size of the capillaries and calculate the Reynolds number according to Equation 4. (D = ~ 0.001 m, L = 0.125 m and number of capillaries = ~ 160)

c) Determine from which flow rate the element would not have a linear pressure-flow characteristic according to Reynolds number.

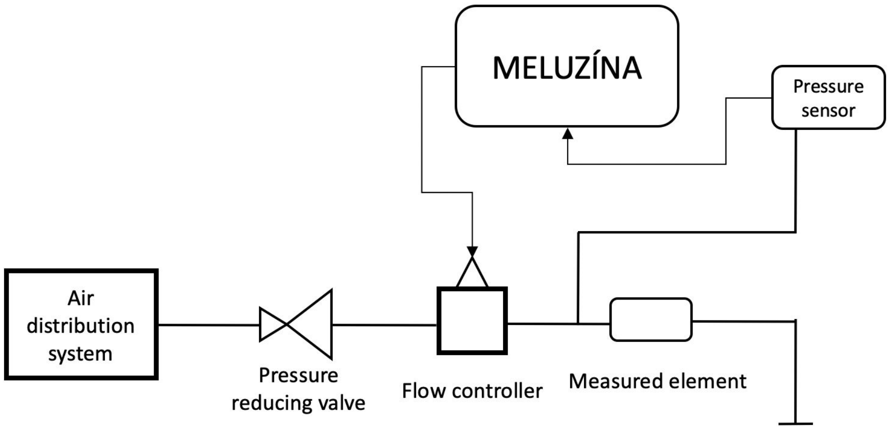

Fig. 13: A scheme of the apparatus for measuring the P-Q characteristic

Fig. 14: The linear resistor

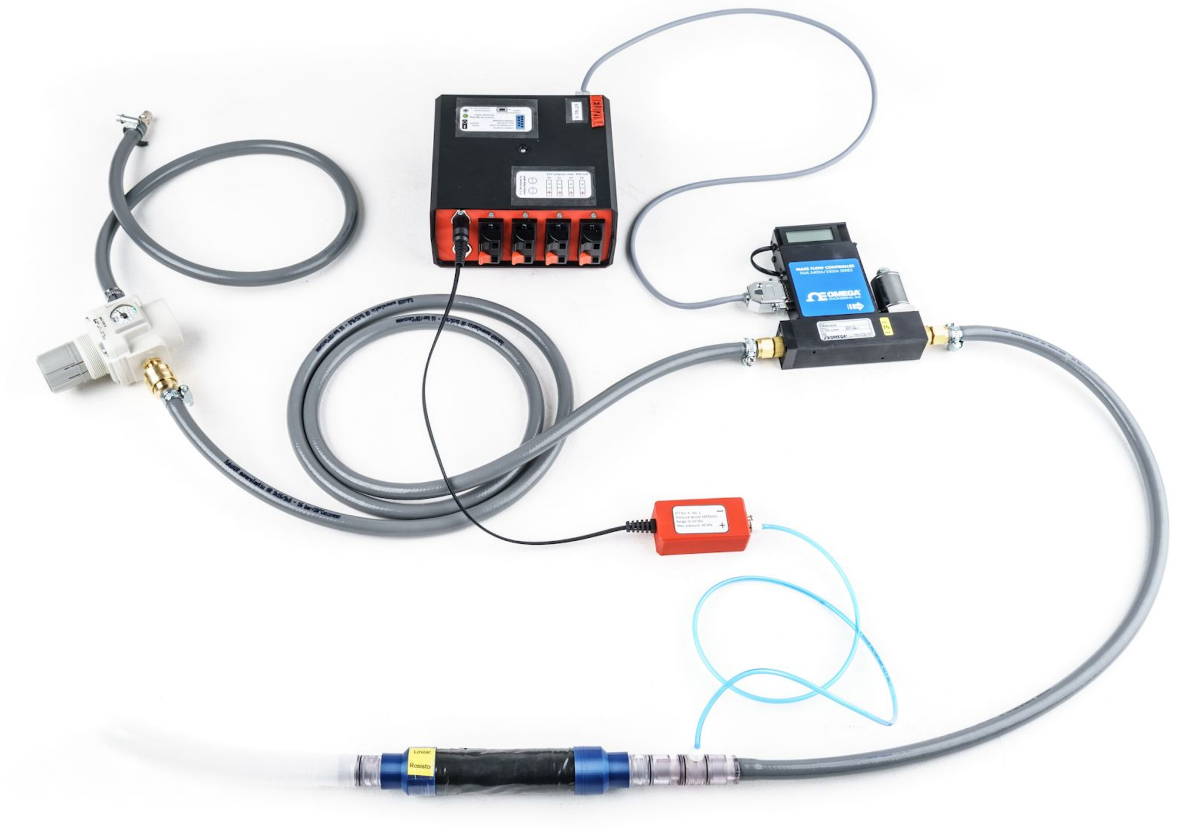

Fig. 15: Typical connection of the apparatus for P-Q measurement

3. Parabolic resistance

a) Measure the P-Q characteristics of parabolic resistances in the range of 10–100 l/min.

b) Determine the coefficients of parabolic resistances according to equation 2.

c) For all the elements plot the measured data on the graph $\Delta p = f(q)$. Fit the $y = ax^b$ curve to the plotted data using Excel. What is the value of the exponent b?

d) Calculate the value of the flow resistance $\boldsymbol{R = \Delta p/q}$ for an i-th flow of each tube. Then recalculate the resistances of each tube per unit; assume the linear dependence of resistance on a tube's length.

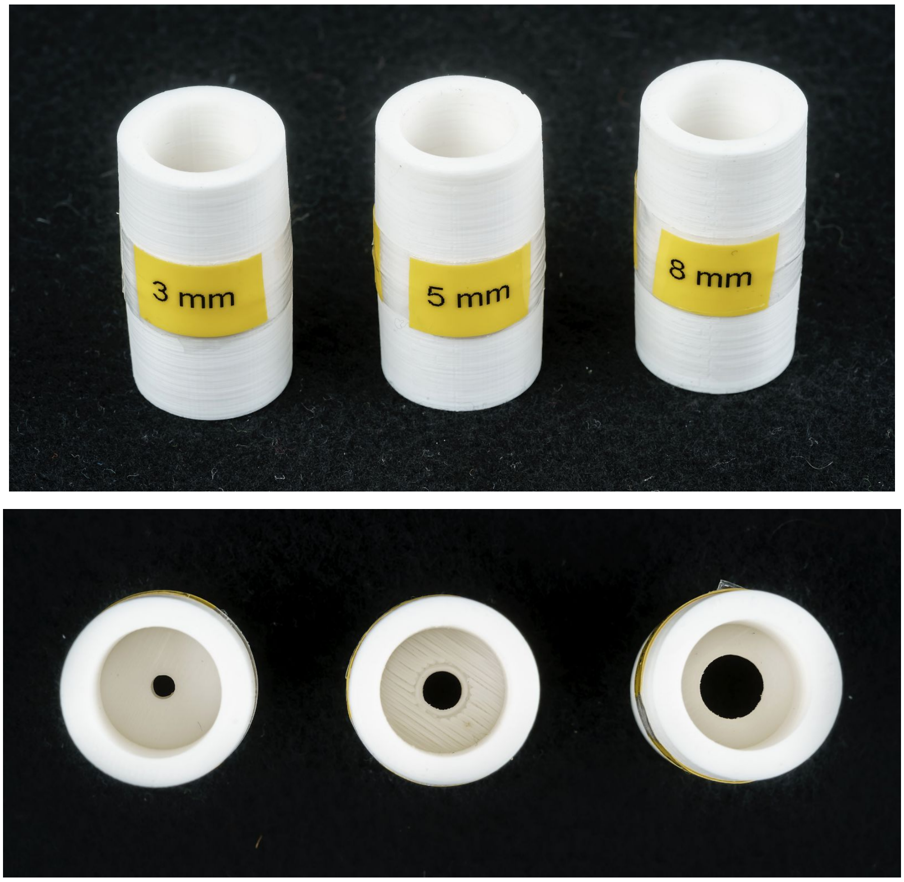

Fig. 16: Parabolic resistors with different diameters

4. Turbulent flow and Reynolds number - Korotkoff sounds

a) Use turbulent flow to measure (blood) pressure.
b) Prepare the orange reservoir full of water.
c) Connect the quick-coupler with the pump.
d) The pump is controlled by a linear voltage source with a potentiometer.
e) Behind the pump, put the model of an arm.
f) Simulate a heartbeat using a pump as a heart.
g) Press the artery in front of the model.
h) Using a stethoscope, you should listen to the Korotkoff sounds behind the narrowed point.

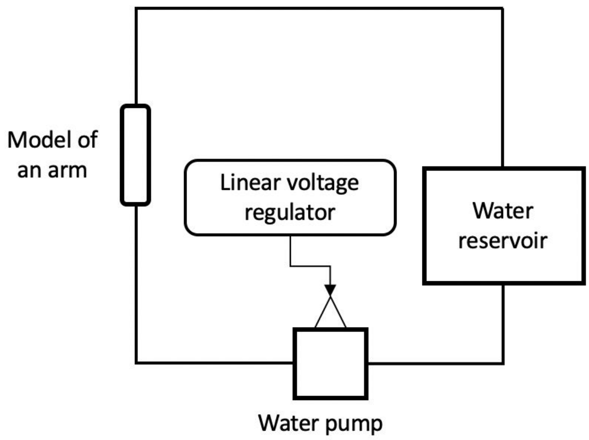

Fig. 17: A scheme of the apparatus

Fig. 18: Typical connection of the apparatus for listening to Korotkoff sounds

Equipment

Pnehykur kit
FMA 5400 flow controller
Linear resistor
Parabolic resistors
VBM couplings with sampling points for pressure measurement
Tubes with the sampling points
Rail with three-way valves and hoses
Kit for Korotkoff sounds demonstration

Examples

The oil at a temperature of 20 °C, which has a density of 888 kg/m^3 and a dynamic viscosity of 0.8 N·s/m^2, flows steadily through a 40m long tube with a circular cross-section with a diameter of 5 cm. The measured pressures at the inlet and outlet of the tube are 745 kPa and 97 kPa. Determine the oil flow rate in the tube when it is horizontal, tilted 15° up and tilted 15° down. Confirm that the flow is laminar in nature. Assume that the flow is fully developed in the tube.

Find out the minimal number of capillaries necessary for the construction of a linear resistor if the maximal volume flow rate is Qmax = 100 L/min and the diameter of one capillary is 1 mm. Dynamic viscosity of the air is 1.71·10-5 Pa·s and its density is 1.293 kg/m^3 .

Questions

What must be the diameter of the hose at a water flow of 10 l/min at a temperature of 25 ℃ to prevent turbulent flow?

Reference

BLOM, J. A. Monitoring of Respiration and Circulation. 1st ed., Boca Raton: CRC Press, 2004. 188 p. ISBN 978-0849320835.

4.3 Obstructive flow measurement

Goals

a) Students will get acquainted with the experiment with the influence of the geometric dimensions of the obstructive element and with the influence of the distance of the sampling points on the range, accuracy and sensitivity of the measurement, as well as on the sensitivity of the given element to noise.
b) The aim of this exercise is to acquaint students more deeply with the most commonly used method of measuring gas flow in health care, with obstructive measuring elements.
c) To determine the advantages and disadvantages of individual obstructive measuring elements (bidirectional measurement, resistance to clogging, size of dead space, robustness and simplicity).
d) To determine examples of the use of elements in healthcare.

Theory

For their simplicity, so-called pneumotachographs are preferably used to measure the flow rate of the ventilation mixture in clinical practice or during ventilation experiments. This is one way to measure fluid flow. In most cases, these elements are several centimeter long tubes with a suitably positioned and suitably shaped resistive member inside. The resistive member may be, for example, a simple constriction, an obstacle, or a system of capillaries. The resistance member causes a pressure difference to occur in front of and behind the resistance element inside as the gas flows through the tube. Thanks to its characteristic design, it makes it possible to convert the information about the gas flow into a pressure difference, which is further converted into an electrical signal by means of a pressure sensor. From the course of this signal, it is possible to determine the flow rate back. At the same time, it is then possible to calculate the total volume of fluid that has flowed through the tube per unit time.

The pressure difference arising on the resistance member is proportional to the velocity of the gas flowing through the sensor. By measuring the pressure-flow characteristic, it is possible to determine the gas flow through a given flow sensor at the value of the unknown flow rate by measuring the pressure difference. Fig. 19 shows the course of the air flow velocity through the selected model of the flow sensor D-Lite. Fig. 20 shows the pressure difference arising during this flow. The air flow is 50 l/min in both figures and is oriented from right to left in both figures. These figures show the principle used by flow sensors.

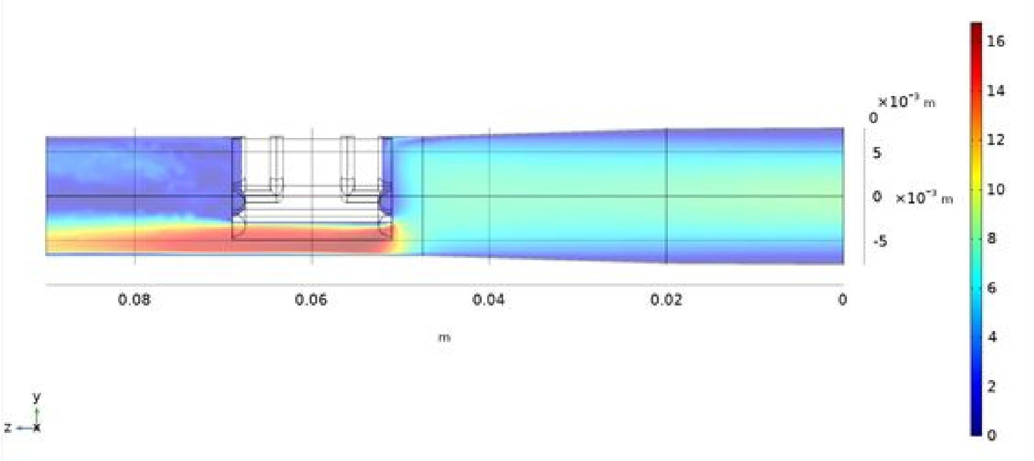

Fig. 19: Flow velocity through the D-Lite flow sensor (flow direction from right to left)

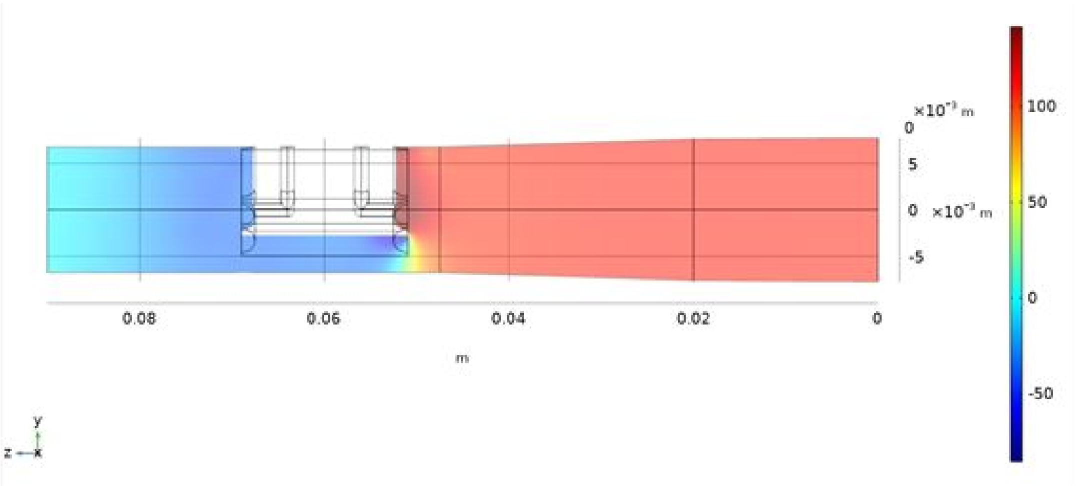

Fig. 20: Pressure difference arising on the resistance member (flow direction from right to left)

Properties of the obstructive elements

P-Q characteristics of the obstructive elements

To describe the dynamic properties of flow sensors, the pressure-flow characteristic of each of the sensors is plotted. This is a graph that shows which flow rates belong to the value of the pressure difference arising on the resistance element of the measuring sensor. It is possible to construct a curve by measuring pressure differences at specific flows. The equation of this curve is then described as a function, which is then converted to an inverse function by mathematical adjustments. When measuring flows, this inverse function inserts information about the detected pressure difference, which was measured by the flow orifice, and the instantaneous value of the volume flow is determined by recalculation within the software of the given device. To illustrate what the pressure-flow characteristic may look like, Fig. 21 is a graph describing the pressure-flow properties of the D-Lite pneumotachograph.

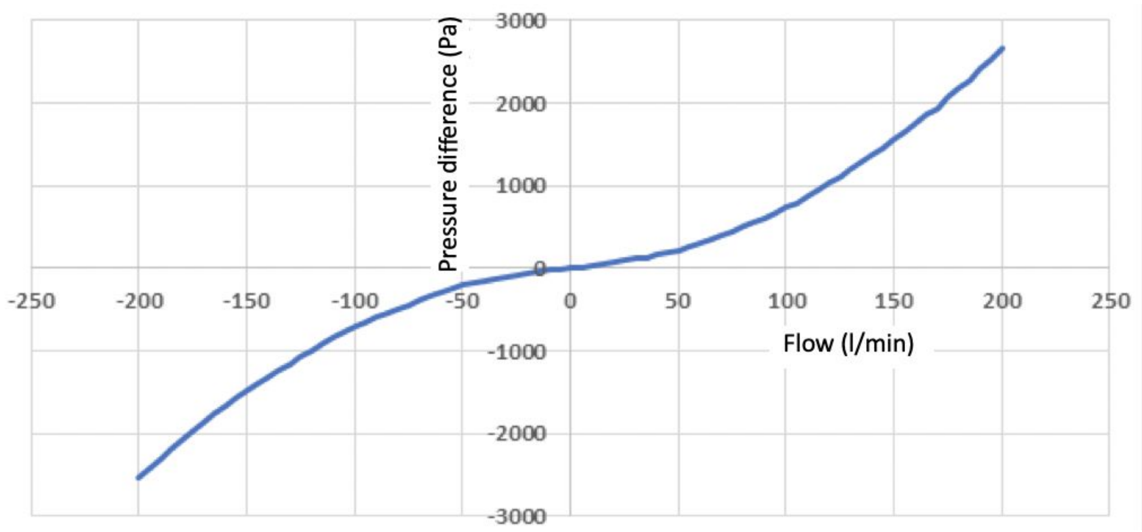

Fig. 21: P-Q characteristics of the sensor D-Lite

Measurement of pressure flow characteristics

The measurement of pressure-flow characteristics of flow sensors is performed on the so-called calibration track. On this track, it is possible to control the air flow using a valve, read the value of this flow using a flow meter and measure the pressure difference that arises on the flow sensor. The valve, flow meter and measured element are in series in the line. Between them, a hose is used to stabilize the asymmetric and turbulent currents that are generated by all the elements in this line during the flow. Omega FMA5400 is used for flow measurement. This device allows to measure and adjust the flow rates of gases and gas mixtures up to a value of 100 l/min. The Testo 512 instrument is used as the differential pressure gauge. The measuring range of this instrument is 0 to 20 hPa with an accuracy of ± 0.1 hPa. (Hoses are connected to the outputs of this device, which carry information about the pressure difference from the flow sensor.) When connecting the device to the flow sensor, it is necessary to pay attention to the correct orientation of the device terminals to the sensor terminals. The outlet on the pressure gauge marked with a plus is connected to the positive output of the flow sensor. A positive sensor output means an output on the side on which a positive overpressure is generated during flow. It is therefore the side that is first in the flow direction, i.e. at the beginning of the resistance member. By using a corrugated hose and straightening the calibration track, undesirable phenomena that could adversely affect the measurement are avoided.

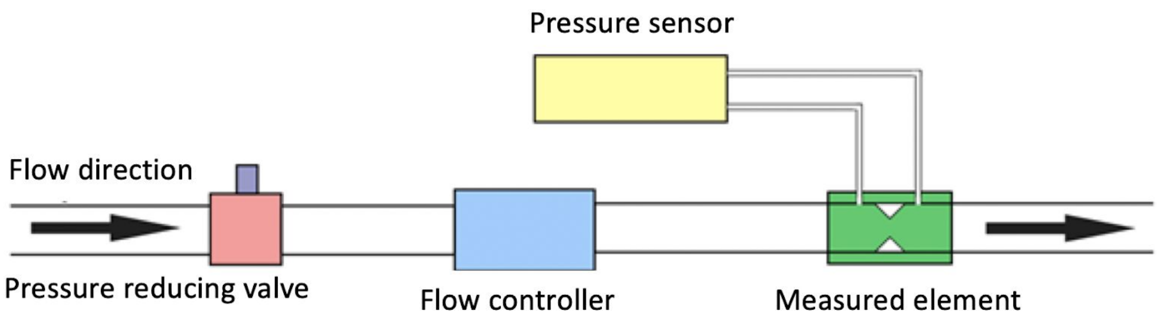

Fig. 22: A typical connecting for measuring P-Q characteristic

Types of obstructive measuring elements

Different designs of the internal resistance member give the flow sensor different properties. There are several basic types of flow sensor design that use this principle. The first of these types is a flow sensor with an inserted orifice plate. This type is constructed in such a way that a partition with a circular opening is inserted into the inner space, which is concentrated in the longitudinal axis of the tube. This solution of the flow sensor arrangement is advantageous mainly because, due to its simplicity, the whole sensor is very mechanically resistant, easy to clean and suitable for long-term use, since possible clogging of airway secretion is not a significant problem for function. The main disadvantage is the fact that these sensors have poor resolution when measuring low flow rates due to their parabolic pressure-flow characteristics. A detailed summary of the rules describing the shape and properties of orifice discs and sampling points for measuring pressure drop is the technical standard EN ISO 5167-2 on measuring fluid flows using differential pressure sensors inserted into a completely filled circular pipe, part 2: Orifices.

Another way to create a pressure difference is to insert a foil with an embossed or cut-out profile. By suitable shaping of this profile, it is achieved that the film gradually opens with increasing flow due to the deflection of the free ends of the film in the punctured profile. Thanks to this element, the pressure-flow characteristic has a linear character and the sensor is thus able to measure with the required accuracy even very small flows of the breathing mixture, which are around 5 litres per minute. The disadvantage of these screens is the lower mechanical resistance and the fact that secretion from the patient's airways may adhere to the inserted film. Therefore, measurement inaccuracies may occur with long-term use. This type of sensor is also more complicated to clean. In most cases, it pays to replace the used flow sensor with a new one. The Spiroquant H flow sensor is then shown in Fig. 23, which uses the principle of a gradually opening foil.

Fig. 23: Spiroquant H flow sensor

Another possible type of flow orifice design is to place a set of thin tubes in the interior of the sensor. In this way, the pressure-flow curve is linearized. These orifices are therefore suitable for measuring even low flow rates. However, the disadvantage of this solution is the fact that in longer-term use, the inserted tubes are prone to clogging with secretions from the patient's airways due to their dimensions. Therefore, this solution is not used in routine clinical practice for long-term monitoring of volume flows in the ventilation circuit. This type of sensor is used for single spirometric examinations. An example is the so-called Fleisch pneumotachograph. Fig. 24 shows this type of flow sensor for illustration.

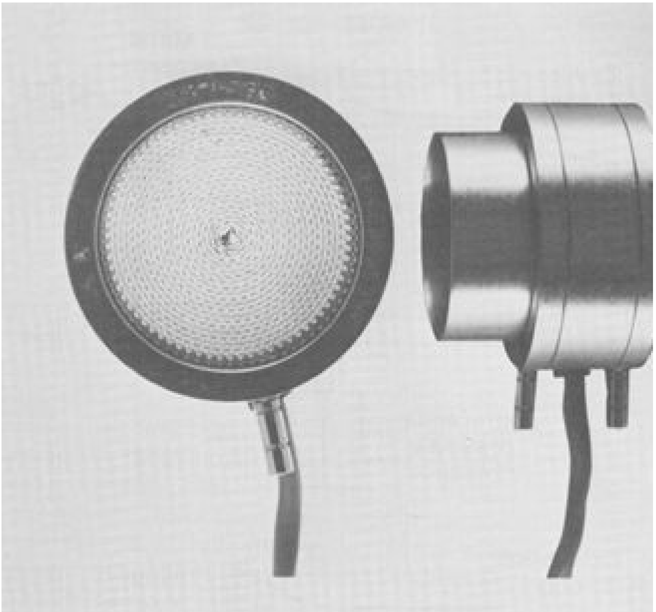

Fig. 24: Fleisch pneumotachograph

In the case of the D-Lite pneumotachograph, a resistance element with a relatively specific shape is used to measure flow rates in ventilation care. The resistance member is a three-arm construction with built-in sampling points for pressure difference measurement and gas analysis. A sensor of this type can thus better measure even lower flow rates compared to a sensor with an inserted orifice plate because it takes advantage of stagnation pressure. On the other hand, due to the fact that no foil or capillaries are used here, there is no risk of loss of the sensor's functionality due to long-term use due to airway secretion. The resistance element of the D-Lite flow sensor, which is very often used in artificial lung ventilation, is shown in Fig. 25.

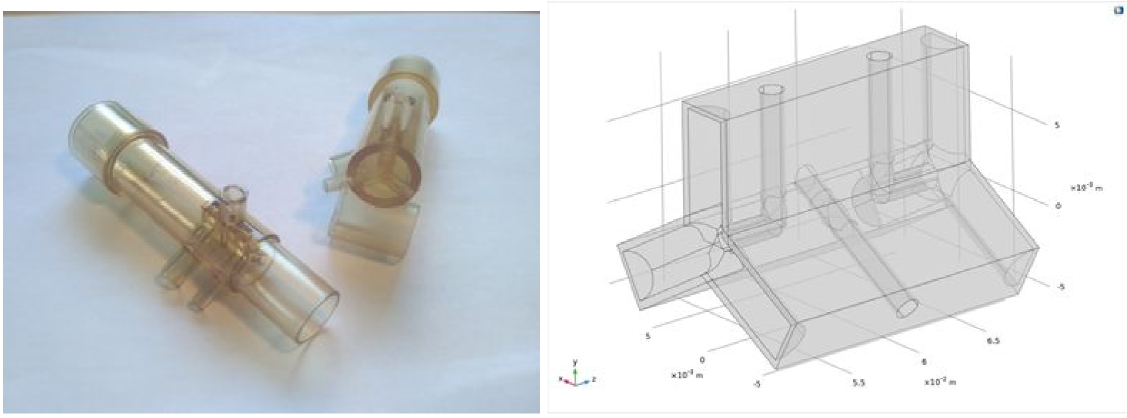

Fig. 25: Flow sensor D-lite

Another flow meter uses the principle expressed by Bernoulli's equation. The closed tube is narrowed in some section (during the flow of the medium, at this point there are changes in the flow rate and pressure) by the throttle member. The throttling element can be, for example, a throttle orifice, a nozzle, a venturi nozzle. A nozzle is a mechanical element used to limit the flow of gases and liquids. It differs from the orifice plate in that it has a continuously changing cross-section (thus having a longer service life). The inlet edge is rounded, the outlet edge is straight (sharp).

The nozzle is a one-way obstruction flow meter. It consists of an obstacle that is circular in shape and, when theoretically viewed through the wall of the flow meter, has the shape of a rounded letter L, and pressure sampling points which are located at defined distances from the obstacle. The Venturi nozzle is in its basic form the same one-way obstructive flow meter but it is possible to modify the Venturi nozzle so that the volume flow can be measured in both directions. The venturi nozzle in its basic form has one of the sampling points for measuring static pressure in front of the obstacle and the other is located directly in the obstacle. In an obstacle, there is an increase in the flow rate and thus a decrease in the static pressure.

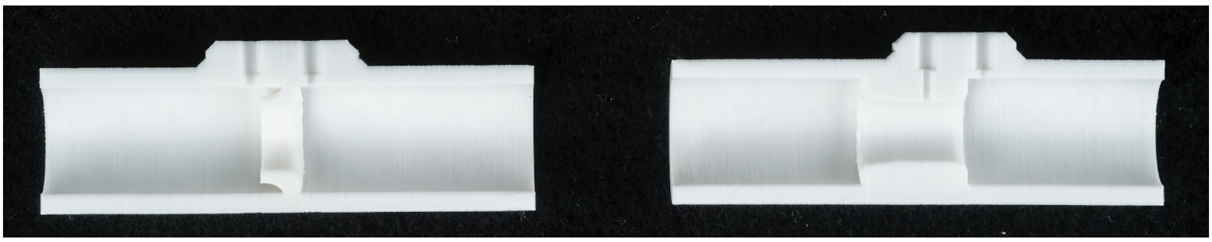

Fig. 26: Cross-section - a nozzle and Venturi nozzle

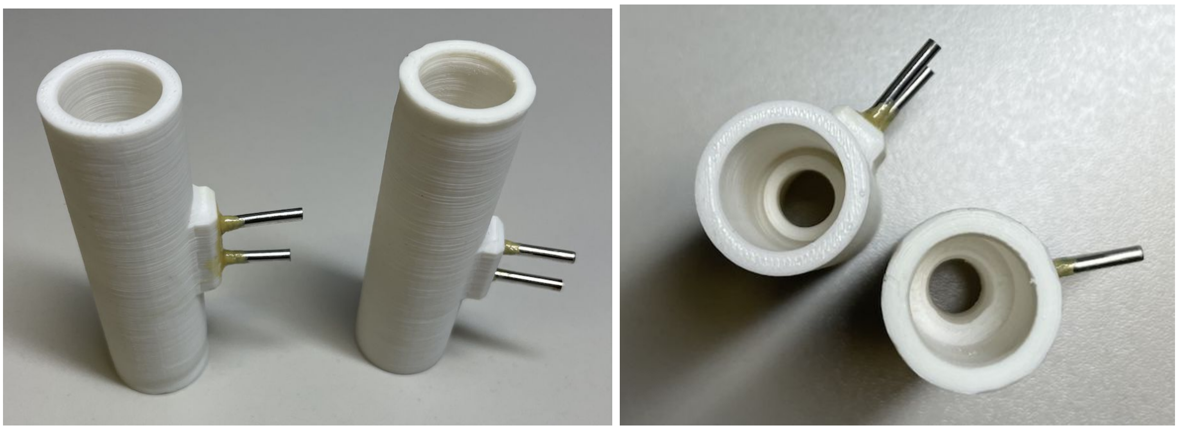

Fig. 27: A nozzle and Venturi nozzle

Experiments

What types of flow sensor designs do you have in front of you? Identify and name each type.

1. The resistance of an obstructive element

a) Connect the computer to Meluzína and connect Omega to Meluzína with cables included in Pnehykur kit.
b) Connect the Omega to a pressure reducing valve **(max. 2 bar).**
c) Connect the apparatus to the air distribution system.
d) You should use an accurate pressure sensor MPX7002. Be careful about the offset on the sensor.
e) Measure the pressure in front of the spirometric sensor D-lite at a flow rate 60 l/min at both directions (with closed sampling points).

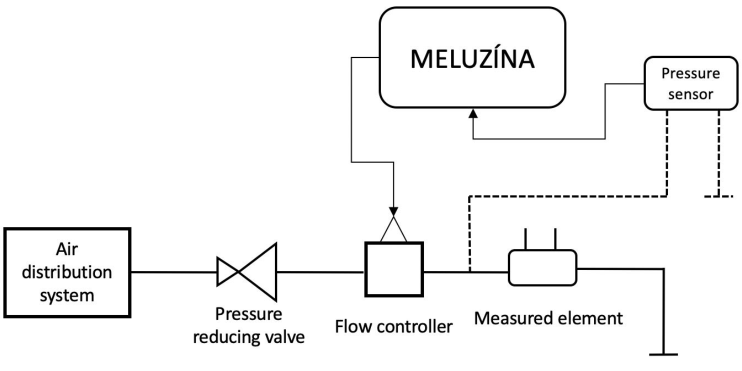

Fig. 28: A scheme of the apparatus for the measurement

Fig. 29: Spirometric sensor D-lite

2. P-Q characteristic of the obstructive elements

a) At a flow rate of 10–80 l/min (step 10 l/min), measure the P-Q characteristic of all obstructive elements in both directions.
b) Compare the P-Q characteristics.
c) You should use an accurate pressure sensor MPX7002. Be careful about the offset on the sensor.

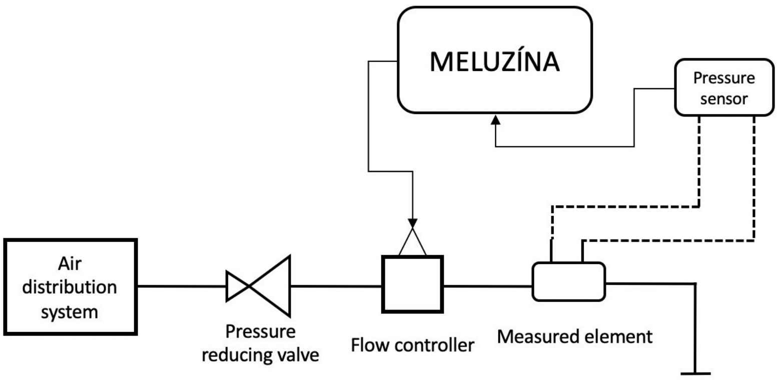

Fig. 30: A scheme of the apparatus for the measurement

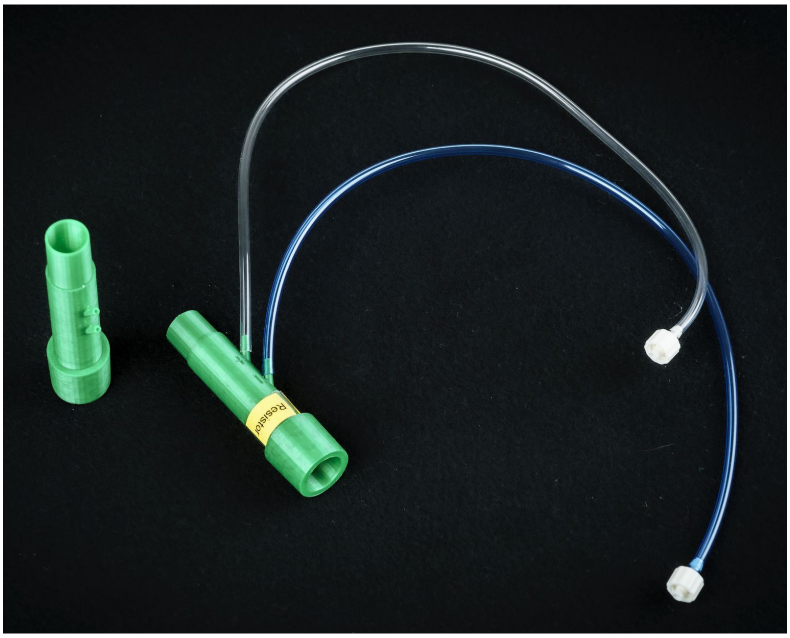

Fig. 31: Parabolic resistor

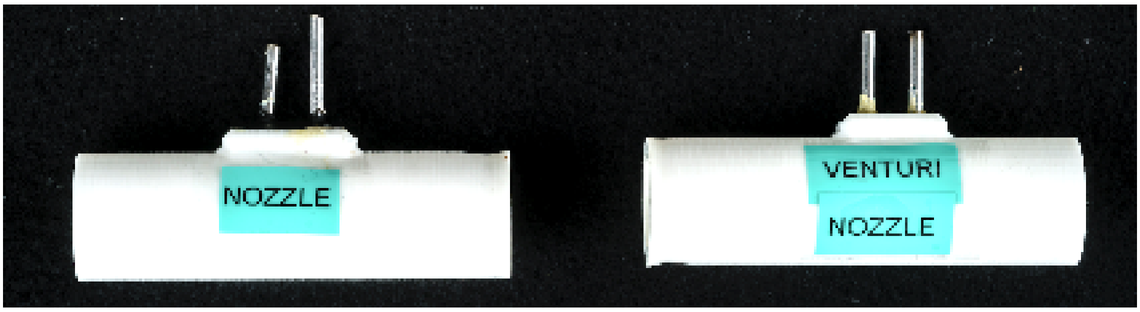

Fig. 32: A nozzle and Venturi nozzle

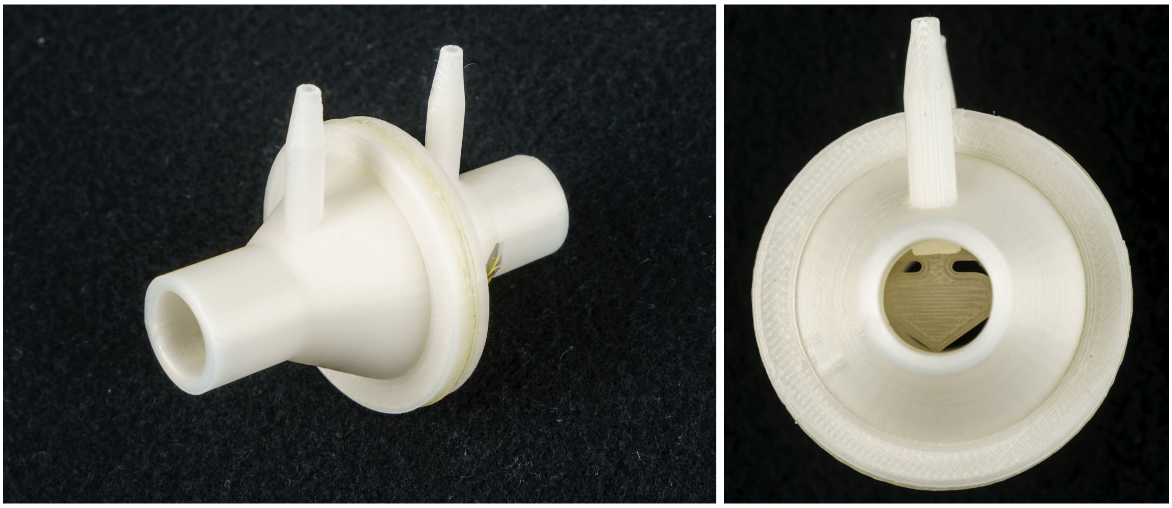

Fig. 33: Foil resistors

What are the advantages and disadvantages of each solution?
Which type of obstructive element is used when long-term use of a flow sensor is required?
What is the most suitable element for low flow rates?

Which element is structurally simplest?
What element works best for bidirectional flow?
Why does the pressure measured in front of a D-lite sensor have a smaller pressure drop than the pressure drop at a sampling point at the same flow? Think about the construction of the sampling point.

3. Measurement of signal properties on differently spaced sampling points

a) Connect the MPX5010 pressure sensor to the three-way valve rails.
b) Connect the positive port of the sensor to the three-way valve rail, which is in front of the obstacle inside the supplied element.
c) Connect the negative port of the sensor to the rail behind the obstacle.
d) Connect the supplied element to the flow source and set the flow to 80 l/min.
e) Determine the effect of the sampling points in front of and behind the obstacle on the measured pressure drop.
f) Rotate the measured element to see if it has symmetrical properties.
g) In what arrangement should the signal have the most noise to signal ratio?
h) In what arrangement is the signal most sensitive (the biggest pressure drop)?

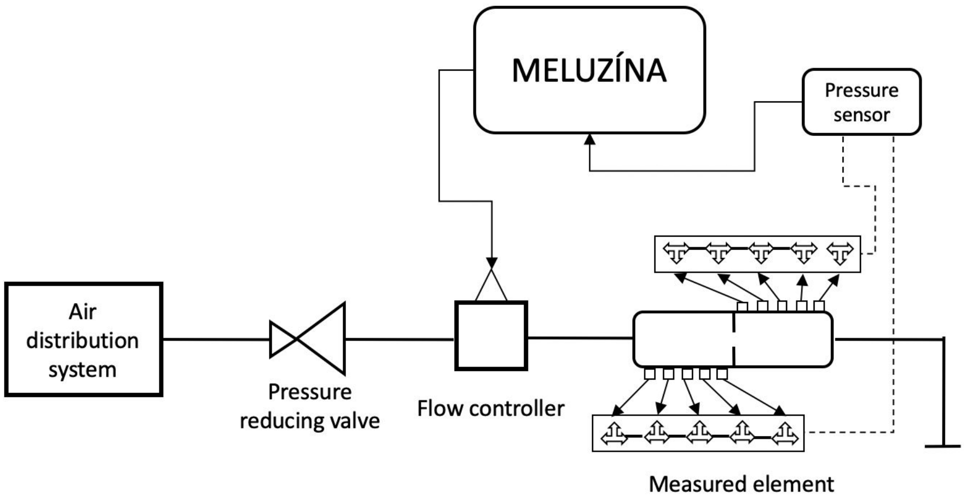

Fig. 34: A scheme of the apparatus for the measurement

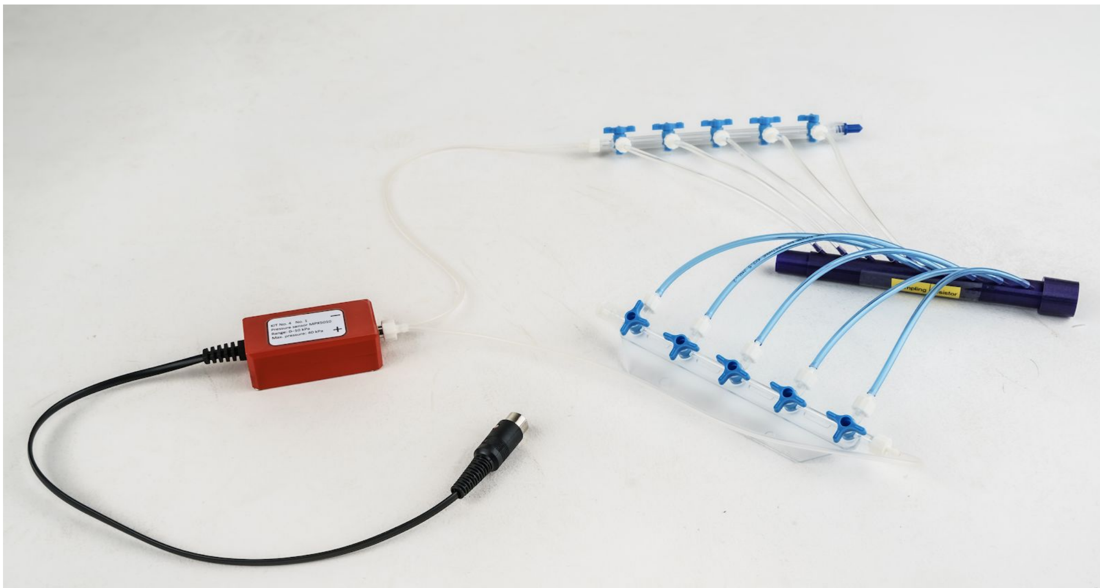

Fig. 35: Typical connecting to the pressure sensor

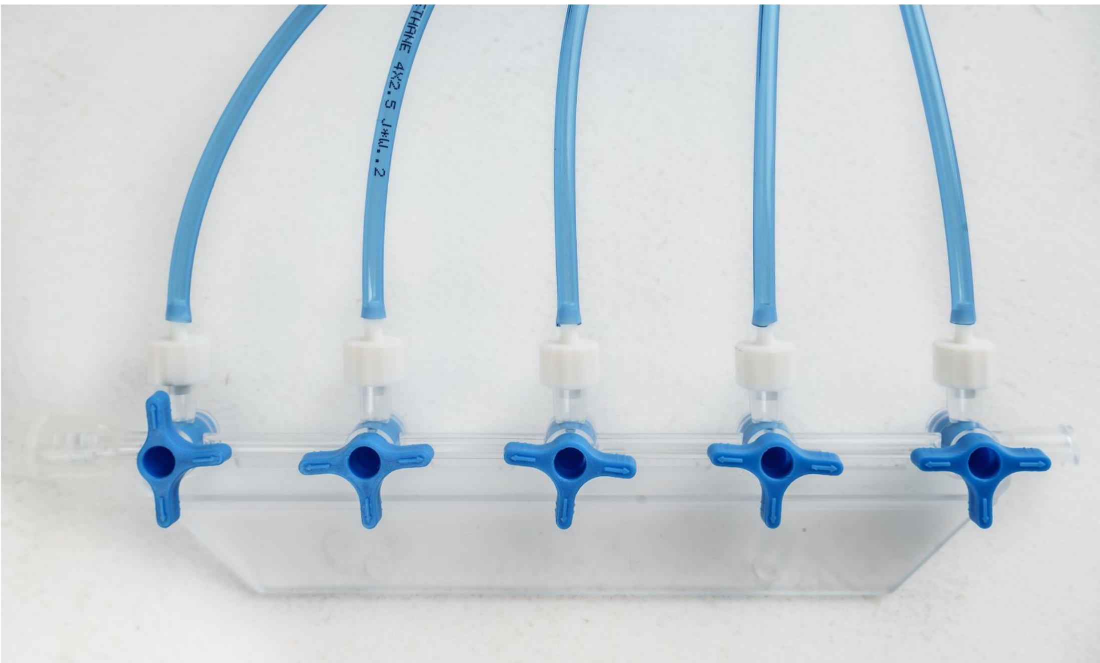

Fig. 36: Rail with three-way valves

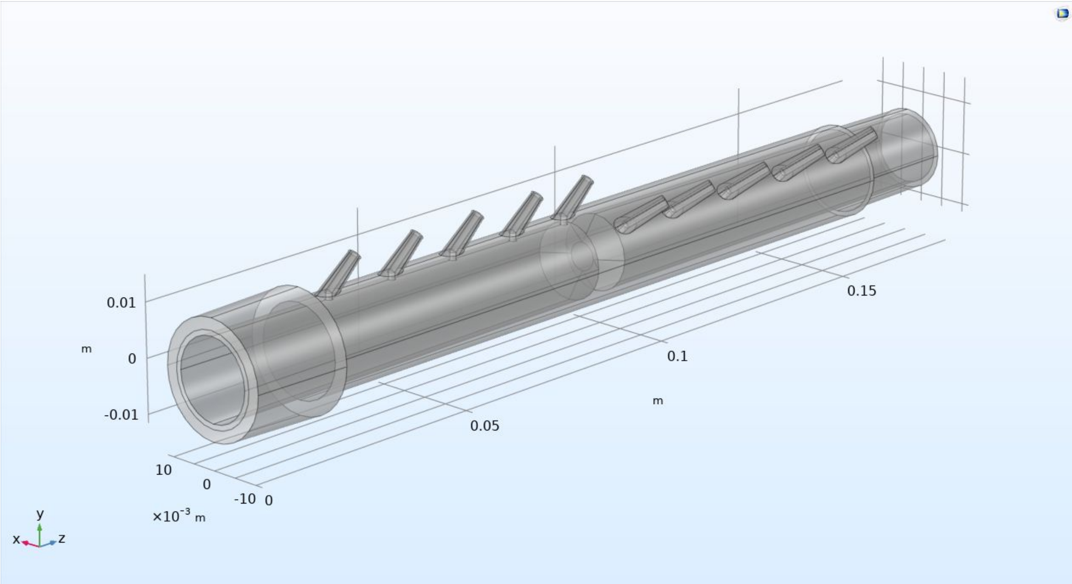

Fig. 37: An obstructive element

Equipment

2x three-way valve rails
Pressure sensor MPX5010
Accurate pressure sensor MPX7002
Long obstructive element with sampling points
Omega controller FMA5400
Hose
Pnehykur kit
Spirometric sensor D-lite
Linear resistance with foil
Parabolic resistors with an orifice disc
Venturi nozzle
Nozzle

Examples

We measure a pressure difference of 17.54 Pa on an orifice with an inner diameter in an obstacle of 3 cm. The orifice is inserted into a tube with a circular cross-section with a diameter of 4 cm, through which methanol flows with a density of 788.40 kg/(m^3). The orifice flow coefficient is 0.61. Calculate the volume flow through the orifice. Assume an incompressible steady flow.

Questions

Why do the obstructive elements used in healthcare not have a higher resistance? A higher element resistance at a higher flow rate would be advantageous in terms of measuring the pressure change but it is not done like this.

Reference

ENRIGHT Paul L., HYATT Robert E., Office Spirometry: A Practical Guide to the Selection and Use of Spirometers, Lea & Febiger, Philadelphia, 1987

Flow Measurement with Respironics Flow Sensors: Respironics, White Paper. Philips [online]. [cit. 2020-05-18]. Dostupné z: https://www.philips.com/static/oemrespironics/wp/Flow%20Measurement%20WhitePaper1.pdf

4.4 Other types of flow measurements

Goals

a) To acquaint students with other methods of flow measurement and to explain to students when these methods are used.
b) Explain the principles of operation of individual measuring elements.
c) To show students the advantages and disadvantages of individual measuring elements at pulse, constant or bidirectional flow rates.

Theory

The measurement of the gas volume flow by using a heated wire or thermoelectric anemometer is based on the change of the electrical resistance of a thin wire or film (hereinafter elements) caused by the cooling of the element by the flowing gas. This means that the higher the value of the volume flow through the anemometer, the higher the change in the resistance of the element. If a wire is used in a thermoelectric anemometer, then its diameter is in units of µm and its length is in units of mm. When using film, its thickness is usually tenths of µm. Thanks to such small element dimensions, thermoelectric anemometers have a fast dynamic response to changes in volume flow. Platinum or tungsten are used as the materials of the elements due to the considerable temperature dependence of the electrical resistance of these materials. An important component in the circuit is the current source, which provides a constant current value for heating the exposed wire in the flow path.

The flow meter with the Hall sensor works on the principle of a mechanical turbine, which reads the speed of the turbine using the Hall sensor. The sensor switches to the output signal of the applied ground or the supplied supply voltage. The output of the sensor is thus a rectangular signal with a varying frequency, which is proportional to the flow driving the mechanical turbine.

The rotameter is a commonly used flow meter for anesthesia devices. Visually, the current flow value can be read immediately from the calibrated scale. The measuring principle is based on the stroke of the obstruction member (most often a ball or cone) to a height that is proportional to the selected flow rate. Rotameters can also be equipped with a throttling element for flow control, and thus indicate the choice of individual fractions in the patient's ventilation mixture.

The orifices (obstructive elements) are based on the measurement of the difference of static pressures in front of and behind the obstacle, which is proportional to the value of the gas volume flow. An obstacle in this case is a step reduction and a subsequent step extension of the aperture cross section. This constricted point therefore has an increased pressure drop, in other words an increased resistance, as a result of which the static pressure decreases. The following two events also increase the measured static pressure difference. First, due to the abrupt reduction of the cross-section of the orifice, the gas particles present near the walls of the orifice at the point of abrupt reduction of the cross-section slow down or completely stop. The second action, due to the stepwise expansion of the cross-section of the screen, the boundary layer is torn off from the wall of the screen at the point of this stepwise extension. Because the static pressure measured on the tube wall is lower in the areas with the tear-off boundary layer than in the areas where the boundary layer is adjacent to the tube wall, the static pressure drops just behind the obstacle. The increased resistance at the constriction and the two mentioned effects together create a difference in static pressures in front of and behind the obstacle, which is measurable even at low values of gas volume flow. However, the accuracy of a flow meter at flow rates up to 20 l/min is often subject to a higher error due to low pressure differences, which are difficult to register with a large range of sensors. Important factors for the creation of a sufficient pressure difference are the shape of the obstacle and the position of the pressure difference sampling points. In this task, a centric circular screen with a spur edge is used. From the point of view of sampling points, sampling points at a distance of one tube diameter are used, which provide a compromise between the magnitude of the measured pressure difference and noise.

Each of the flow meters is limited when measuring in a different direction. The obstruction screen is a robust measuring element that is variable in its shape and the choice of sampling points. For low flow rates, however, it is burdened with a larger error, however, its resistance characteristic has the character of a parabola, which significantly affects the flow measurement ranges. The flow meter with a Hall probe is limited by a mechanical construction when it has poor inertia and the absence of orientation of the flow direction. The anemometer with a hot wire reacts very quickly to a change in flow, thus having the highest inertia of these sensors. As with the Hall sensor, the flow direction cannot be determined from just one probe present. The flow limit for a hot wire means that the wire is cooling, which the current source cannot cover. The rotameter is most limited only by its calibrated scale, which is specified by the manufacturer, and when the values are exceeded, the sensor becomes saturated.

Experiments

Measure the characteristics of flow meters based on different flow measurement principles (turbine with hall probe, hot wire, rotameter and obstructive element).

1. Calibration track

a) Assemble a calibration track for the measurement according to a scheme.

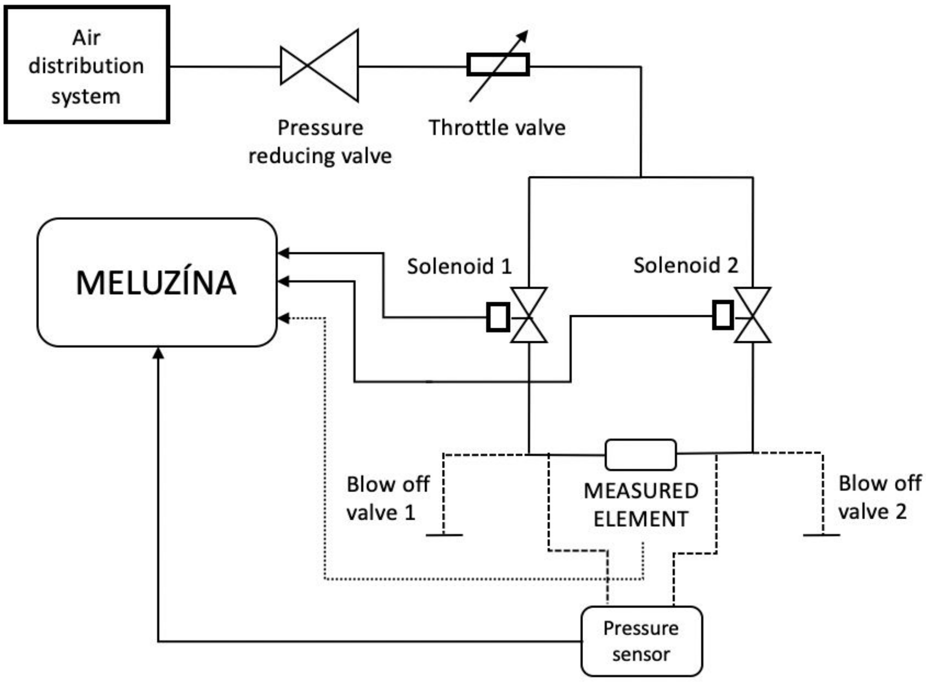

Fig. 38: A scheme of the apparatus

b) Put the wires of the solenoids into Meluzína. The one wire with a red line is put into the red socket and the other one into black one.
c) Connect the pressure reducing valve to the air distribution system and set the pressure to max. 2 bar.
d) At the computer, you can set if the solenoid should be opened or closed and for how long time the solenoid should be opened or closed.

Fig. 39: Blow off valves

Fig. 40: Blow off valves

2. Setting the flow

a) Connect a rotameter to one branch.
b) Leave the second branch closed.
c) Set the constant flow to 10 l/min according to the rotameter.

Fig. 41: A rotameter

3. Properties of flow meters

a) Switch a set flow rate in the positive direction to all flow meters and record the waveform.
b) Switch a set flow rate in the negative direction to all flow meters and record the waveform.
c) Run a pulse flow at a frequency of 5 Hz in the positive direction into all flow meters and record the waveform.
d) Run a two-way flow into all flow meters, alternating after 1 second and record the waveform.

Which flow meter only works in one direction?
What are the advantages and disadvantages of a rotameter?
Which flowmeter has the greatest inertia?
For which flow meters do we record a change in the flow direction?

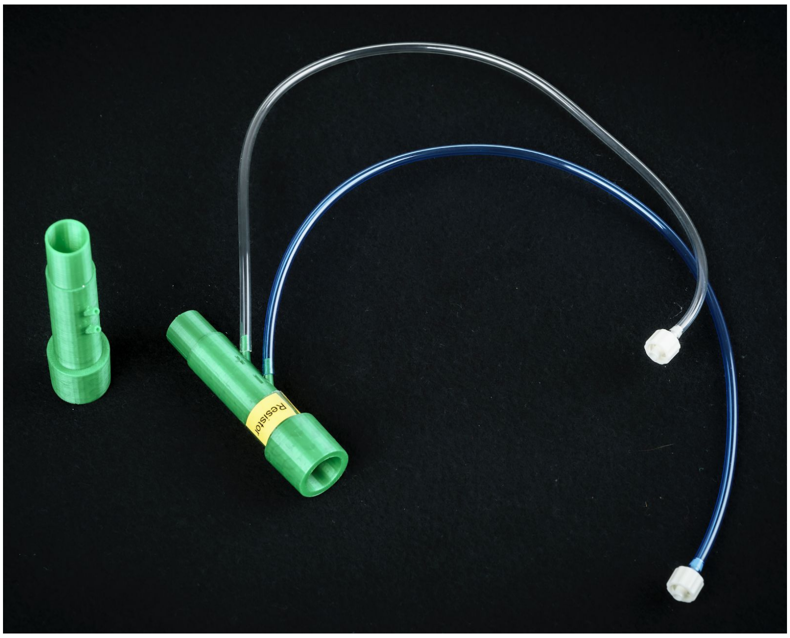

Fig. 42: Parabolic resistors

Fig. 43: Hot wire anemometer

Fig. 44: Flow meter with Hall sensor

Equipment

Pnehykur kit
Hot wire flow meter
Flow meter with Hall sensor
Differential orifice
Rotameter
Hose
Quick couplings
Blow off valve

Examples

What is the flow in the Hall sensor when the output is a rectangular signal with a frequency of 50 Hz? The flow rate of 1 l/min corresponds to an output signal of 2 Hz.

Questions

What types of measuring elements would you not use for two-way directional flow?
What types of measuring elements would you not use for pulse flow?

Reference and recommended readings

ENRIGHT Paul L., HYATT Robert E., Office Spirometry: A Practical Guide to the Selection and Use of Spirometers, Lea & Febiger, Philadelphia, 1987

Flow Measurement with Respironics Flow Sensors: Respironics, White Paper. Philips [online]. [cit. 2020-05-18]. Available at: https://www.philips.com/static/oemrespironics/wp/Flow%20Measurement%20WhitePaper1.pdf

4.5 Compliance

Goals

a) To understand the meaning of the term compliance in pneumatics and respiratory care.
b) To understand the connection between the compliance of a rigid container and its dimensions.
c) To understand the differences between adiabatic and isothermal processes and the importance of thermo-compensated models.
d) Furthermore, students will get acquainted with the possibility of modeling compliance (rigid container modeling compliance with its volume vs. flexible container modeling compliance with its stiffness).

Theory

Compliance of a pneumatic system is a parameter that describes how easily the system can accumulate gas. Compliance ***C*** is defined as

$$C = \frac{\Delta V}{\Delta p}, \tag{1}$$

where ΔV is the volume of gas delivered into the system and Δp is a unity increase in pressure in the system due to the gas delivery. The fundamental unit of compliance is m^3/Pa; however, in respiratory care L/kPa or L/cmH2O are used more frequently.

Compliance is a typical property of lungs. Assume the gas compression in the lungs to be negligible. Then the volume of gas delivered into the lungs equals the increase in volume of the lungs, and it is possible to define the lung compliance as the change in the lung volume per change in transmural pressure, i.e., the difference between alveolar and pleural pressure. During the inflation of lungs, retractive force of lung tissue has to be overcome. The greater is the retractive force, the smaller is the compliance and vice versa.

When calibrating mechanical ventilators or building physical models of the respiratory system, we need a model with compliance exactly defined and stable in time. A container with a large volume and rigid walls, e.g., made of glass, is suitable for this role. Gas delivered into the container accumulates in the container due to the gas compressibility, and the pressure within the container increases. If the pressure increase is Δp when the volume of gas ΔV is delivered, the equation (1) can be utilized. Obviously, containers with small volume have small compliance and larger containers have bigger compliance.

Even if the volume of a container is known and constant, to determine the compliance we need to know the thermodynamic process which occurs in the container. Two limit cases are the isothermal process and adiabatic process. During the isothermal process temperature remains constant in a system and state variables follow the formula:

$$pV = konst. \quad (2)$$

where ***p*** (Pa) is pressure of gas and ***V*** (m^3) its volume. If gas in the system cannot exchange heat with the surrounding environment or changes in pressure in the system are very fast, the adiabatic process occurs in the system, which follows Poisson formula:

$$pV^{\kappa} = konst., \quad (3)$$

where κ (-) is the adiabatic index. The value of the index is approximately κ ≈ 5/3 for single atom gases (in respiratory care for example helium He) and κ ≈ 7/5 for two-atom gases (nitrogen, oxygen).

The type of the thermodynamic process depends, among others, on the ventilatory frequency. Isothermal process occurs during the low-frequency conventional ventilation, whereas the process is close to the adiabatic process during the high-frequency ventilation. Often, we talk about the polytropic process, which follows the formula:

$$pV^{\alpha} = konst., \quad (4)$$

where α (-) is the polytropic index; $1 \leq \alpha \leq \kappa$. The compliance of a rigid container during a polytropic process can be calculated as:

$$C = \frac{\Delta V}{\Delta p} = \frac{V_0}{\alpha \cdot p_0} \quad (5)$$

where $\boldsymbol{V_0}$ (L) is the volume of a container and $\boldsymbol{p_0}$ (kPa) is the mean pressure in the container, i.e., most often the atmospheric pressure Pa. (Note: Do not interchange the volume of the container $\boldsymbol{V_0}$ with the volume of gas $\boldsymbol{\Delta V}$ delivered into the container by, for example, a mechanical ventilator.)

In so-called thermo-compensated models, the dependency of a rigid container's compliance on the change in temperature is eliminated. In such a container there is a large amount of thin copper wire with good thermal conductivity and high thermal capacity. The heat in the container is thus effectively removed; the temperature of gas in the container is nearly constant during the breath cycle and does not depend on ventilatory frequency. For the thermo-compensated model, we can assume α = 1 in (5). Thermo-compensated models better approximate behavior of the real respiratory system.

Experiments

1. Compliance

a) Use a calibration syringe (Hans Rudolph, USA), gradually add volumes of 100 ml, 200 ml, 300 ml, 400 ml and 500 ml of air to a small glass demijohn (V = 10 L).
b) After pressing, keep the syringe pressed.
c) Using the pressure gauge Testo 512 or pressure sensor MPX5010, read the pressures in the demijohn after stabilization.
d) Calculate the compliance of the glass demijohn for the measured pressure changes and supplied air volumes.
e) Pour 2 liters of water into the demijohn and repeat the procedure as in point a), b), c) and d).
f) Pour 5 liters of water into the demijohn and repeat the procedure as in point a), b), c) and d).

Fig. 45: A typical connecting of the apparatus

Fig. 46: A 1L calibration syringe and a connecting of a syringe to demijohn

2. Adiabatic and Isothermal compression

a) Use a calibration syringe (Hans Rudolph, USA), inject 500 ml of air into the glass demijohn.
b) Using a pressure sensor MPX connected to a computer via Meluzína, monitor the course of the pressures in the demijohn in comparison with the atmospheric pressure and read the value of the pressure change after its stabilization.
c) Place your hands on the demijohn and observe the pressure change with the syringe still pressed.
d) Insert the copper wire into the demijohn and proceed as in a) and b).
e) Discuss the different behavior of pressure waveforms.

3. Rigid container vs. flexibil container

a) Determine the compliance of the Smartlung artificial lung by injecting 500 ml of air from a calibration syringe (Hans Rudolph, USA). Measure the pressure with the MPX pressure sensor pressure gauge.

Fig. 47: Smartung and the typical connection of the apparatus

Equipment

Glass demijohn
Seal
Calibration syringe
Meluzína
MPX pressure sensor
Smartlung
Copper wire
Testo 512 (200 hPa)

Examples

1) Derive the formula (5) for n = 1. (Hint: Use the ideal gas law and express the relation between the gas volume ΔV delivered into the container and the amount of gas Δn which constitutes the delivered volume if the mean pressure in the container is p_0. Also, express the 3 relation between

the pressure increment Δp of gas in the container of volume V_0 and the delivered amount of gas Δn. Substitute both the expressions into the equation (1).

2) Calculate the volume of a rigid-wall container which should have, during the isothermal process, a compliance of a lung of an adult healthy human; that is, approximately 1 L/kPa. What will be the volume of the container during the adiabatic process if the main gas in the ventilatory mixture is a) nitrogen, b) helium?

Questions

How large should the volume of the vessel representing the compliance of the respiratory system of a person suffering from Acute Respiratory Distress Syndrome (ARDS) be? (Instructions: Data on lung compliance with ARDS can be found, for example, in [1].)

Reference

[1] LUMB, A. B. Nunn's applied respiratory physiology. 7th ed. Oxford: ButterworthHeinemann, 2010. xii, 556 p. ISBN 978-0702029967.

4.6 Automatic measurement of a compliance

Goals

a) To design an apparatus which can automatically measure the compliance of respiratory system models. The device allows the measurement of all data needed for the calculation of compliance after pressing the Start button in the ***Automatic measurement of compliance*** application. You will not need to perform any manual operations other than pressing the button to measure the data. At the same time, it will be possible to perform three such measurements immediately after each other, again without any other manual intervention. The result of each of the measurements is a set of exported data, for which an automatic script for calculating compliance will be created in Excel or Matlab or another application of this type.

b) To deepen knowledge in the topics covered in previous tasks.
c) Learn how to work with parts used in pneumatic systems - muffler, pressure relief valve, solenoid valve.

Theory

For more information about the Compliance (see Laboratory task No. 5).

The muffler is engineered as an acoustic device to reduce the loudness of the sound pressure created by the engine by acoustic quieting.

A relief valve or pressure relief valve (PRV) is a type of safety valve used to control or limit the pressure in a system; pressure might otherwise build up and create a process upset, instrument or equipment failure, or fire. The pressure is relieved by allowing the pressurized fluid to flow from an auxiliary passage out of the system. The relief valve is designed or set to open at a predetermined set pressure to protect pressure vessels and other equipment from being subjected to pressures that exceed their design limits. When the set pressure is exceeded, the relief valve becomes the "path of least resistance" as the valve is forced open and a portion of the fluid is diverted through the auxiliary route. A solenoid valve is an electromechanically-operated valve.

Fig. 48: A pressure relief valve

Solenoid valves differ in the characteristics of the electric current they use, the strength of the magnetic field they generate, the mechanism they use to regulate the fluid, and the type and characteristics of fluid they control. The mechanism varies from linear action, plunger-type actuators to pivoted-armature actuators and rocker actuators. The valve can use a two-port design to regulate a flow or use a three or more port design to switch flows between ports. Multiple solenoid valves can be placed together on a manifold.

Solenoid valves are the most frequently used control elements in fluidics. Their tasks are to shut off, release, dose, distribute or mix fluids. They are found in many application areas. Solenoids offer fast and safe switching, high-reliability, long service life, good medium compatibility of the materials used, low control power and compact design.

Experiments

a) Connect the OMEGA FMA5400 behind the pressure reducing valve and connect it to Meluzina with the connecting cable.
b) Connect the pressure reducing valve **(max. 2 bar)** to the air distribution system.
c) Assemble a model of the respiratory system: The basis of the model of the respiratory system is a rigid container with an ideal volume of about 50 L (for this laboratory task we only have 10 L rigid container.
d) Insert the adapter between the ending of the neck of the container (15mm I.D.) and the 6mm tube. Connect a 6mm hose to the adapter

Note: The length of the 6mm tube has to be long enough to reach the work table.

e) Connect a T-connector with a pressure relief valve to the end of the tube. The pressure relief valve is factory set to 40 kPa and ensures safety when pressurizing a rigid container. **THE PRESSURE VALVE MUST ALWAYS BE CONNECTED !!!**
f) Prepare the software ***Automatic measurement of compliance*** .
g) Connect the computer to Meluzína with the USB cable.
h) Start the application and select the connected device in the dialog.

Note: The application allows sequential control of up to four two-state valves. The sequence consists of five steps, and it is not necessary to use all of them in this task. In each step of the sequence you can select the duration of the step in milliseconds, the status of each of the connected valves (true = open, false = closed) and the status of data recording from pressure sensors (true = data is stored in the graph, false = data is not stored in the graph). The graph has a memory for 10 seconds of recording, while the new data overwrites the old data.

i) Use the slider on the flow control to set the desired flow through Omega.
j) Press the Start button to start one sequence.
k) Use the Export button to export the data from the graph to the clipboard (as if you pressed Ctrl + C).
l) Use the Zero button to reset the pressure sensor.
m) Press the STOP button to close the entire application properly.
n) Assemble a pneumatic system. Build a pneumatic system between the air distribution system from and the respiratory system model to meet the objectives of the task.

Note: From the previous tasks, a method for measuring compliance with a calibration syringe is known. The same principle must be applied here.

o) The volume of gas delivered here is defined by the flow controlled by OMEGA FMA5400 and the time for which the flow is applied to the model.

p) Control the flow time with a 2/2 electromagnetic solenoid valve controlled by the ***Automatic measurement of compliance.***

q) The recommended flow rate for this task is around 20 L/min.

r) Check the OMEGA FMA5400 display to check the correct flow during the measurement.

s) The pressure change will be measured using a 10kPa pressure sensor connected to the pressure port of a rigid lung model.

Note: The maximum allowable pressure in the model during the measurement is 8 kPa. When this value is exceeded, the measurement is interrupted, all valves are closed and an error message is triggered in the application.

t) Based on the knowledge of the rigid container volume, the maximum allowed pressure according to the note above and the selected flow rate, select the optimal delivered volume controlled by the time of application of the flow into the rigid container.

u) Two-state 2/2 electromagnetic solenoid valves will be controlled sequentially using the ***Automatic measurement of compliance*** application. With the help of appropriately connected electromagnetic solenoid valves, it is necessary to solve all the tasks in the previous exercise performed manually.

v) After a successful measurement, export the measured data using the Export button.

w) Paste the data into a suitable environment (Excel or Matlab or something else).

x) In this environment, create a script that automatically calculates the compliance of the connected model from the measured data.

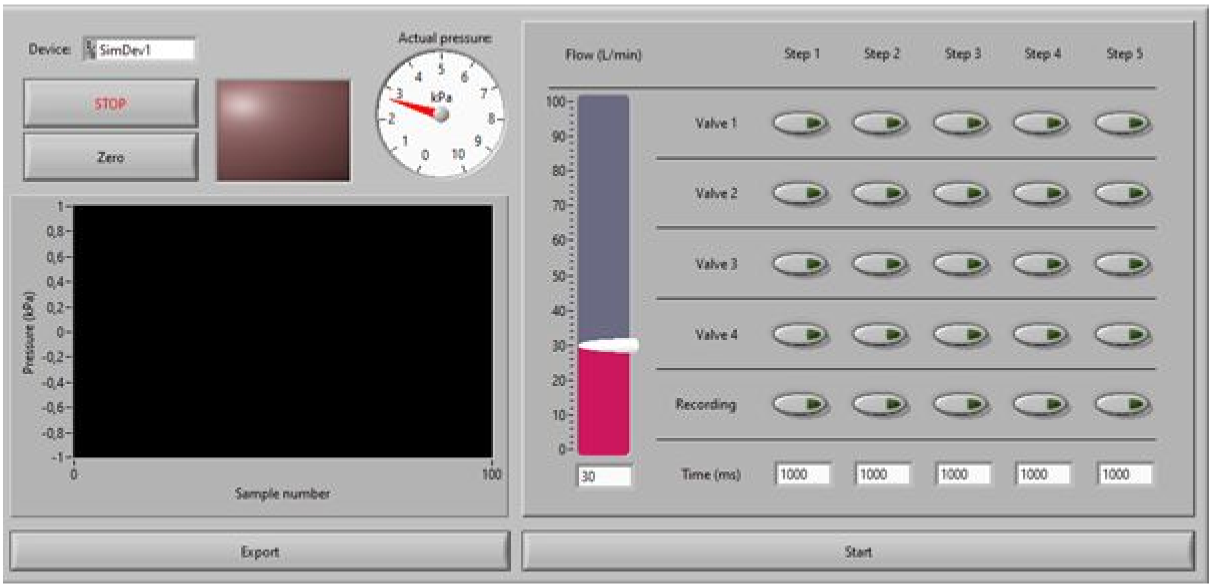

Fig. 49: The application for the measurement of compliance

In case of problems, see the tips here:

1. Software overpressure protection: Too much gas is supplied, resulting in a higher than maximum allowable pressure in the system. Check the time and flow settings when pressurizing the model. When measuring, observe the OMEGA FMA5400 display to check the correctness of the supplied flow.
2. Place the safety valve close to the connection to the respiratory system model and pressure measurement.
3. It is important to connect the valve in the correct direction, in the opposite direction, even with a higher pressure difference, a closed gas can pass through.
4. Omega does not supply the set flow: Omega acts as a feedback source of gas flow. When the flow is closed (2/2 electromagnetic solenoid valve), OMEGA FMA5400 still tries to deliver the set flow in the application. This leads to the full opening of the proportional valve in OMEGA FMA5400. After opening the 2/2 valve, the maximum flow flows through the fully open valve for a certain time before the flow stabilizes. **It is recommended to perform this stabilization before measuring with the exhaust outside.** The pressure in the measured model may not be zero at the beginning of the measurement.
5. Use more than just one electromagnetic solenoid valve. There are more possibilities how to do it. It is also possible to use 3/2 electromagnetic solenoid valve.
6. Three consecutive measurements cannot be made. The second or third measurement will provide overpressure protection: The pressure from the previous measurements from the model was probably not released. It is necessary to release this accumulated pressure from the system automatically during the measurement.

Equipment

Air distribution system
Pressure reducing valve
Omega FMA 5400 flow controller
Pnehykur kit (2/2 directly operated solenoid valve, 3/2 directly operated solenoid valve, 1x safety valve (40 kPa), Meluzína with connectors, pressure sensor, T-fittings, Y-fittings, direct connection fittings, muffler)
Pieces of polyurethane hoses for compressed air
An adapter from 6mm polyurethane hose to an ending of the neck of the rigid container
Compliance model (like in previous laboratory task no. 5)

Questions

Try to think if there is any other possibility how to automatically measure the compliance with this hardware and software.
What would you do differently if the rigid container has the volume of 50 L?

Reference

Measurement of respiratory compliance. Available at: https://derangedphysiology.com/main/cicm-primary-exam/required-reading/respiratory-system/Chapter%20032/measurement-respiratory-compliance

How Reliable is Automatic or Manual Calculation of Lung Compliance using Ventilator Readouts? A Model Study. Available at: https://www.nature.com/articles/pr2011743

4.7 Acoustic weight, Resonant circuits

Goals

a) The aim of this laboratory task is to familiarize students with the inertia in the pneumatic circuits, analogous to an inductor in electronics.

Theory

Each rigid system with known geometrical parameters can be considered as an acoustic system that can be solved by the means of electro-acoustic analogy. Respiratory system (with some simplifications) or a bottle (beer bottle for example) can be considered as acoustic systems. If we want to describe an acoustic system, it is necessary to know the geometrical parameters of the system. Acoustic elements describing the bottle correspond to its elementary parts. Because the electrical elements correspond to its acoustic equivalents it is possible to use electric laws to study the acoustic system. It is possible to compute the acoustic elements (acoustic weight $\boldsymbol{m_a}$, acoustic resistance $\boldsymbol{r_a}$ and acoustic compliance $\boldsymbol{c_a}$) describing the system, if we know the geometrical dimensions, according to the following equations:

$$m_a = \frac{\rho_0 l}{S}, \qquad [\mathrm{kPa.s^2.l^{-1}};\ \mathrm{kg.m^{-3}},\ \mathrm{m},\ \mathrm{m^{-2}}]$$

$$c_a = \frac{V}{\rho_0 c_0^{\,2}}, \qquad [\mathrm{l.kPa^{-1}};\ \mathrm{m^3},\ \mathrm{kg.m^{-3}},\ \mathrm{m.s^{-1}}]$$

$$r_a = \frac{8\mu l}{\pi R_t^{\,4}}, \qquad [\mathrm{kPa.s.l^{-1}};\ \mathrm{N.s.m^{-2}},\ \mathrm{m},\ \mathrm{m}]$$

where $\boldsymbol{\rho_0}$ stands for air density, ***l*** stands for length, ***S*** stands for cross-section area, ***V*** stands for volume, $\boldsymbol{c_0}$ stands for velocity of propagation, ***µ*** stands for dynamic air viscosity and ***Rt*** stands for tube radius.

Physical constants required for computation:

Air density: $\boldsymbol{\rho}$ = 1,293 kg/ m^3

Dynamic air viscosity: ***µ*** = 1,84.10-5 N.s. m^{-2}

Velocity of propagation of sound in air: $\boldsymbol{c_0}$ = 340 m/s

Experiments

1. Resonant frequency of the bottle

a) Measure the resonant frequency of the glass bottle by whistling on it. Use the microphone connected to the PC with Oscillometer software.

Fig. 50: Frequency analyzer for windows

b) Let's consider the bottle as an acoustic system. Neck of the bottle is possible to describe by acoustic resistance ***ra*** and acoustic weight ***ma*** that represent the acoustic properties of the bottle neck in the final equivalent electric circuit. Volume of the bottle can be described by acoustic compliance ***ca***. It is possible to derive the electric resonant circuit using the electro-acoustic analogy that corresponds to the acoustic system (bottle).

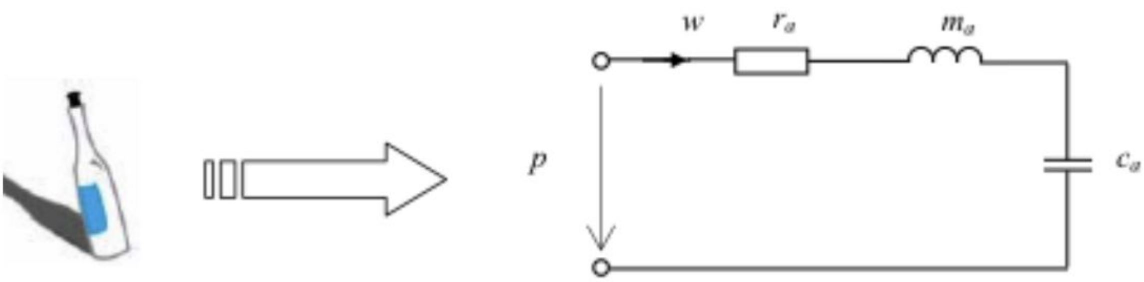

Fig. 51: An electro acoustic scheme of a bottle.

Use electro-acoustic analogy and compute the resonant frequency of the bottle according to the Thompson equation. Compare the computed value with measured resonant frequency. Measure the geometrical dimensions and volume of the bottle.

Thompson formula:

$$f_r = \frac{1}{2\pi\sqrt{m_a . c_a}}$$

Computed resonant frequency: fr = Hz.

Compare both results and explain the difference:

c) Fill the bottle partly with water (change of resonant frequency: acoustic resistance and acoustic inertance do not change, acoustic compliance is changed because of change in the volume of the air in the bottle) and measure the resonant frequency of the bottle again by the means of program Oscillomater.

Measured resonant frequency (bottle with water): Hz.

Describe the change of the resonant frequency after the water filling.

d) Compute the amount of air in the bottle after the fill by water from measured resonant frequency and geometrical dimensions of the bottleneck: Computed volume of air in the bottle: V = ml.

e) Empty the bottle and measure the amount of water from the bottle. Measured volume of air in the bottle: V = ml.

Equipment

Drawer
Meter
Glass bottles
Computer with application with the possibility of measuring frequency (oscillometer)

Fig. 52: Glass bottles as models for resonant circuits

Note: The value of the resonant frequency of an empty bottle should be around 100–200 Hz.

Examples

Theoretical compliance of the respiratory system can be found in literature. The compliance of the lungs is approximately 2 l/kPa for adult man lungs. Compare the physical units of formula for theoretical computation of compliance ($m^4 \cdot s^2$ /kg) with one from literature (l/kPa).

[ca] = l/kPa =

Questions

Which electric quantity corresponds to acoustic pressure according to electroacoustic analogy?
From which parameters are computed acoustic elements describing acoustic systems?
What is the velocity of propagation of sound in the air during standard conditions?

Reference and recommended readings

Acoustic resonance frequency locked photoacoustic spectrometer

Acoustic-frequency vibratory stimulation regulates the balance between osteogenesis and adipogenesis of human bone marrow-derived mesenchymal stem cells

4.8 Electro acoustic analogies

Goals

a) To familiarize the students with the application of electro acoustic analogies.
b) To apply the gained knowledge in the previous tasks.

Theory

The electroacoustic analogy describes the connection between acoustic and electrical circuits. There is a certain equivalence between these systems. When using it, it is possible to use electrical laws known from electrical circuit solutions to solve acoustic systems.

There are many reasons why an analogy with electrical circuits is used in solving various systems. These include, for example:

1. The methodology of solving electrical circuits is extremely elaborate and there are a large number of auxiliary algorithms and methods.

2. For the solution of any system it is possible to use non-traditional procedures in the given system, which are common in electrical systems, such as Fourier analysis, study of resonance properties, use of phasors, introduction of transmissions, etc.

3. There are a large number of high-quality computer programs for solving electrical systems, whether for circuit analysis, design, simulation, optimization or solution of electric field distribution by finite element method, etc. All these programs are applicable to any studied system after the introduction of analogy. .

4. An important advantage of using electrical analogy is the possibility of converting different types of systems forming one unit into one analog electrical system, in which the individual parts of the whole model represent partial subsystems (mechanical, thermal, diffusion, etc.), and the studied system can be easily solved as one whole in the form of one electrical circuit.

In acoustic systems, both Kirchhof's laws apply as in electrical systems. 1. Kirchhof's law can be shown on a flow divider (analogy to a current divider) and 2. Kirchhof's law on a pressure divider (analogy to a voltage divider).

Last but not least, it is necessary to realize the importance of performance in acoustic systems. In the case of more complex acoustic systems, there can be such a high pressure drop and reduced flow that there could be a malfunction of, for example, ventilation devices in healthcare.

$$V = p \cdot q \tag{1}$$

A very simplified procedure for creating a linear electrical analogy of the respiratory system for investigating pressure-flow characteristics may be the lungs.

We are interested in the relationship between pressure ***p*** and flow ***q*** at the beginning of the airways. For conventional ventilation, i.e. low frequencies, we can model the whole system with a rigid tube connected to a balloon capable of expanding with increasing pressure. To create the following model, we consider that for a tube only its resistance component prevails and for a compressible volume only its compliance (you will learn more about compliance in the laboratory exercise: Compliance). Under these assumptions, we can arrive at a model that shows the electrical analogy of the respiratory system, because it describes the relationship between voltage and current, i.e. between quantities analogous to pressure and flow. The transition from the model to its electrical analogy is obvious. It is only necessary to note in this case that we are not able to determine specific values of resistance ***R*** and capacitance ***C*** for electrical analogy, but only the time constant τ, which is the product of these values. This is a situation quite analogous to the investigation of electrical circuits. The given example is very simple. This method of electro-acoustic analogy can be elaborated in detail for modeling the respiratory system. By combining models of a sufficiently large number of tubes respecting the anatomical structure of the respiratory system, an accurate analogous model of the respiratory system can be created.

Electrical system		Acoustic system	
voltage u current i charge q		pressure p volume velocity W volume shift Ξ	
Element		Element	
Inductor resistor capacitor	inductance L resistance R capacity C	ac. inertor ac. resistor elastor	ac. weight m_a ac. resistance r_a ac. compliance c_a

Fig. 53: Electrical system units x acoustic system units

Experiments

1. 1. Kirchhoff's law in acoustic circuits (flow divider).

a) Assemble a circuit for the measurement according to a scheme.

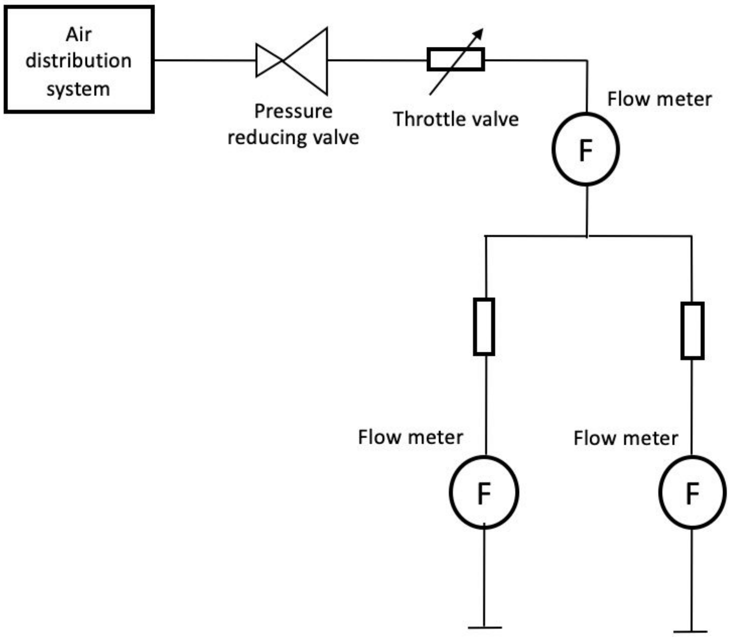

Fig. 54: A scheme of the apparatus for the measurement

b) Connect a pressure reducing valve to the air distribution system and set the pressure to 2 bar.
c) Use the adapter (shown at picture) from the 6mm hose to the 15mm female and a T-coupling behind the adapter.

Fig. 55: An adapter between 6mm tube and 15mm I.D.

d) Place pieces of hoses of the same length on both branches.
e) Place one of the supplied resistors on each hose.
f) Set the flow rates between 10 – 100 l/min with step 10 l/min.
g) Measure the flow rates in both branches with different resistance configurations.

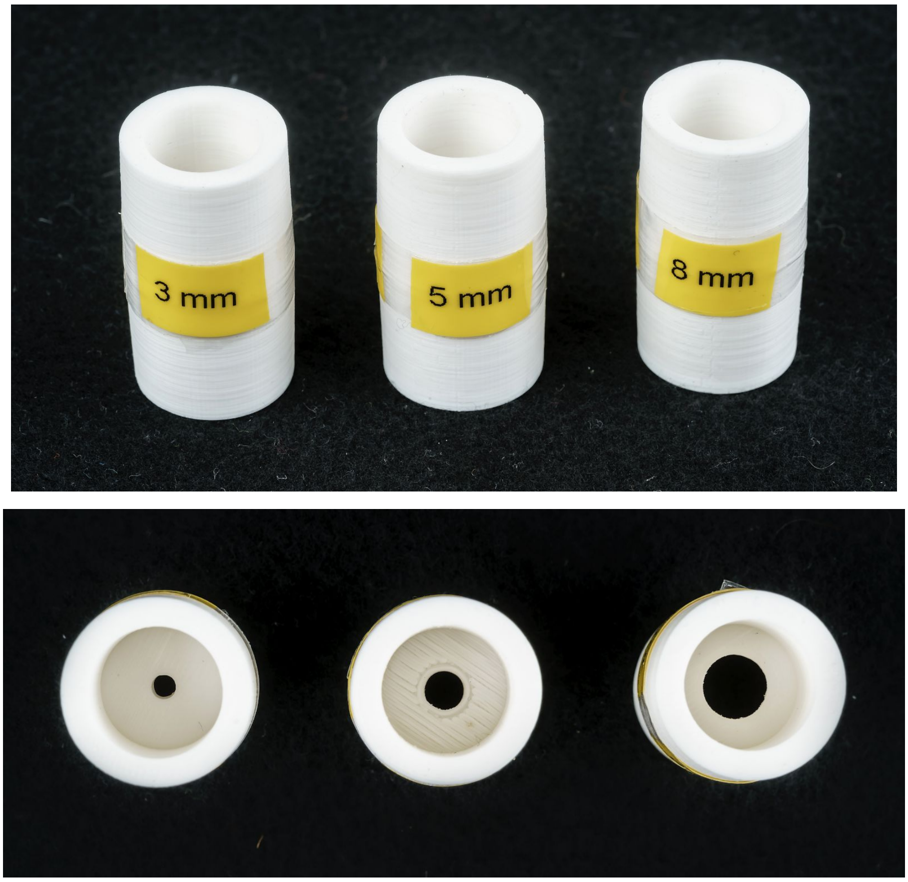

Fig. 56: Parabolic resistors of different diameters

2. 2. Kirchhoff's law in acoustic circuits (pressure divider).

a) Assemble a circuit for the measurement according to a scheme.
b) Connect a pressure reducing valve to the air distribution system and set the pressure to 2 bar.

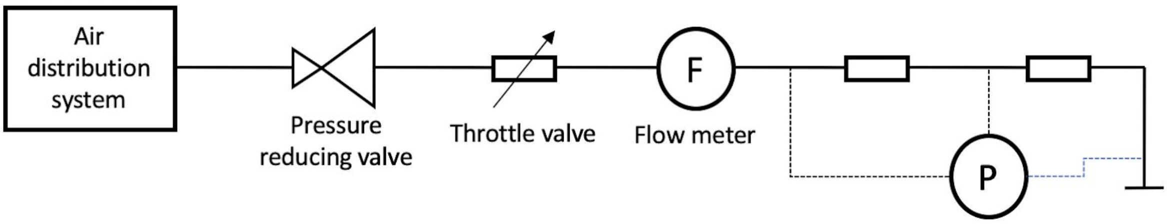

Fig. 57: A scheme of the apparatus for the measurement

c) Place an adapter from a 6mm hose to a 15mm behind the throttle valve.
d) Set flow rates between 10–100 l/min with step 10 l/min.
e) Use a Testo 512 pressure gauge to measure the pressure drops before each resistance to each other and to the atmosphere.

3. Wheatstone bridge

a) According to previous experiments, try to build a wheatstone bridge as an electro acoustic analogy to wheatstone bridge in electric circuits.

4. Low pass filter

a) Assemble a circuit for the measurement according to a scheme.

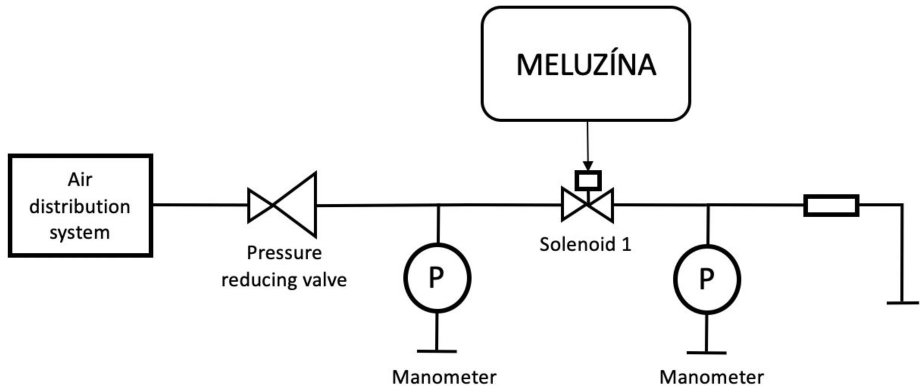

Fig. 58: A scheme of the apparatus for the measurement

b) Connect a pressure reducing valve to the air distribution and first set the outlet pressure to 2 bar.
c) Connect a sufficiently large resistance to the end of the circuit to have sufficient pressure in the apparatus (for example, a long narrow hose).
d) On the Meluzína, set the switching frequency of the three-way valve to 8 Hz.
e) You should see big oscillations of the manometers.
f) Use the supplied compliances, resistors and throttle valves to minimize the oscillations on the second manometer.

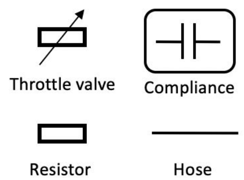

Fig. 59: Supplied components

g) What can be a problem when using the throttle valve?
h) Does it help to minimize oscillations when using a compliance in front of the manometer?

Fig. 60: Models of compliance

Equipment

Air distribution system
Pressure reducing valve
Manometers 0–4 bar
T-couplings
Three-way solenoid (max 2 bar) or 2/2 solenoid (max 1.5 bar)
6mm hose
Pnehykur kit
Throttle valve
Compliances
VBM couplings
Adapters from 6 mm to 15 mm
Testo 512 pressure gauge with a range of 200 hPa
Resistors
Hose

Examples

Find the current flowing in the 40 Ω Resistor, R3

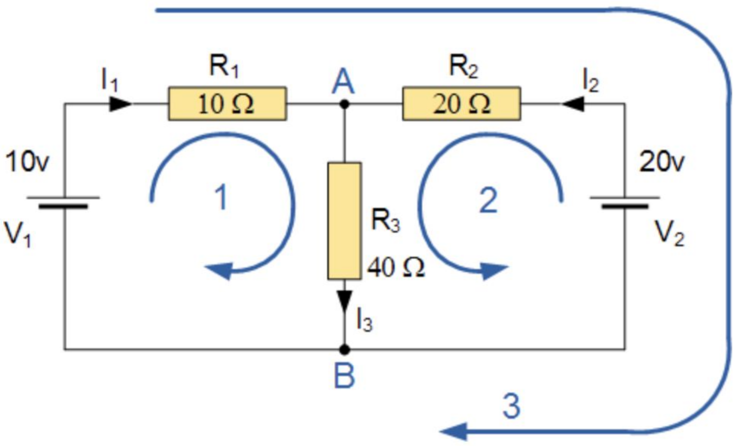

Fig. 61: The electrical system

Is it possible to make the same with the pneumatic circuits? What are the differences?

Questions

What is the Wheatstone Bridge used for?
Explain Kirchhof's laws.
What physical unit corresponds to the sound pressure according to the electroacoustic analogy?
What is the effect of using a throttle valve on the pressure?

Reference and recommended readings

West, J. B.: Respiratory Physiology: The Essentials. (7th ed.). Lippincott Williams and Wilkins, 2004.

Davis, P. D., Kenny, G. N. C: Basic Physics and Measurement in Anaesthesia. (5th ed.). Butterworth-Heinemann, 2003.

https://www.electronicshub.org/wheatstone-bridge/

4.9 Bernoulli equations, Losses in the pipeline

Goals

a) Students calculate the flows in individual parts of the pipeline based on Bernoulli's equation.
b) Students determine the losses occurring in individual parts of the pipeline.

Theory

Bernoulli's equation is a relation that expresses the law of conservation of mechanical energy for a steady flow of an ideal fluid:

$$\frac{1}{2}\rho v^2 + p + \rho g h = \mathrm{konst.} \tag{1}$$

where ρ is the density of the liquid, v is the flow velocity, p is the pressure in the liquid, g is the gravitational acceleration and h is the height of the water column. The first term in Bernoulli's equation is called the dynamic pressure and represents the volume density of kinetic energy, the second term represents the pressure potential energy of the fluid unit and the third term the potential energy of the fluid volume unit in the force field of external conservative mechanical force in which the fluid is located.

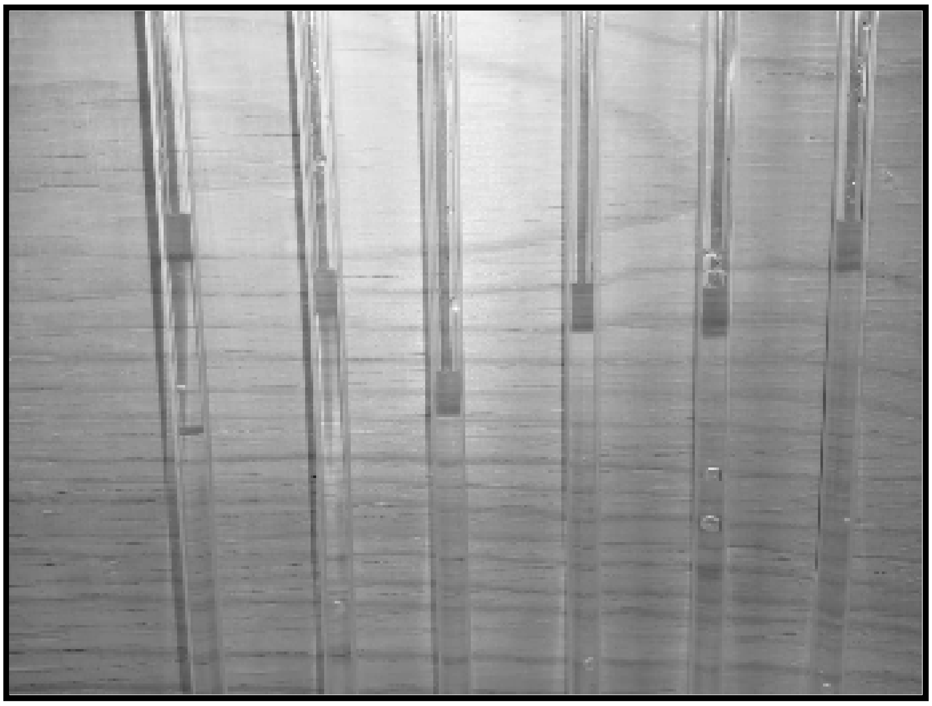

Fig. 62: Pressure change in Venturi tube due to flow rate change

In technical practice, we often need to calculate the friction pressure loss in a circular pipe. Because this loss depends on a number of factors (flow rate and medium temperature, material and pipe diameter, etc.), tables or nomograms are usually used to determine it.

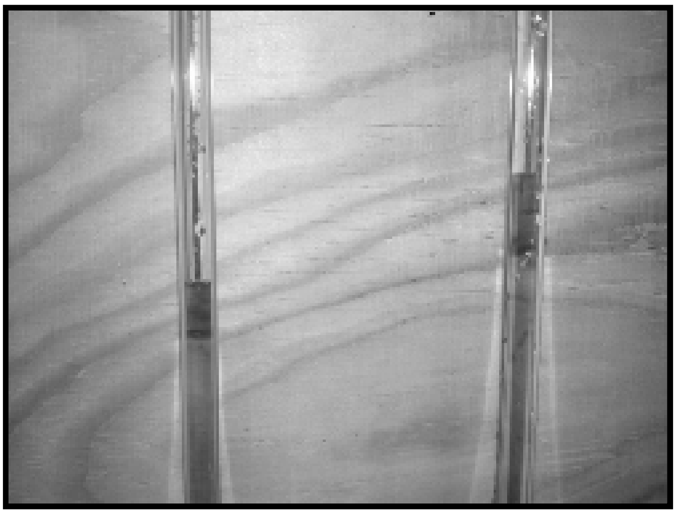

Fig. 63: Pressure drop due to pressure loss

Experiments

a) Theoretically determine the proportionally measured pressures in the capillaries based on the dimensions of the Venturi tube.

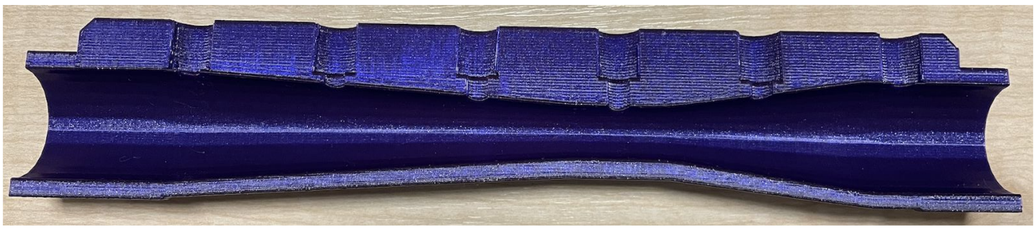

Fig. 64: Cross-section of the Venturi tube

b) Screw the individual capillaries into the threads (use teflon tape to ensure sufficient tightness of the apparatus).
c) Determine the internal diameters of the individual parts of the apparatus (the inside diameter of the flow meter and piping).
d) Connect the apparatus to the water pump (maximum 12 V).
e) Remove the bubbles in the capillaries with a long wire or use a ball valve to close the piping. (Water can flow into the big washer collecting the water in case of water leakage.)
f) Use a ball valve to ensure that the level is such that the differences are obvious.
g) Determine the flow using the flow meter in metres per second (calculate with the internal diameter of flow meter).
h) Measure the pressures in the Venturi tube and compare it to a theoretical proportionally values according to a).
i) Analyse the problem.

j) Is it possible to use a Bernoulli equation? Have you taken into account all members of Bernoulli's equation (static, stagnant, dynamic pressure)?

k) Determine the pressure drop between each capillary on the apparatus (1 cmH2O = 98.1 Pa).

l) According to the knowledge of flow and pressure in the capillaries, determine the resistance.

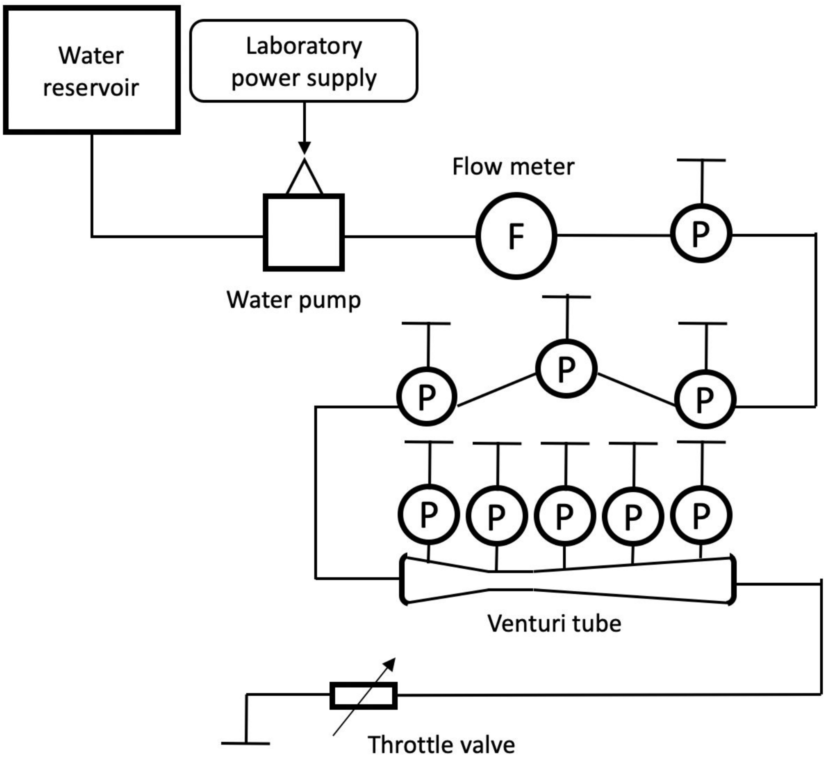

Fig. 65: A scheme of the apparatus for the measurement

Fig. 66: The disconnected apparatus

Fig. 67: The assembled apparatus

Fig. 68: The assembled apparatus with a water tank and a water pump

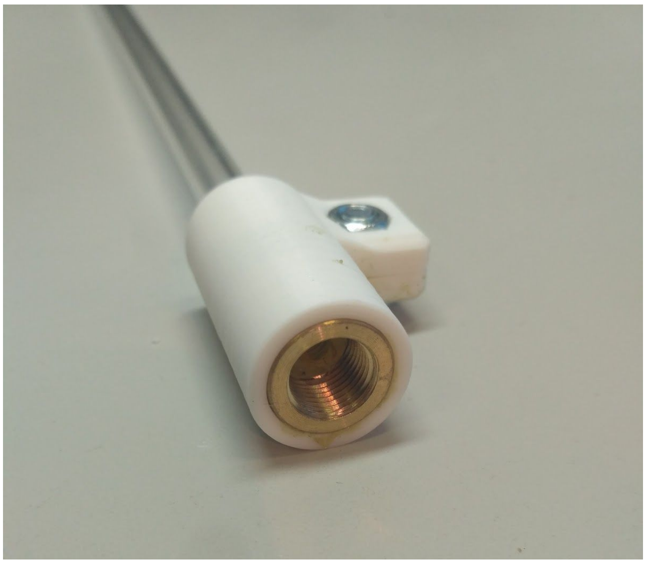

Fig. 69: A detail of the capillary sleeve

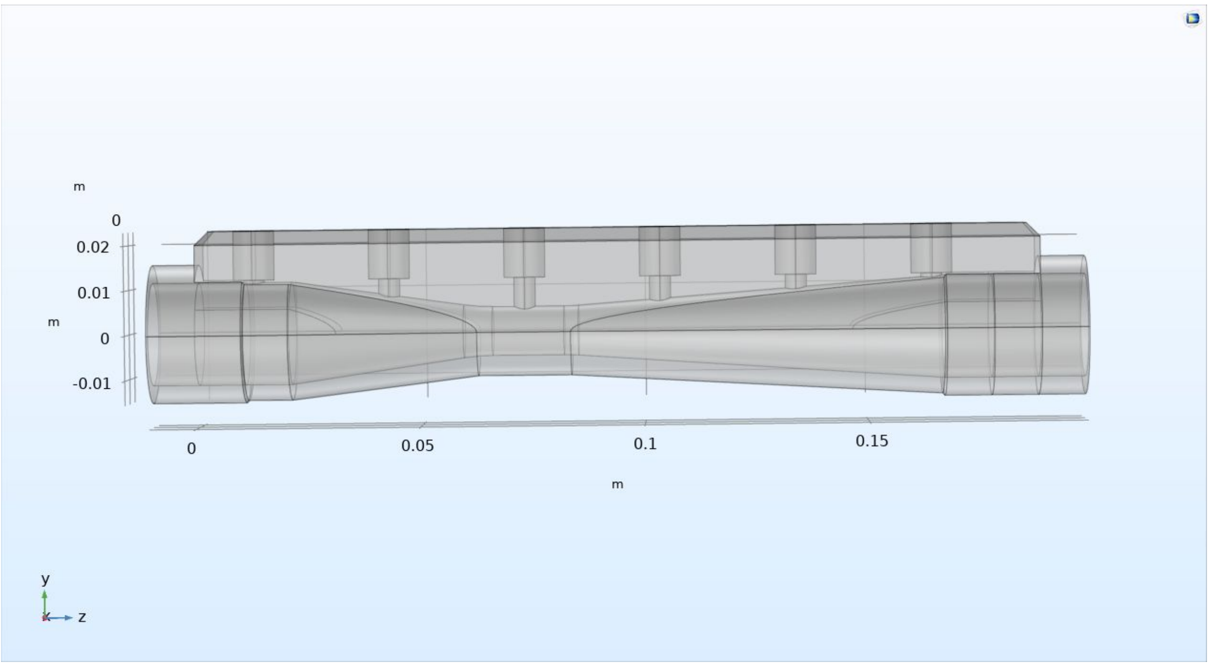

Fig. 70: Venturi tube profile

Equipment

The main apparatus, water pump, water tank, laboratory power supply, flow meter, capillaries to sampling points, washer for water collection in case of water leakage from sampling capillaries, meter.

Spare parts: pipes, spare Venturi tube, capillaries, flow meter

Examples

The air volume flow through a tube with a radius of 2 mm is 0.1 l/min at a static air pressure of 10 cmH2O. The air density is 1.12 kg /(m^3) and its temperature is 40 °C. Said tube then opens into another one stored in the device 20 cm higher with a radius of 1 mm. During the journey, the air temperature drops to 30 °C, which increases its density. Calculate the static pressure, air density and flow rate in the second tube. Neglect the energy losses of the air flow.

Questions

What is the difference between static and stagnation pressure?

Reference and recommended readings

Bernoulli's equation. Available at: http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html

FALAHATPISHEH, Ahmad. *Simplified Bernoulli's method significantly underestimates pulmonary transvalvular pressure drop*. Available from: doi:10.1002/jmri.25097

4.10 Static, stagnation a dynamic pressure - Pitot tube

Goals

a) To acquaint students with flow measurement using a pitot tube.
b) Point out the analogy with kinetic, potential and internal energy (the law of conservation of mechanical energy).

Theory

Pitot tube is a flow measurement device used to measure fluid flow velocity. The pitot tube was invented by the French engineer Henri Pitot in the early 18th century. It is usually used to determine the airspeed of an aircraft, water speed of a boat, and to measure liquid, air and gas flow velocities in certain industrial applications. The basic pitot tube consists of a tube pointing directly into the fluid flow. As this tube contains fluid, a pressure can be measured; the moving fluid is brought to rest (stagnates) as there is no outlet to allow flow to continue. This pressure is the stagnation pressure of the fluid, also known as the total pressure or (particularly in aviation) the pitot pressure.

The measured stagnation pressure cannot itself be used to determine the fluid flow velocity (airspeed in aviation). However, Bernoulli's equation states:

Stagnation pressure = static pressure + dynamic pressure

Which can also be written

$$p_t = p_s + \left(\frac{\rho u^2}{2}\right), \tag{1}$$

solving that for flow velocity gives

$$u = \sqrt{\frac{2\,\Delta h\,\rho_l g}{\rho}}, \tag{2}$$

where $\boldsymbol{u}$ is the flow velocity, $\boldsymbol{p_t}$ is the stagnation or total pressure, $\boldsymbol{p_s}$ is the static pressure, $\boldsymbol{\rho}$ is the fluid density, $\boldsymbol{\Delta h}$ is the height difference of the columns, $\boldsymbol{\rho_l}$ is the density of the liquid in the manometer and g is the standard acceleration due to gravity.

Note: 1 cmH2O = 98.1 Pa.

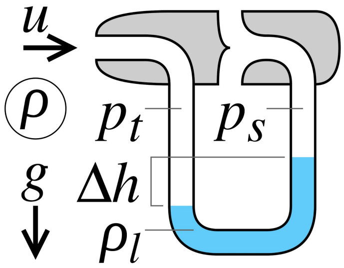

Fig. 71: A scheme of the U-meter

Experiments

a) Assemble the apparatus according to figure 1.
b) Pour liquid (water, oil, low density liquids) into the capillaries in the U-tube to the 18 cm mark.
c) Slowly release the flow into the tube.
d) Record the level differences for different random flows.
e) Based on the calculation, determine the flow in the tube in litres per minute.
f) Determine the maximum flow from the air distribution system.
g) What fluid in the U-tube captures the lowest flow?
h) Determine static, dynamic and stagnation pressure in the tube (be careful about high pressure differences because of overflow from one of the capillaries).
i) Slightly plug the end of the tube and observe the change in all pressures.

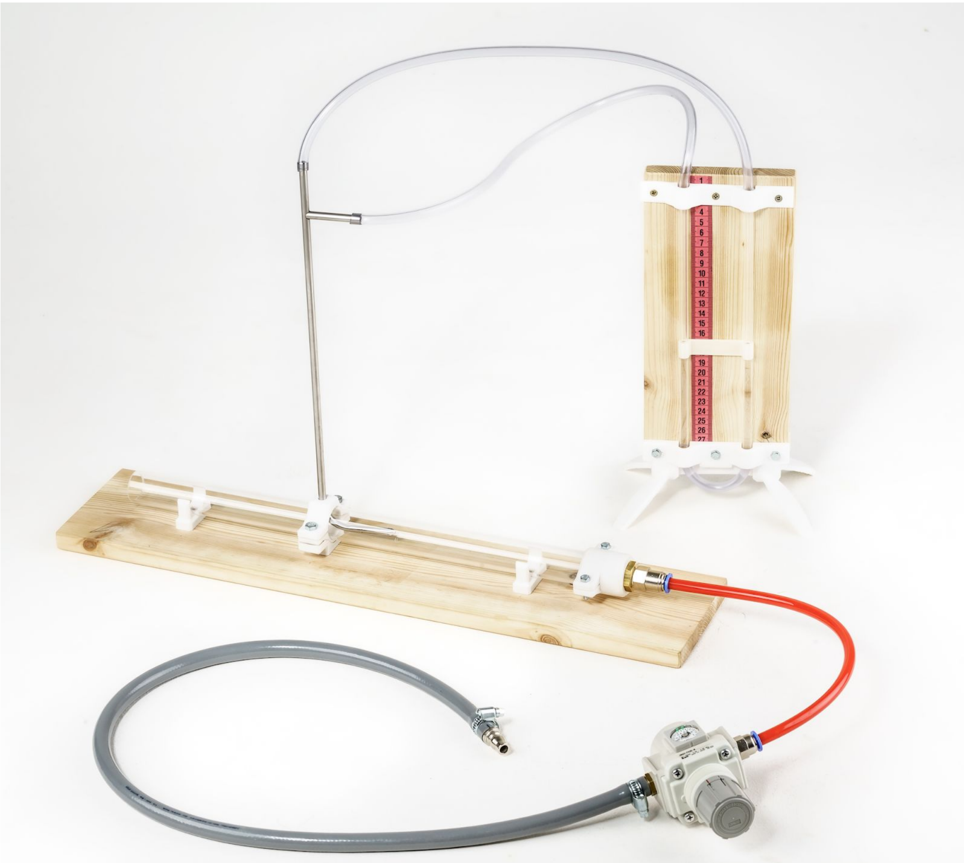

Fig. 72: The assembled measuring apparatus

Fig. 73: Fixing the Pitot tube to the interior of the flow pipe

Fig. 74: A stand with capillaries for displaying the difference in levels during air flow

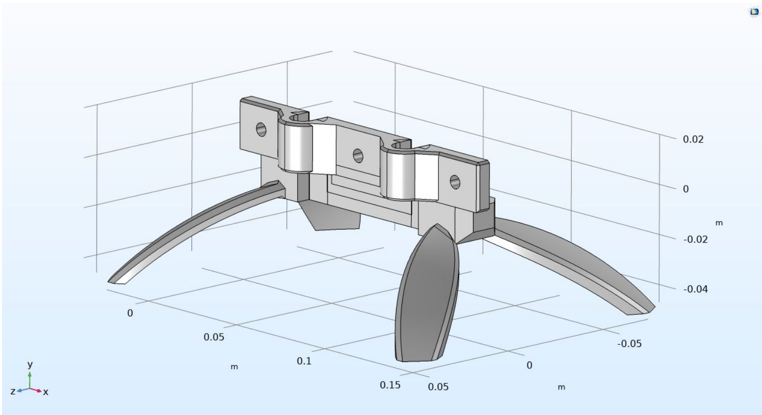

Fig. 75: The stand in COMSOL Multiphysics program

Examples

Consider a steady, incompressible flow of water in a tube of circular cross-section with a radius of 3 cm. Perpendicularly upwards, there is an outlet in the tube in which the level is 7 cm (point 1 in the figure is in the center of the tube below the outlet). Behind this outlet, a Pitot tube is placed in the tube, in which we read the level height of 19 cm (point 2, Stagnation point in the picture). The difference in level heights in the outlet and in the Pitot tube is therefore 12 cm. Calculate the water flow velocity v1 in the center of the tube. Neglect energy losses of water flow.

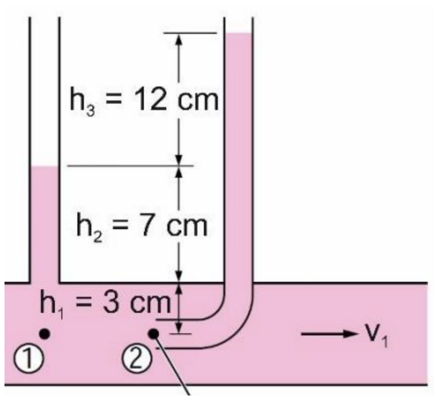

Fig. 76: A picture for the calculation of the flow rate

Equipment

Air distribution system
Pitot tube
Plexiglass tube
Stand with U-tube
3D printed ABS parts and components
10mm tube

Pressure reducing valve

Questions

What is the flow in the tube when Reynolds number is 2300? Does it affect measured pressures?

Reference and recommended readings

Pitot tube. Available from: https://en.wikipedia.org/wiki/Pitot_tube

WOLF, A. R. *A modified Pitot tube for the accurate measurement of tidal volume in children*. Available from: doi:10.1097/00000542-198711000-00023

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