Plumbing

Laboratory tasks specially developed by Non-conventional Ventilatory Team (NVT) at the Faculty of Biomedical Engineering at the Czech Technical University in Prague for education at the University of Health Sciences and the Institute of Technology of Cambodia in order to increase knowledge in the field of Biomedical Engineering:

1. Gas distribution system and proper handling with air-compressor
2. Electro-Pneumatics in air distribution systems
3. Air drier in distribution systems
4. Pressure, pressure reducing valve and manipulation with pressure vessel
5. Valves in medicine
6. Vacuum, suction units in medicine
7. Gas blending in medicine
8. Humidifiers and Nebulizers
9. Torricelli's law
10. Water pumps

Content

1. List of quantities

Quantity	Symbol	Unit
Volume	V	m^3, L
Volume flow rate	Q	$m^3 \cdot s^{-1}$
Pressure	P, p	Bar, Pa, cmH_2O
Force	F	N
Cross-section area	S	m^2
Partial steam pressure	P_{H2O}	kPa
Partial steam volume	V_{H2O}	m^3, L
Saturated water vapor	P''	kPa
Relative humidity / Speed outflow coefficient	φ	-
Normal air pressure	p_n	Atm, Pa
Amount of substance	n	mol
Molar gas constant	R	$J \cdot K^{-1} \cdot mol^{-1}$
Thermodynamic temperature	T	K, °C
Density	ρ	$kg \cdot m^{-3}$
Velocity	v	$m \cdot s^{-1}$
Gravitational acceleration	g	$m \cdot s^{-2}$
Height	h	m
Narrowing factor	ε	-
Area of hole at outlet	S_0	m^2
Time	t	s

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*.

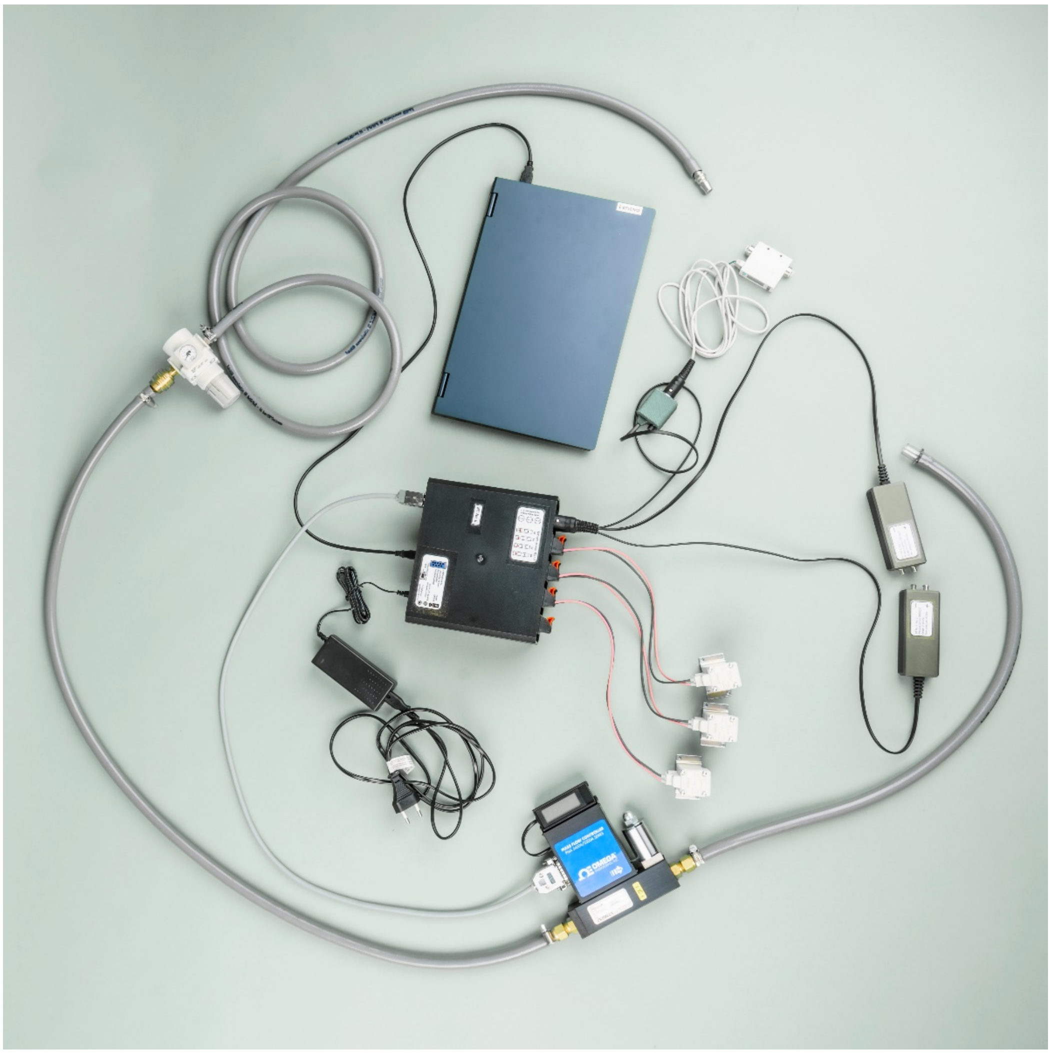

Fig. 1: A fully assembled PNEHYKUR kit 2.0

2.1 Every PNEHYKUR kit 2.0 contains:

1. PC
2. Meluzína
3. Pressure reducing valve
4. 2x pressure sensor
5. Air flowmeter 0–100 L/min with G1/4 or 6mm connector
6. Connector between Meluzína and OMEGA FMA5400 flow controller
7. Power adapter
8. Power supply 12V
9. Connector between Meluzína and PC
10. 2x extension cable for the air flowmeter
11. Manometers (2x 0–1 Bar, 2x 0–4 Bar, 0–8 kPa, 0–100 mbar, 0–100 cmH_2O)
12. Thermometer with 4mm connector
13. 3x 2/2 electromagnetic solenoid
14. Throttling scissors
15. 2x teflon tape
16. 6mm particulate filter
17. 6mm pressure indicator
18. 6mm ball valve with release
19. 2x internal G3/8 connector
20. Push-in coupler with external G1/4 connector
21. Push-in coupler with internal G1/4 connector
22. Push-in quick coupler (Asian type)
23. Push-in quick coupler (European type)
24. 6x 6mm straight coupler with external G1/4 connector
25. 2x 6mm T-connector with internal G1/4 connector
26. 6x 6mm straight coupler with internal G1/4 connector
27. Pressure relief valve
28. Muffler
29. 4x sealing ring
30. 2x internal reduction
31. Female quick coupler with external G1/4 connector (European type)
32. 2x 6mm straight connector
33. 3x 6mm–4mm straight connector
34. 6mm Y-connector
35. 4x 6mm T-connector
36. 6mm X-connector
37. 2x 6mm ball valve
38. 2x 6mm throttle valve

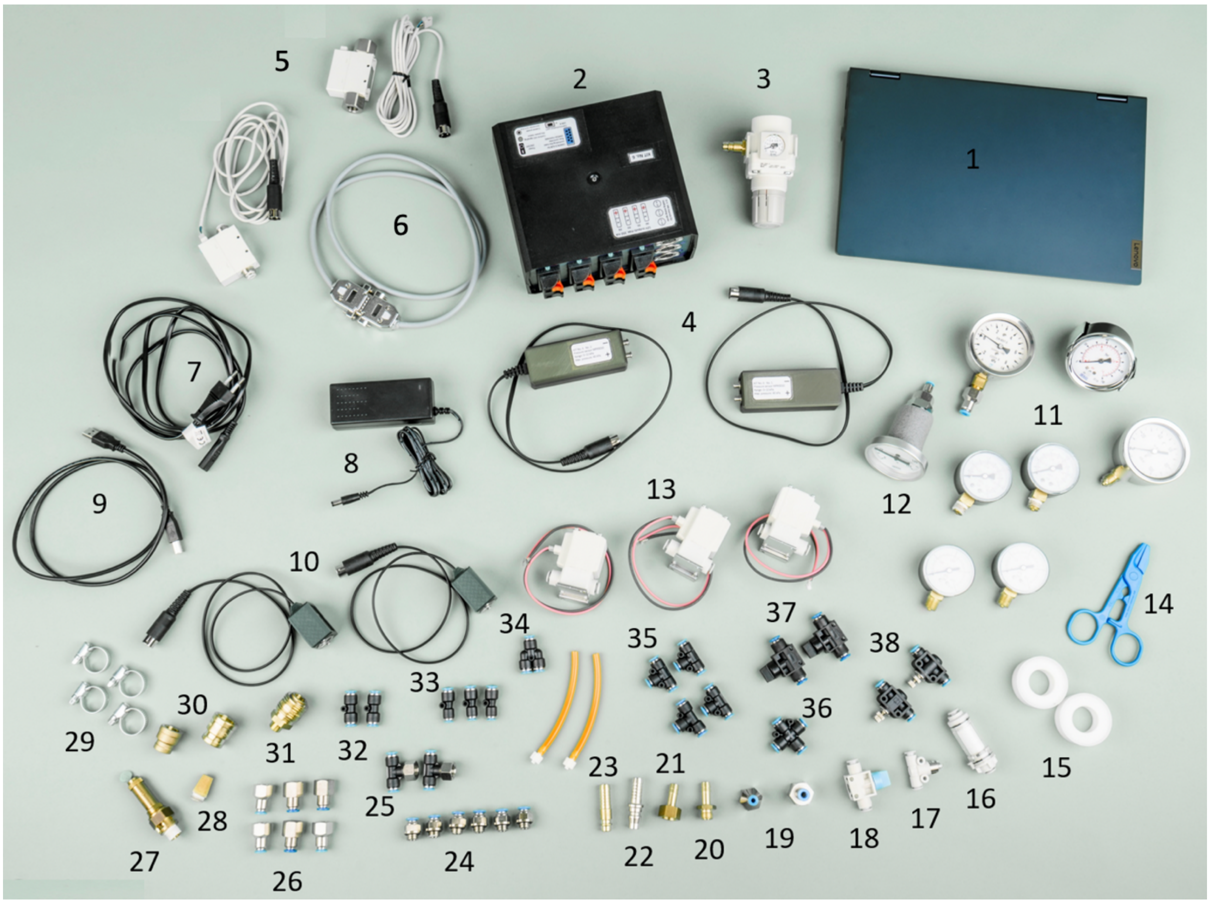

Fig. 2: All components of the PNEHYKUR kit 2.0

3. Software for Plumbing laboratory tasks

1. ---
2. ---
3. Omega control / Valve cycling
4. ---
5. Manual PQ measurement
6. Pressure measurement
7. Valve cycling / Pressure measurement
8. Valve cycling
9. ---
10. Valve cycling

4. Plumbing laboratory tasks

4.1 Gas distribution system and proper handling with air-compressor

Goals

a) To acquaint students with the principle of operation of the compressor and air treatment in air distribution systems.
b) Teach students to perform basic compressor maintenance.
c) To acquaint students with the basic elements of air distribution and with the basic plumbing parts and components.

Theory

The use of compressed air dates to antiquity. It has its fixed place in use for drives, control and regulation of machines and other equipment. Compressed air has many uses. On the one hand, it measures the pressure of the fluid in the human eye, on the other hand, it is used to drive a drill for drilling in concrete.

The basic compressed air circuit consists of two main sections:

a) Production, treatment, and distribution of compressed air

1) Compressor - Air is sucked in by a compressor, compressed and then transported to the distribution network.

2) Electric motor - It is a source of mechanical force of the compressor. Converts electrical energy to mechanical energy.

3) Pressure switch - Controls the operation of the electric motor according to the air pressure in the air reservoir.

4) Check valve - Allows air to flow from the compressor to the air reservoir.

5) Air reservoir - It serves as a reservoir for compressed air.

6) Manometer - Measures the air pressure in the air vent.

7) Condensate drain - A device designed to drain condensate.

8) Pressure relief valve - Safety element to prevent the operating pressure in the air reservoir from being exceeded.

9) Air dryer - Cooling the compressed air separates the condensate.

10) Filter - Separates dirt, condensate, and oil before entering the air distribution duct.

b) Distribution of compressed air to the place of its consumption

11) Branches - They are connected to the compressed air distribution system so that condensate from the main distribution branch cannot flow into them.

12) Condensate drain - The piping must be able to drain condensate at the lowest point.

13) Compressed air treatment - Provides air with the required purity and optimum pressure.

14) Consumption points - Places allowing connection to the compressed air supply.

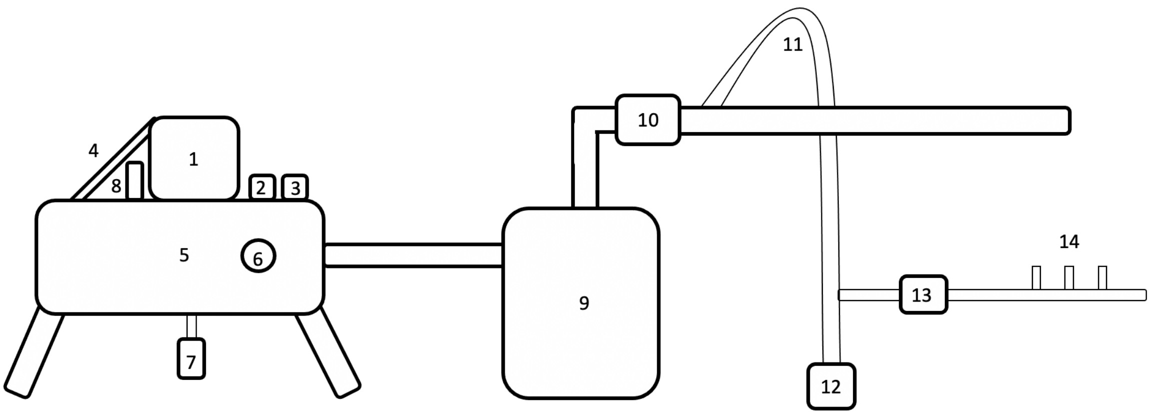

Fig. 3: A basic circuit with compressed air

The compressor is used to compress the air. The amount of air supplied, and the maximum achievable pressure are decisive for choosing the right compressor. Linear compressors are divided into piston and diaphragm. In a piston compressor, air is sucked in as the piston moves from the cylinder head and is compressed by the movement of the piston to the cylinder head. In the case of a diaphragm compressor, the drive (gear) is separated from the compression space. These compressors deliver clean, oil-free air, which is used mainly in healthcare. Other types of compressors are the so-called vane (lamellar) compressor and screw compressor. Both compressors use rotary motion. The vane type compressor has a rotor with grooves in which the blades move. As the rotor rotates, the blades extend and press against the compressor wall. The space between the blades decreases and thus the intake air is compressed. In the screw type, the two rotors rotate against each other. The space between the rotors decreases as it moves, which compresses the air.

The air reservoirs ensure a smooth and stable distribution of compressed air. If the product of the volume of the air reservoir V (L) and the overpressure p (MPa) is greater than 10, then the air reservoir is considered to be a pressure vessel and is subject to regular inspections and pressure tests. The air tank must be equipped with a pressure relief valve, manometer, and condensate trap. Drops of water in the air are trapped and flow into the sump as they pass through the separator. After reaching a certain level of condensate, the float opens the valve and discharges the condensate into the prepared collection container. There can be up to 40 million solid particles in 1 m^3 of air at atmospheric pressure. It is therefore necessary to use a suitable and efficient filter for the compressor to function properly.

For correct and trouble-free operation, it is necessary to perform basic maintenance of the compressor:

Suction filter - Ambient air flows into the compressor via the suction filter. If the filter is clogged with dirt, the compressor performance will be reduced. If the filter even ruptures, dirt may enter the compressor unit and damage it. Filters must be kept clean, clear. If the filter can no longer be cleaned or is damaged, the filter insert must be replaced.

Oil - Check the oil mark or dipstick to see if there is enough oil in the compressor and top it up regularly. When changing the oil, the compressor must be disconnected from the mains and must be "depressurized".

Condensed water in the air reservoir - Condensed water may accumulate in the air tank during compressor operation. This can impair the trouble-free and economical operation of the compressor, as the compressor must then switch on more often. Water can even enter pipes or hoses. Therefore, check the air vent regularly and drain the water using the drain valve on the bottom wall of the air reservoir.

Dryer - Dryers are not maintenance intensive. Depending on the type of dryer, we either clean the condenser or change the contents with the drying material.

Fasteners

In pneumatic circuits it is necessary to use connecting material (fasteners). Plug-in couplings are the simplest system for connecting plastic hoses. Insert the hose into the coupling, where the hose will easily get stuck in the connection and will hold perfectly. To remove the coupling, simply release the pressure, press the ring, and pull out the hose. For this type of coupling, it depends on the outer diameter of the hose, where a diameter of 4, 6, 8 or 10 mm is usually used. The screw connection allows you a quality connection. However, with the wrong choice, there will undoubtedly be a media leak. Nickel-plated fittings and brass fittings are mainly used in compressed air for automation, measuring and control technology. You can combine stainless steel fittings with the highest demands on hygiene. When choosing a fitting, pay close attention to the threads - in the assortment you will most often encounter threads G, R and M.

Fasteners are also used in anesthesiology and intensive care. However, the dimensions, shape and material of these couplings are different. Typical dimensions of these couplings are 15-mm or 22-mm inner diameters and 15-mm or 22-mm mm outer diameters. The coupling has a standard conical shape to jam sufficiently into another coupling. Many of these couplings are complemented by a sampling point that uses a so-called Luer lock.

Experiments

1. The main air-compressor

a) Identify the individual parts of your compressor.
b) Perform (simulate) basic compressor maintenance according to the theory for this exercise or according to the instructions of your compressor supplier.

2. Panel model of the gas distribution system - Pneumate 200 - E

a) Plug in the small compressor.
b) Plug in the panel model and turn it on.
c) Connect the 4mm hose to the compressor and to the pressure reducing valve at the top left of the panel model and close the ball valve.
d) Set the outlet pressure to 3 Bar.
e) Connect the hose to the element marked DIS (division of the system into several branches).
f) When you finish the preparation of the task, open the ball valve.

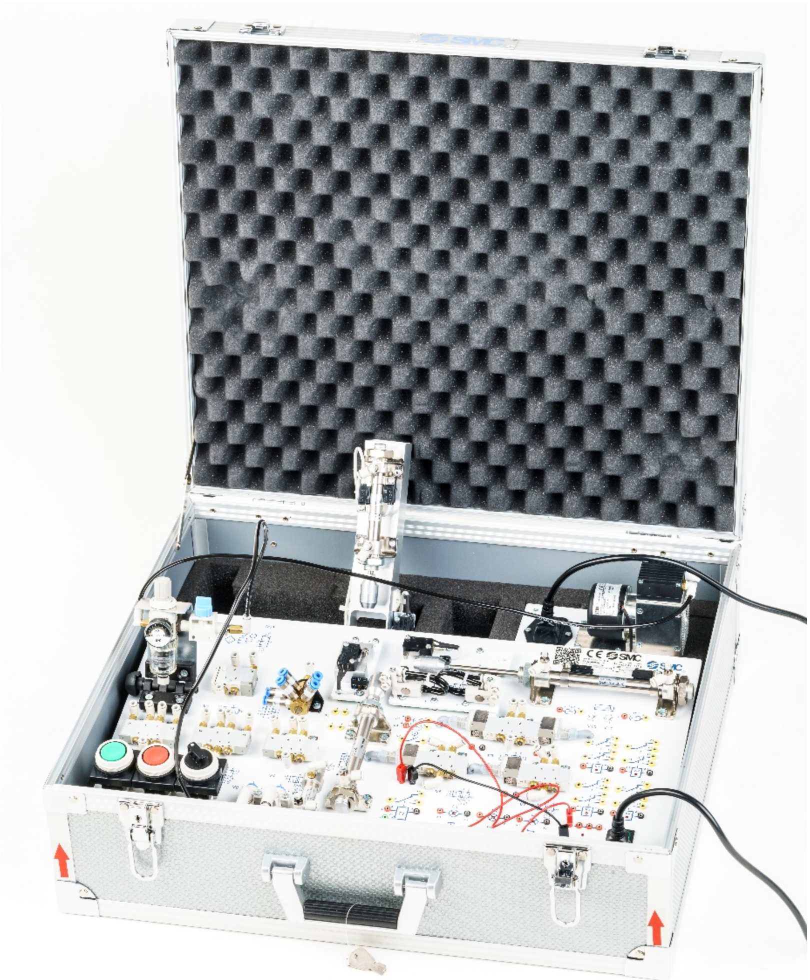

Fig. 4: Pneumate 200 – E

Fig. 5: The air-compressor of the Pneumate 200 – E

2.1 Purification of supplied air

a) Add a particulate filter in front of the pressure reducing valve.


Fig. 6: Particulate filter

2.2 Measurement of air temperature in the system

a) Measure the air temperature between the OZ1 ball valve and the DIS element.

Fig. 7: Thermometer

2.3 Double acting cylinder V10 / V11 control

a) Connect one hose to the outlet of the DIS element and connect it to the input of the green mechanical button.
b) Connect the output of the button to one input of the Double acting cylinder V10 / V11.
c) Connect another hose to the outlet of the DIS element and connect it to the input of the red mechanical button.
d) Connect the output of the button to one input of the Double acting cylinder V10 / V11.
e) Press the buttons to control the Double acting cylinder V10 / V11.
f) Test the effect of the throttle valves on the Double acting cylinder V10 / V11 on the piston movement.

2.4 Measurement of air pressure in the system

a) Connect pressure gauges between the button output and the Double acting cylinder V10 / V11 input.
b) Watch for changes as you press buttons.

Fig. 8: Pressure gauges

2.5 Pressure indicator valves

a) Try the connection of the pressure indicator valve in the system.

Fig. 9: Pressure indicator

2.6 Pressure relief valve

a) Try the connection of the pressure relief valve (0.4 bar) in the system.

Fig. 10: Pressure relief valve

Equipment

Pneumate 200 - E with accessories
The main air-compressor
Additional parts from the PNEHYKUR kit 2.0

Questions

What causes a reduction in the outlet pressure of the pressure reducing valve?
What can result in air pollution in the distribution system?
Where would you use a double acting cylinder?

Reference

SMC training - https://www.smctraining.com/en/webpage/indexpage/455
SMC Brochure (included in the Pneumate 200 kit)

4.2 Electro-Pneumatics

Goals

a) To acquaint students with the use of valves in air distribution.
b) To teach students to work with mechanically and electromagnetically controlled valves.

Theory

The valve is a mechanical device regulating the flow of fluids (gases, liquids, or liquefied solids) in the pipeline. The valves make it possible to control pneumatic actuators, the direction of air flow or to be part of logic control circuits. Some valves allow you to control the pressure or flow of compressed air.

Valves can be found in every industrial process. People use valves in their daily lives, including plumbing valves, gas or small valves fitted to washing machines. Also, in nature exists valves (one-way valves in veins controlling the blood circulation, and heart valves controlling the flow of blood).

According to the method of control, we distinguish between valves for valves operated mechanically, by human force, air and electromagnetically. Mechanically and pneumatically operated valves are used to control simple mechanisms. For air-operated valves, the slide is displaced by the pressure of the air supplied to the valve control chamber. Controlling valves with solenoids is one of the most widely used control methods. When electric current flows through the coil, the magnetomotor force pulls the solenoid armature against the spring pressure upwards and the valve opens.

Another way to divide valves is by number of inputs and outputs. Operating positions for 2-port valves can be either shut (closed) so that no flow at all goes through, fully open for maximum flow, or sometimes partially open to any degree in between. Valves with three ports serve many different functions.

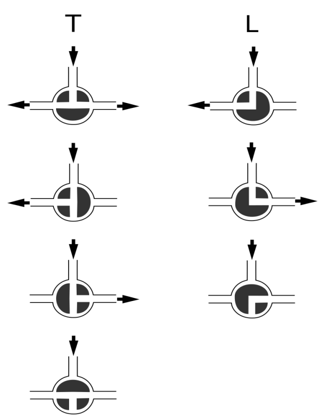

Fig. 11: Schematic 3-way ball valve: L-shaped ball right, T-shaped left
Source: https://en.wikipedia.org/wiki/Valve

Furthermore, we can divide the valves into Monostable and Bistable. The monostable valves return to their initial position immediately after the control signal is canceled. The impulse to operate the valve (electrical, mechanical, manual, etc.) must last as long as it is moved to the desired position. The bistable valve has no defined starting position. Two independent pulses are needed to control it. The bistable valve remains in the position corresponding to the last impulse for its adjustment after adjustment.

Sometimes it is useful to use logic valves in pneumatic circuits. “OR” - allows the flow of compressed air only if we apply pressure to one, the other or to both inlets at the same time. “AND” - allows compressed air only if pressure is present in both inlet ducts.

Valve positions are operating conditions determined by the position of the disc in the valve. Some valves are made to be operated in a gradual change between two or more positions. Typical valves and their schematic symbols are shown in the picture.

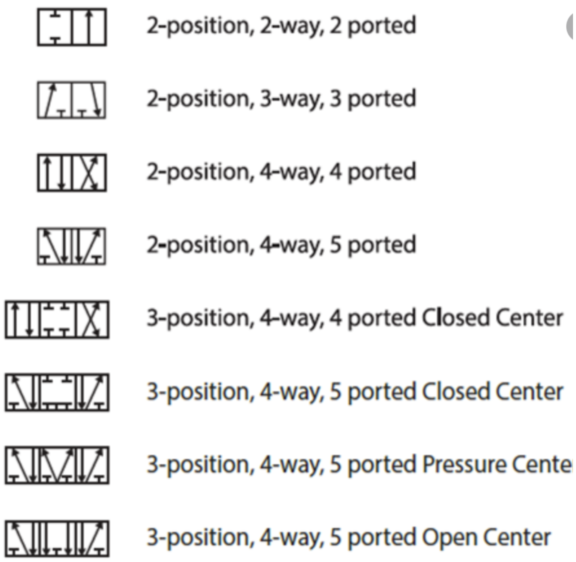

Fig. 12: Typical valves and their symbols
Source: https://www.instrumentationtoolbox.com/2016/10/common-symbols-used-in-pneumatic.html

Experiments

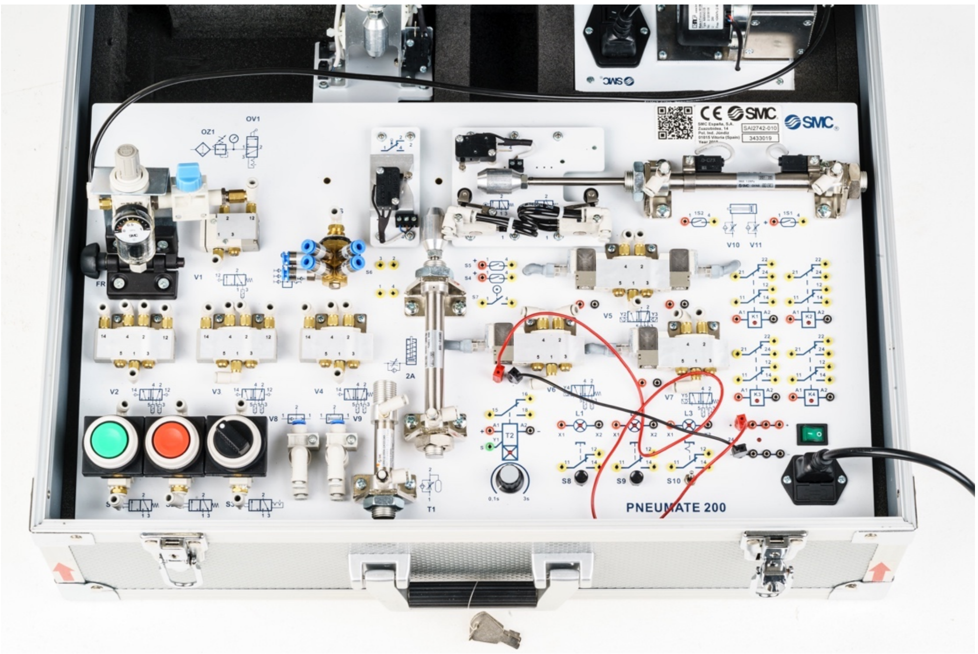

Fig. 13: Pneumate 200 – E

1. Panel model of the gas distribution system - Pneumate 200 - E

a) Plug in the small compressor.
b) Plug in the panel model and turn it on.
c) Connect the 4mm hose to the compressor and to the pressure reducing valve at the top left of the panel model and close the ball valve.
d) Set the outlet pressure to 3 bar.
e) Connect the hose to the element marked DIS (division of the system into several branches).
f) When you finish the preparation of the task open the ball valve.

1.1 Pneumatic logic - OR / AND

a) Connect the hose to the outlet of the DIS element and to the lower inlet of the V8 element.
b) Connect the hose to the output of the DIS element and to the input of the green button.
c) Connect the output of the green button to the upper input of the V8 element.
d) Connect the output of the V8 element to the single acting cylinder 2A.
e) Open the ball valve and test the push-button effect.
f) Do the same for V9 and discuss the differences.

1.2 Pneumatic valves

a) Operate the Double acting cylinder V10 / V11 via the V3 element (5/2-way pneumatic double valve).
b) Connect outputs 4 and 2 of element V3 to Double acting cylinder V10 / V11.
c) Connect the input of the V3 element to the DIS element.
d) Check the switching of the outputs of the element V3, which control the Double acting cylinder V10 / V11, with the mechanical red and green button.
e) Try the same with V4 (5/2-way pneumatic single valve).

1.3 Electromagnetic valves

a) Use the V5 element to control the Double acting cylinder V10 / V11 control.
b) Connect the red socket on the left of element V5 to socket 12 of element S10 via the red socket of element L1.
c) Connect the black socket on the left of element V5 to the black socket on the bottom right via the black socket of element L1.
d) Connect the socket 11 of the S10 element to the 24V DC at the bottom right.
e) Connect the red socket on the right of element V5 to the socket 14 of element S10 via the red socket of element L2.
f) Connect the black socket on the right of the V5 element to the black socket on the bottom right via the black socket of the L2 element.

1.4 Combination of Pneumatic and Electromagnetic valves

a) Repeat the points from task 2.3 (Double acting cylinder V10 / V11 control) of laboratory task No. 1.
b) Closing the Double acting cylinder V10 / V11 connects the valve V6.
c) Valve V6 causes the single acting cylinder 2A to open.
d) Connect the red wire to the red 24V socket at the bottom right and to the red socket of element S1.
e) Connect the yellow socket of element S1 to the red socket of element V6.
f) Connect the black socket of the V6 element to the black socket at the bottom right.
g) Connect one output of element V6 to single acting cylinder 2A.
h) Block the second outlet of the V6 element.
i) If it works, insert the delay element T2 into the circuit.

Equipment

Pneumate 200 - E with accessories
Additional parts from the PNEHYKUR kit 2.0

Questions

What is the advantage of electronically controlled valves?
What is the difference between a 5/2 way pneumatic single and double valve?
Where would you use an AND type pneumatic valve?

Reference

Christopher., Dickenson, T. (1999). *Valves, piping, and pipelines handbook*(3rd ed.). Oxford, UK: Elsevier Advanced Technology. ISBN 9781856172523. OCLC 41137607.

https://tameson.com/check-valves.html

https://en.wikipedia.org/wiki/Valve

4.3 Air dryers in distribution systems

Goals

a) Experimentally acquaint students with the principles of air drying.
b) Explain to students the importance of air drying.

Theory

If the air is humid, it contains water vapor as a gas. The same laws (Dalton's law, Equation of state, etc.) and the same relations apply to water vapor. The only difference is that we must be careful not to make such a change with the humid air that would result in the liquefaction of part of the water vapor contained in the humid air (condensation of water in the ventilator circuit). When the liquid meets dry air, it begins to evaporate. Saturation occurs when further addition of water molecules to the gas causes water to coagulate and thus water droplets to form. This condition is called saturated steam. This vapor contributes to the total volume of gas above the liquid and, according to Dalton's law, also contributes to the total pressure. The partial steam pressure P_{H2O} can be calculated from the total pressure P, the steam volume V_{H2O} and the total volume V:

$$P_{H2O} = P \cdot \frac{V_{H2O}}{V} \tag{1}$$

If this partial pressure is calculated for the maximum volume of water vapor that can exist in a gaseous mixture above the liquid, this partial vapor pressure is called the saturated vapor pressure and is denoted *P”.*

Saturated steam pressure depends only on the temperature. For this reason, saturated vapor pressure is the basic variable for solving the problems of liquid evaporation and gas vapor saturation.

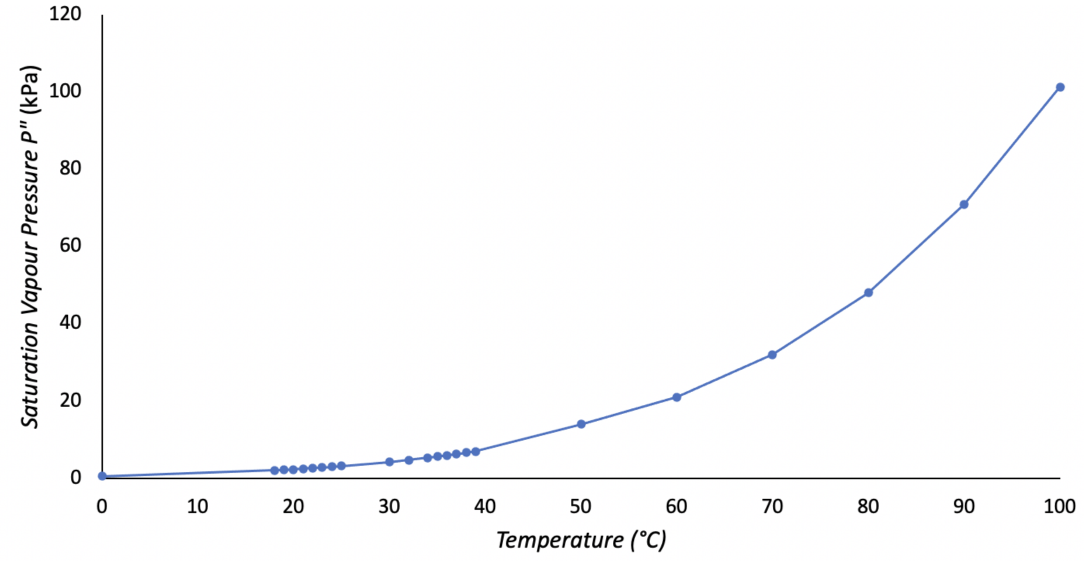

Fig. 14: Graph of the dependence of saturated water vapor pressure on temperature.

If the steam content at a given temperature in the air is not the maximum possible, the gas is not fully saturated with steam and therefore does not contain saturated steam. The partial steam pressure is less than the saturated steam pressure at a given temperature. We call this superheated steam. When we know the terms saturated and superheated steam, it is possible to define the relative humidity. It is defined as the ratio of the partial pressure of water vapor in the studied gas P_{H2O} to the pressure of saturated water vapor P'' at the same temperature:

$$\varphi = \frac{P_{H2O}}{P''} \tag{2}$$

Relative humidity is expressed either as a dimensionless decimal number or as a percentage. If the partial pressure of water vapor in the gas is equal to the pressure of saturated steam, the relative humidity is 100%. The dew point temperature is the temperature of such saturated steam, the pressure of which is identical with the actual value of the partial pressure of water vapor. When cooled below this temperature, the water from the mixture begins to condense.

Compressed air is produced by compressing atmospheric air, which always contains a certain amount of water. It is not a defect if it remains in a gaseous state, i.e. as water vapor. However, the compressed air can cool down on the way to the appliances and the water vapor will partially or completely liquefy and can cause considerable damage: wear and damage to pneumatic tools and machines, clogging of valves and orifices and corrosion of pipes. This, of course, increases maintenance costs.

The warmer the air, the more steam it absorbs without the steam starting to condense. Water droplets begin to form in the air as soon as the air cools below a temperature called the dew point. If the air has a dew point temperature, it is completely saturated with water vapor (relative humidity reaches 100%). When the air cools below the dew point temperature, the water vapor turns into water. The goal of air drying is to reduce the amount of water vapor in the air so that the dew point reaches the desired value. In order to be able to use the compressed air at normal temperatures, it is advisable for its pressure dew point to be 10 °C lower than the operating temperature.

Absolute humidity - The weight of water vapor in grams contained in cubic meters of air

Relative humidity - The ratio in percent between the amount of water vapor in the air and the amount of vapor that air with the same pressure and temperature would have at full saturation

Dew point (dew point temperature) - The temperature at which the air is maximally saturated with water vapor (relative humidity reaches 100%)

Pressure dew point - The temperature at which steam in compressed air condenses at a given pressure

We use so-called air dryers to remove water from the air. We recognize the basic 2 types, which differ in their principle of removing water from the air.

In condensing dryers, the compressed air is first cooled to a temperature lower than the pressure dew point temperature. This condenses water vapor in the air and turns it into water, which is removed from the air. The air is cooled in a heat exchanger, where the refrigerant removes heat from the moist warm air. The exchanger has two circuits, for refrigerant and for air, so that the air does not come into direct contact with the refrigerant.

In adsorption dryers, the air is dried by flowing through a vessel filled with a drying material which binds water to itself. Water adheres to its surface or in its pores and dry air comes out of the container. The drying material must be very porous, most often activated alumina alumogel (Al_2O_3) or silica gel (SiO_2) is used. The drying material is saturated with moisture from the air within a few minutes and is not capable of further adsorption. Therefore, the air is redirected by valve systems to the second drying branch, where the regenerated drying material awaits it.

Experiments

1. Condensing dryer

1.1 Peltier effect

a) Assemble the apparatus according to the scheme.
b) Maximum of 2 Bar at the pressure reducing valve.
c) Pour enough water into the humidifier (Fisher-Paykel) and connect it to the power supply.
d) Switch on the humidifier and let it warm up with water for 10 minutes.
e) Set the flow rate using the software for flow controlling of Omega FMA5400 to 5 L/min.
f) Connect the dryer to a power source.

g) Use the hygrometer Testo 625 to check the humidification and the temperature before entering the humidifier and behind the humidifier.
h) At a time of 90-100% air saturation with water, connect the dryer behind the humidifier.
i) Measure the temperature and humidity of the air at the outlet of the dryer.
j) Determine the efficiency of the dryer.

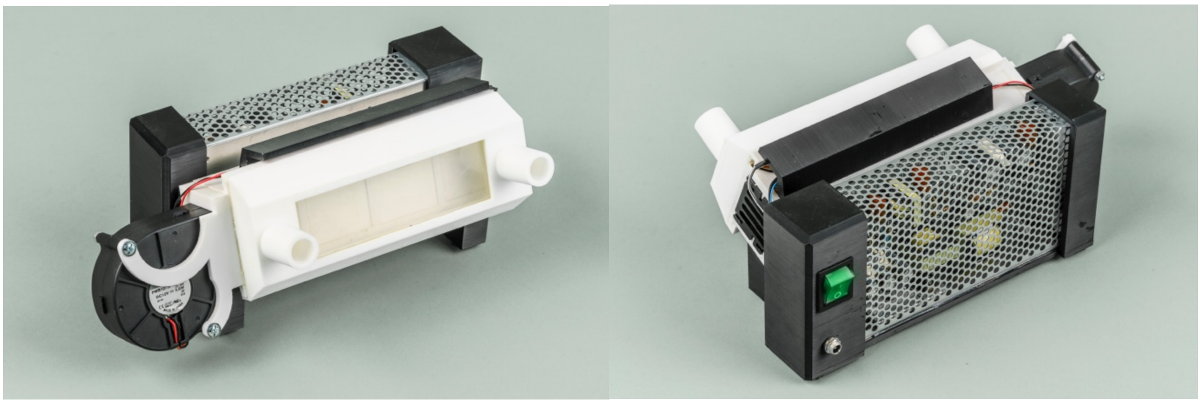

Fig. 15: Peltier dryer

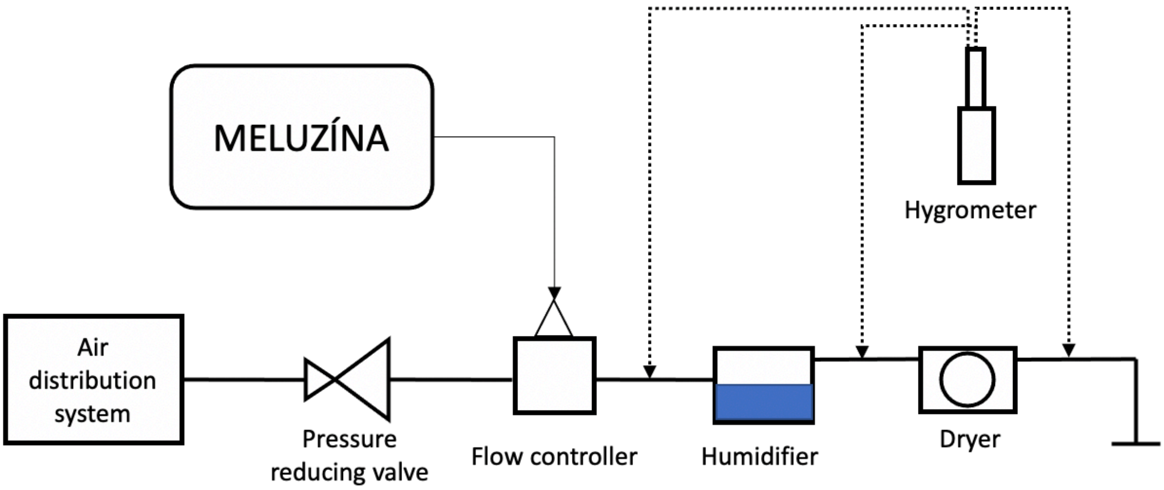

Fig. 16: A scheme of the Peltier apparatus

Fig. 17: The Peltier apparatus

1.2 Cooling mixture

a) Assemble the apparatus according to the diagram.
b) Maximum of 2 Bar at the pressure reducing valve.
c) Pour enough water into the humidifier (Fisher-Paykel) and connect it to the power supply.
d) Prepare a container with water and ice.
e) Switch on the 12V water pump using software for valve controlling or laboratory power supply.
f) Switch on the humidifier and let it warm up with water for 10 minutes.
g) Set the flow rate using the software for flow controlling of Omega FMA5400 to 5 L/min.
h) Use the hygrometer Testo 625 to check the humidification and the temperature before entering the humidifier and behind the humidifier.
i) At a time of 90-100% air saturation with water, connect the dryer behind the humidifier.
j) Measure the temperature and humidity of the air at the outlet of the dryer.
k) Determine the efficiency of the dryer.
l) Increase the temperature gradient between the water-saturated air and the dryer by forming a cooling mixture.
m) Add the appropriate amount of salt to a container of water and ice.
n) Determine the effectiveness of this solution.
o) Increase the air flow to 10 L/min.
p) Determine the efficiency of the dryer at this flow rate.

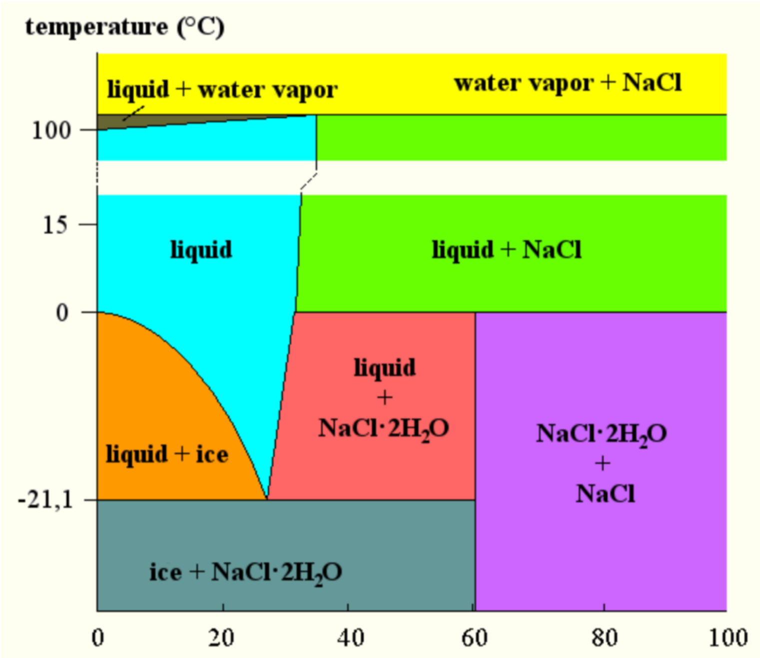

Fig. 18: Cooling mixture of water, ice and salt
Source: http://physicsexperiments.eu/2047/cooling-mixture-of-water,-ice-and-salt

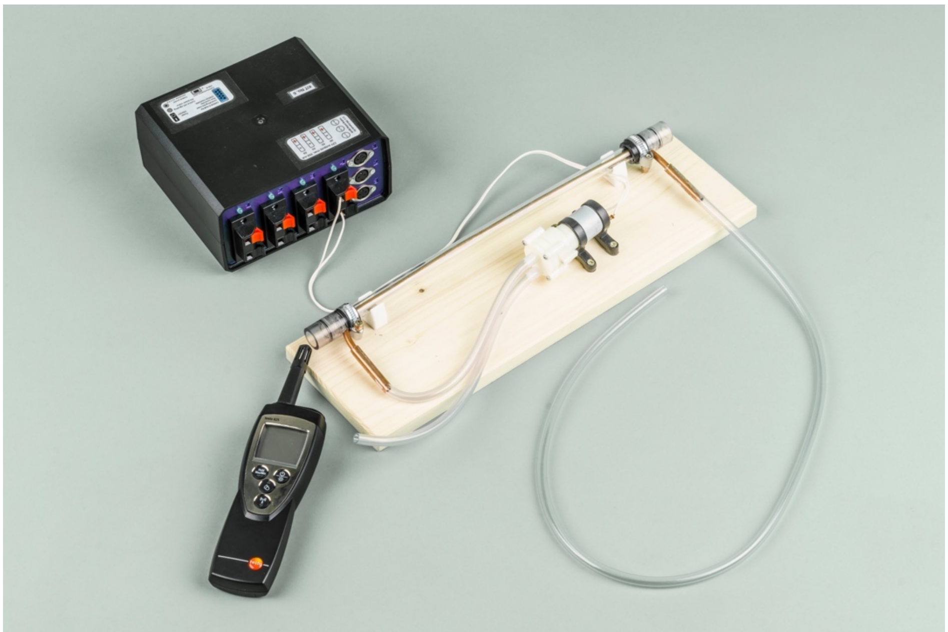

Fig. 19: Condensing dryer

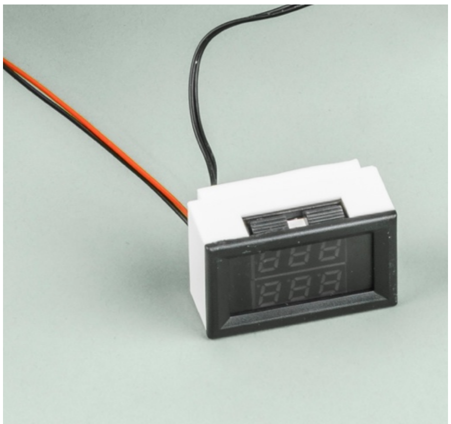

Fig. 20: Thermometer

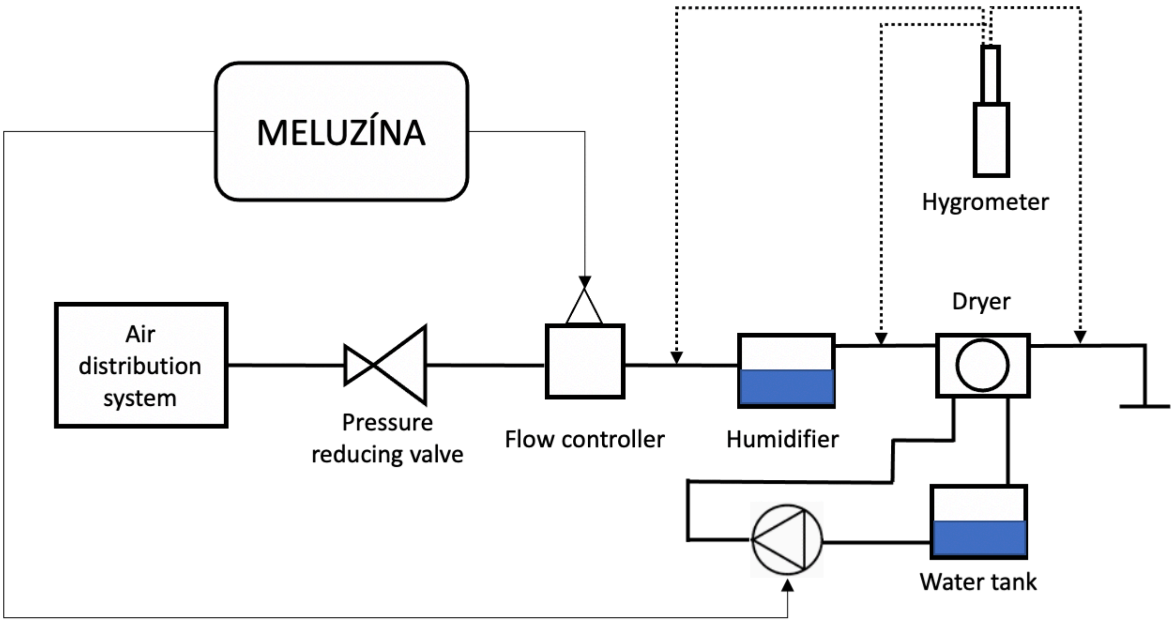

Fig. 21: A scheme of the cooling mixture apparatus

2. Adsorption dryer

a) Assemble the apparatus according to the scheme.
b) Fill both silica boxes with dry silica gel.
c) Maximum of 2 Bar at the pressure reducing valve.
d) Pour enough water into the humidifier (Fisher-Paykel) and connect it to the power supply.
e) Switch on the humidifier and let it warm up with water for 10 minutes.
f) Set the flow with Omega FMA5400 to 5 L/min.
g) Connect both three-way valves to Meluzína.
h) Use the software for valve cycling.
i) Change the direction of the flow through the dryer every 5 minutes.
j) When changing the direction, let both three-way valves open for 1 second.

(Never close both three-way valves at one time and be carefull about the orientation of three-way valves and Ambu valves. Risk of overpressure!!!)

k) Use the hygrometer Testo 625 to check the humidification and the temperature before entering the humidifier and behind the humidifier.
l) At a time of 90-100% air saturation with water, connect the dryer behind the humidifier.
m) Measure the temperature and humidity of the air at the outlet of the dryer.
n) Determine the efficiency of the dryer using different resistors.

(If there is no resistor at the end of the tubing then no flow is going through the saturated silica box. So it will never be dry again.)

Fig. 22: The adsorption dryer

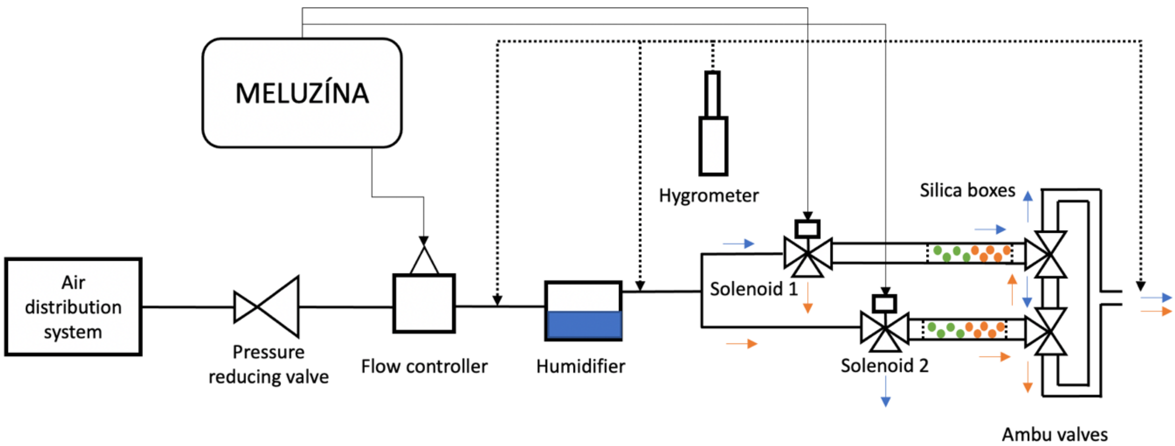

Fig. 23: A scheme of the adsorption dryer apparatus

Equipment

Hygrometer Testo 625
Peltier dryer
Adsorption dryer set
Meluzína
Pnehykur kit
Water pump
Water tank
Humidifier Fisher-Paykel
Thermometer
Omega FMA5400 flow controller
Silica boxes
Three-way valves
Ambu valves with 3D printed connectors
Resistors

Questions

Which solution was the most effective?
How would you increase the effectiveness of individual solutions?

Reference

https://www.quincycompressor.com/types-compressed-air-dryers/
https://www.kompresory-vzduchotechnika.cz/poradna/proc-a-jak-susit-vzduch/

4.4 Pressure, pressure reducing valves and manipulation with pressure vessels

Goals

a) Explain to students the principles of safety associated with the use of high pressure and pressure cylinders and legislation associated with the use of high pressure.
b) To acquaint students with different types of pressure reducing valves.
c) Measure the pressure and flow characteristics of pressure reducing valves.

Theory

Pressure is a physical quantity, usually denoted by the symbol P, expressing the ratio of the magnitude of the force F, acting perpendicular to a planar surface, and evenly distributed over this surface, and the content of this surface S:

$$P = \frac{F}{S} \tag{1}$$

Atmospheric pressure is the force exerted by the planet's atmosphere on a unit area at a given location. Pressure less than barometric (average atmospheric pressure) is called underpressure, pressure greater than barometric is called overpressure. The air pressure depends on the altitude, the magnitude of the gravitational acceleration, the thickness, temperature and density of the atmosphere in the place. In order to make it easier to compare the results of different barometric pressure measurements, the normal air pressure (normal atmospheric pressure) p_n was determined. It is defined by the exact value:

$$p_n = 101\ 325 \text{ Pa}$$

Using normal air pressure, the unit physical atmosphere was defined:

$$p_n = 1 \text{ atm}$$

Equation of state

To describe the mutual relations of state quantities in thermodynamic processes in ideal gases, relation (2) was derived based on relation (1) with the following conditions:

- pressure P is the pressure of the ideal gas particles on the walls of the vessel in which they are enclosed,
- the container is closed, which means that no particles escape or enter it (the number of gas particles does not change),
- each particle can move in three independent directions,

- the temperature inside the vessel is constant.

$$PV = nRT, \quad (2)$$

where P is the gas pressure, V is the gas volume, n is the mass, R is the molar gas constant and T is the thermodynamic temperature.

Containers called cylinders are used to store and transport gases at pressures above atmospheric pressure. Cylinders have a wide range of uses depending on the filling. They can contain medicinal gases, breathing mixtures, gases used in the food industry, technical gases, heating gases, extinguishing agents, etc. For technical gases, steel seamless cylinders with a so-called water volume of 50 liters are most often used.

Because the contents are under pressure and are sometimes hazardous materials, handling bottled gases is regulated. Regulations may include chaining bottles to prevent falling and damaging the valve, proper ventilation to prevent injury or death in case of leaks and signage to indicate the potential hazards If a compressed gas cylinder tips over, causing the valve block to be sheared off, the rapid release of high-pressure gas may cause the cylinder to be violently accelerated, potentially causing property damage, injury, or death. To prevent this, cylinders are normally secured to a fixed object or transport cart with a strap or chain. Design involves parameters such as maximum safe operating pressure and temperature, safety factor, corrosion allowance and minimum design temperature.

All persons involved in the transport of cylinders must be adequately instructed in the potential risks and follow-up actions to mitigate the negative effects.

Gas cylinders have a stop angle valve at the end on top. During storage, transportation, and handling when the gas is not in use, a cap may be screwed over the protruding valve to protect it from damage or breaking off in case the cylinder was to fall over. Instead of a cap, cylinders commonly have a protective collar or neck ring around the service valve assembly.

When the gas in the cylinder is to be used at low pressure, the cap is taken off and a pressure-regulating assembly is attached to the stop valve. This attachment typically has a pressure regulator with upstream (inlet) and downstream (outlet) pressure gauges and a further downstream needle valve and outlet connection. For gases that remain gaseous under ambient storage conditions, the upstream pressure gauge can be used to estimate how much gas is left in the cylinder according to pressure. For gases that are liquid under storage, e.g., propane, the outlet pressure is dependent on the vapor pressure of the gas, and does not fall until the cylinder is nearly exhausted although it will vary according to the temperature of the cylinder contents. The regulator is adjusted to control the downstream pressure, which will limit the maximum flow of gas out of the cylinder at the pressure shown by the downstream gauge. The valves on industrial, medical, and diving cylinders are usually of different sizes and types, as are the valves for different categories of gases, making it more difficult to mistakenly misuse a gas. For example, a hydrogen cylinder does not fit an oxygen supply line which would end in catastrophic failure.

Tab. 1: Indication of cylinders

Gas	Neck	Shell
Oxygen medicinal (O_2)	white	white
Nitrous oxide (N_2O)	blue	white
Carbon dioxide (CO_2)	grey	white
Oxygen technical (O_2)	white	blue
Nitrogen (N_2)	black	Green (grey)
Helium (He)	brown	brown
Hydrogen (H_2)	red	red

Air pressure regulation

The pressure regulator is required to maintain a constant value of the pressure in the operating circuit independently of the pressure fluctuations in the air distribution network and at the same time independent of the amount of air taken. The air pressure in the air distribution network must always be higher than the air pressure behind the pressure regulator.

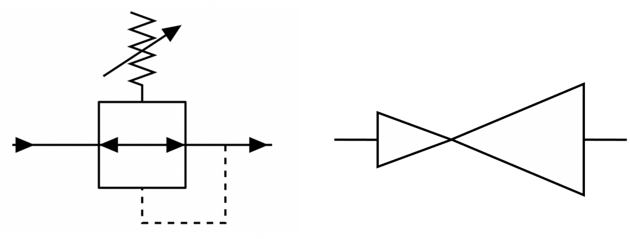

Fig. 24: A scheme and a symbol of pressure reducing valve

The design of most pressure regulators is based on a piston or diaphragm. The pressure of the air on their surface balances the force of the spring acting on these elements. The spring preload is adjusted by turning the adjusting screw. To increase the setting value, simply turn the valve knob clockwise. The spring is compressed so that more pressure is needed behind the valve to push the spring back. Valve adjustment is possible only under conditions of zero consumption behind the valve. At the same time, it is necessary to install a manometer in the distribution behind the valve in order to be able to read the set value. When the valve is opened behind the pressure reducing valve, the pressure drops behind the diaphragm. At this moment, the force of the spring overcomes the force acting on the diaphragm and thus moves the valve closure downwards. This increases the flow through the valve. The greater the intake behind the pressure reducing valve, the greater the pressure drop under the diaphragm and the more the valve subsequently opens. Under conditions where the tapping points behind the valve are closed, the pressure behind the valve increases until it equalizes the set spring pressure force. After balancing the forces, the valve closes the valve so that the pressure conditions behind the valve are maintained at the user-set value. When the intake of compressed air fluctuates, the valve opens and closes in such a way that the balance of forces acting on the diaphragm is always maintained.

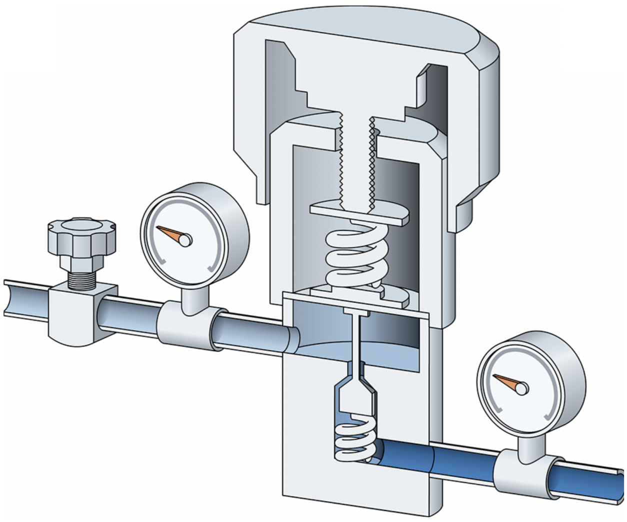

Fig. 25: A principle of pressure reducing valves.
Source: https://industry.airliquide.us/single-stage-versustwo-stage-regulators

Flow compensation - At high flow rates, the pressure regulator valve opens more. The ratio of the spring force to the force exerted by the air pressure on the diaphragm surface deteriorates in proportion to the elongation of the spring and thus deteriorates the accuracy of the set pressure control. This problem is solved by creating a third chamber in the regulator body. If the air flows at a higher speed, an underpressure is created in the chamber, corresponding to the pressure and flow in the secondary circuit. The higher the flow rate, the greater the pressure difference and the more the diaphragm bends and opens the valve. This compensates for the loss of force caused by the extension of the spring.

Compensating for the action of air pressure on the pressure regulator valve increases the accuracy of the outlet pressure control. The higher the inlet air pressure, the greater the force acting on the surface of the valve closing element and trying to close it. Changes in the inlet pressure have an immediate effect on the change in the outlet pressure and have a negative effect on the flow characteristic of the pressure regulator. This shortcoming is eliminated by using a pressure balanced valve.

Other types of pressure regulators are: indirectly controlled pressure regulator, pressure regulator with non-return valve or pressure regulator with filter in one.

Experiments

1. Fire syringe

Students can use the Fire syringe demonstration in an investigation to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.

a) The Fire syringe is very sensitive to moisture, so to ensure the proper results, first clean the apparatus thoroughly. Simply wipe the piston thoroughly using a clean, dry paper towel.
b) Next, twist a piece of paper towel into a long slender swab, and clean the chamber all the way to the bottom. The goal is to remove all the oil from inside the chamber. A small amount of oil on the O-rings is sufficient lubrication.
c) Next, place a small piece of dry material in the chamber of the syringe. Paper or cotton fibers are common samples. Our personal favorite is cotton from cotton balls. You want only a "thin wisp" of cotton fibers for each demonstration. Pluck it off the edge of a cotton ball and then "tease out" the fibers to maximize the surface area of your cotton sample. Push the sample to the bottom of the chamber with a pencil or other long thin object.
d) Push the piston FAST and HARD.
e) Observe the condensation and probably ignition.
f) Change the cotton.
g) Calculate the minimum pressure which will cause the ignition.

Note: It is not easy to cause ignition, but it really works. Try it several times in dark. At least, you should see condensation. Try to change the gasket/seal which prevents air leak. The work done on the air as it is compressed is transferred/converted to heat which ignites the small ball of cotton. The trick seems to be: keep the apparatus vertical and to push downward on the plunger as quickly as possible. It is also a good demonstration of diesel engines and how they ignite the fuel.

Fig. 26: Fire syringe

2. Dependence of outlet pressure on inlet pressure

a) Make the connections according to the following diagram. Use the shortest hoses possible so that they do not cause too much resistance. If the throttle valve cannot stop the flow, use two throttle valves.

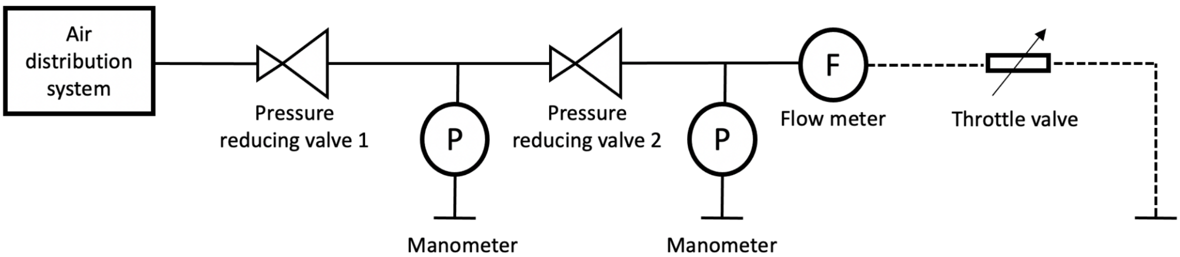

Fig. 27: A scheme of the apparatus

b) Set the pressure on the first pressure reducing valve to 1 bar.
c) Open the second pressure reducing valve to the maximum.
d) Completely close the air flow with throttle valves.
e) Determine the outlet pressure at the pressure reducing valve 2.
f) Remove the part of the apparatus with the throttle valves.

g) Determine the outlet pressure at pressure reducing valve 2 and the flow at a given pressure.
h) Again, attach apparatus with throttle valves.
i) Repeat the same for all pressure settings on pressure reducing valve 1.
j) Now use another pressure reducing valve as pressure reducing valve 2.
k) Compare the differences between the pressure reducing valves.
l) Plot the flow rates versus outlet pressure from the pressure reducing valve 2.
m) Determine the pressure drops occurring on the pressure reducing valve 2 according to the inlet pressure from the pressure reducing valve 1.

(During the measurement it is necessary to change the manometers due to different measuring ranges.)

Tab. 2: Dependence of outlet pressure on inlet pressure

Pressure reducing valve 1 [Bar]	Pressure reducing valve 2 fully opened with totally closed throttle valve [Bar]	Pressure reducing valve 2 fully opened with no throttle valve [Bar]	Flow [L/min]
1			
0.9			
0.8			
0.7			
0.6			
0.5			
0.4			
0.3			
0.2			
0.1			
0.08			
0.06			
0.04			
0.02			

Fig. 28: Pressure reducing valves

3. Pressure dependence on flow

a) Use the same apparatus as in the previous experiment.
b) Set the first pressure reducing valve to 1 Bar.
c) Set the second pressure reducing valve to 0.7 Bar with fully closed throttle valve.
d) Set the flow to 5 L/min and write down the pressure at the outlet.
e) Measure the pressure for other flow rates.
f) Do the same for different pressure settings of pressure reducing valve 2.

Tab. 3: Pressure dependance of flow

Pressure reducing valve 2 with fully closed throttle valve [Bar]	Flow [L/min]									
	5	10	15	20	25	30	40	50	60	70
	Pressure at the outlet [Bar]									
0.7										
0.6										
0.5										
0.4										
0.3										
0.2										
0.1										
0.08										
0.06										
0.04										
0.02										

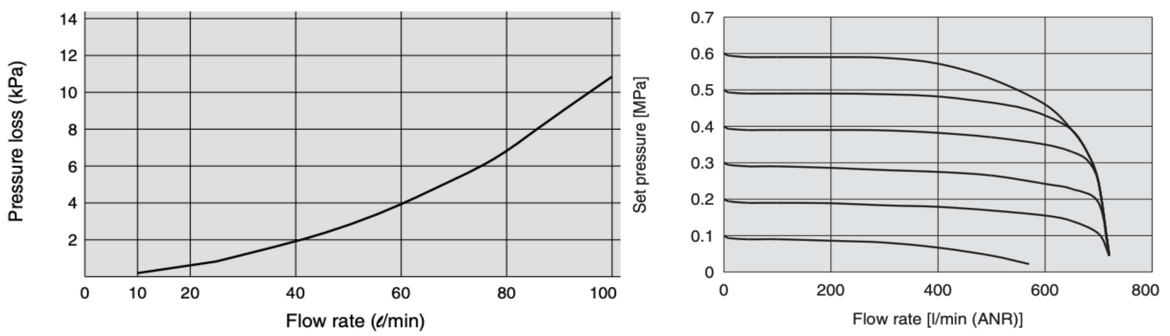

Fig. 29: Typical results of the pressure dependance on flow

4. Pressure characteristics

a) Use the same apparatus as in the previous experiment.
b) Set the first pressure reducing valve to 3 Bar.
c) As a second pressure reducing valve, choose one valve which can be set to 1 Bar.
d) Set the second pressure reducing valve to 1 Bar with adjusted throttle valve to flow rate 20 L/min.
e) Change the pressure at the first pressure reducing valve between 1 and 5 Bar.

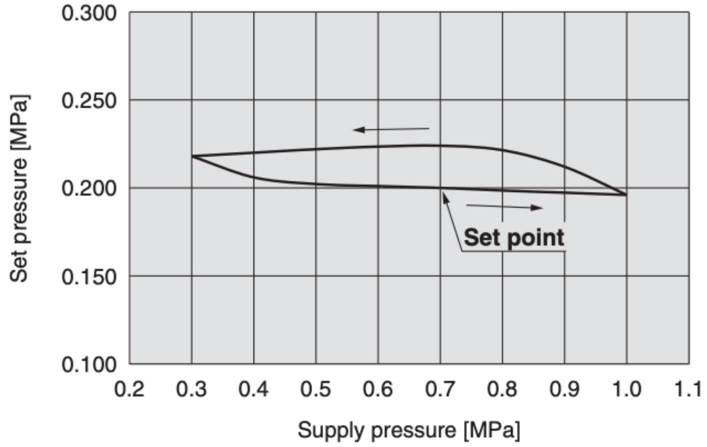

Fig. 30: Typical characteristics of a pressure reducing valve

Equipment

Fire syringe
Cotton
Pressure reducing valves
Manometers
Pressure sensors
Pnehykur kit
Flowmeters
Extension cable for the air flowmeter with 24V power supply

Fig. 31: 12V supply from Meluzína for measuring range of 0–50 L/min of the flowmeter or 24V supply from the distribution network for measuring range of 0–100 L/min.

Questions

Describe the principle of a diesel and internal combustion engine according to the Fire syringe demonstration.
What gas can be dangerous if handled carelessly?

Reference

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Perrot, Pierre (1998). *A to Z of Thermodynamics*. Oxford University Press. ISBN 978-0-19-856552-9.

EN 13445: The current European Standard, harmonized with the Pressure Equipment Directive (Originally "97/23/EC", since 2014 "2014/68/EU").

https://en.wikipedia.org/wiki/Gas_cylinder

https://s3.amazonaws.com/cdn.teachersource.com/downloads/lesson_pdf/FIR-150.pdf

4.5 Valves in medicine

Goals

a) To acquaint students with the principles of individual pneumatic valves used in healthcare.
b) Measure the pressure-flow characteristics of individual valves.
c) Show students the use of electroacoustic analogies.

Theory

An essential part of the devices in anesthesiology and resuscitation care are various types of valves, which not only ensure patient safety, but also improve the parameters of the treatment procedure.

Artificial lung ventilation is a method of breathing in which the flow of gases through the respiratory system is ensured by a mechanical device. Ventilation is used in situations where it is necessary to support the respiratory system of patients who have developed a serious ventilation or oxygenation disorder. A ventilator typically includes one-way valves, pressure relief valves, pressure reducing valves, PEEP valves, an expiration valve, a sampling valve, or an adjustable pressure-limiting valve.

For a better understanding of the principles of individual valves, an electroacoustic analogy is also mentioned for some valves.

A **check valve**, non-return valve, retention valve, or one-way valve is a valve that normally allows fluid (liquid or gas) to flow through it in only one direction. These valves have two openings in the body, one for fluid to enter and the other for fluid to leave. There are various types of check valves used in a wide variety of applications. Check valves work automatically, and most are not controlled by a person or any external control; accordingly, most do not have any valve handle or stem. A diode is equivalent to a one-way check valve. As with a diode, a small pressure difference is needed before the valve opens. And like a diode, too much reverse bias can damage or destroy the valve assembly. Also, there is always some pressure loss (voltage loss) at the valve. The main purpose of a check valve in a system is to prevent backflow, which could damage equipment or contaminate media upstream. Common check valve problems are: noise, water hammer, vibration, reverse flow, sticking, leakage, and component wear/damage. To prevent issues, it is crucial that a check valve is specified correctly for the application and media.

Depending on the design of the check valve, they operate differently. The most common check valve is a spring-loaded check valve. When flow enters the input port of the valve, it must have enough pressure (force) to overcome the cracking pressure and the spring force. Once overcome, it pushes the disc, opening the orifice and allowing flow to move through the valve.

When the input pressure is no longer high enough, or there is a backpressure, then the backpressure and spring push the disc against the orifice and seal the valve shut. Spring loaded y-check valves operate very similar to in-line spring loaded check valves. The spring and movable disc are positioned at an angle. This creates a 'y' shape. The moveable components are at an angle, so it can be inspected and serviced while it is still connected to the system. A ball check valve uses a free-floating or spring-loaded ball that rests on the sealing seat to close the orifice. Diaphragm check valves consist of a rubber diaphragm that flexes open when the inlet pressure is increased.

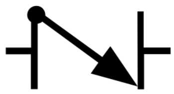

Fig. 32: Check valve

A sampling valve is a type of valve that allows taking a representative portion of a fluid (gases, liquids) to test physical or chemical. They are typically used for the purposes of identification or quality control. The sampling valve allows the operator to extract a sample of the product and safely store it for transportation to the place where it will be analyzed.

An adjustable pressure-limiting valve (APL valve) is a type of flow control valve used in anesthesiology as part of a breathing system. It allows excess fresh gas flow and exhaled gases to leave the system while preventing ambient air from entering. The valve is adjustable and spring-loaded, allowing the opening pressure of the valve to be controlled by screwing the valve top which modifies the pressure on the spring. A very light spring is used, so that at its minimum setting the valve can be opened by the patient's breathing alone using low pressures.

A relief valve or pressure relief valve is a type of safety valve used to control or limit the pressure in a 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. It works the same as Zener diodes in electronic systems.

Finally, exspiratory valve is really important for ventilatory techniques. This valve is used when we need positive pressure in the alveoli of a patient at the end of exspiration phase. Positive end-exspiratory pressure (PEEP) prevents the opening and closing of small airways and helps to recruit collapsed alveoli. It also improves oxygenation, increases lung compliance, and reduces the risk of developing ventilator-induced lung injury. The applied pressure is set on one side of the valve. The other side of the valve is connected to the expiratory branch of the patient circuit. During exspiration, the valve opens, but as the pressure in the patient's airways drops to the set pressure of the exspiratory valve, the expiratory valve closes.

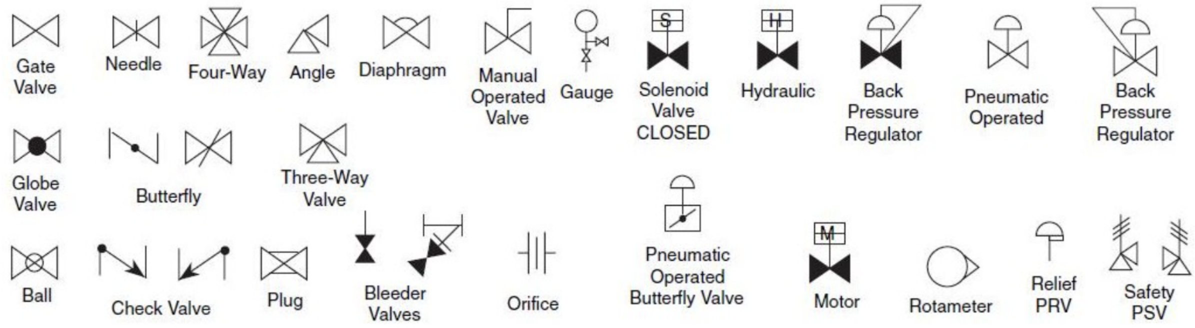

Fig. 33: List of valves
Source: https://www.valvesonline.com.au/references/valve-pneumatic-symbols/

Experiments

1. PEEP valve

a) Make the connection of the apparatus according to the following scheme.
b) Fully close the throttle valve 1 and the ball valve 1.
c) Fully close the PEEP valve.
d) Connect the apparatus to the air distribution system.
e) Set the pressure to 0.2 Bar using the pressure reducing valve 1.
f) Open the ball valve 1.
g) Slowly release the throttle valve 1 (you should see pressure at the manometer 2).
h) By opening the PEEP valve, you can set the pressure in the system.

(Always be careful about the ranges of Manometers.)

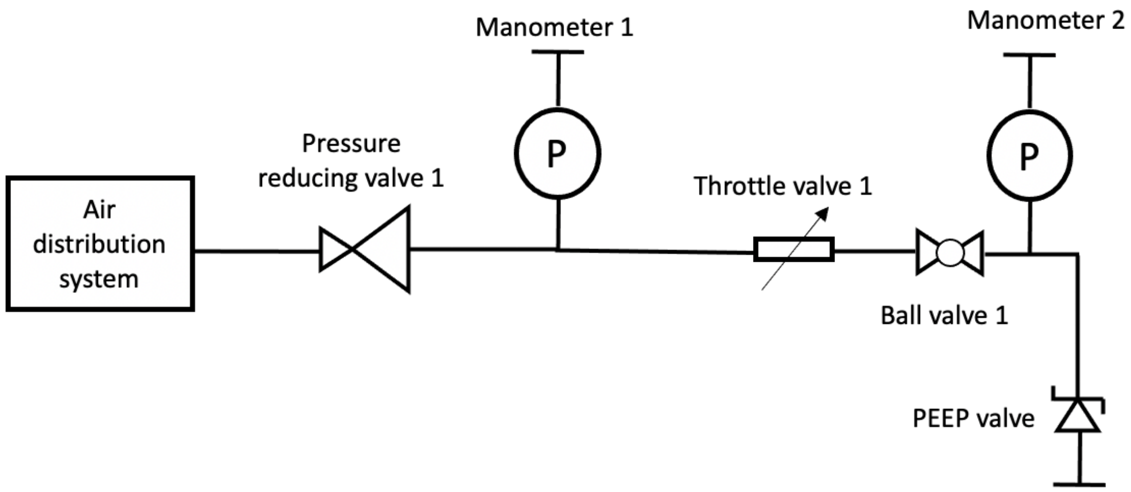

Fig. 34: A scheme of the apparatus

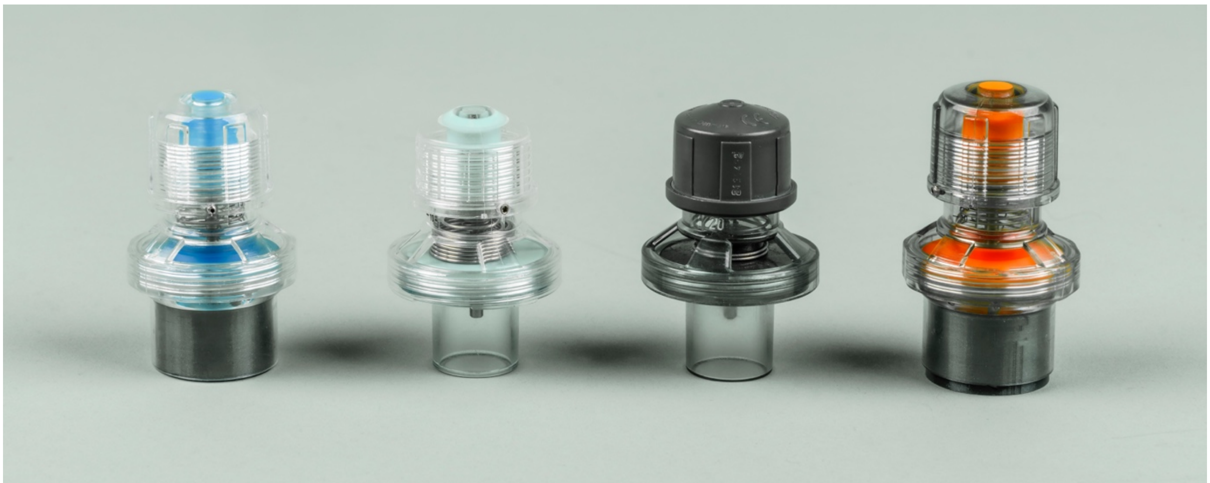

Fig. 35: PEEP valves

2. PEEP valve as a pressure regulator or stabilizer

a) Repeat all the points a) – h) from part 1.

The PEEP valve serves as a Zener diode. You can set the pressure at the manometer 3 by adjusting the pressure at the PEEP valve.

b) Open the ball valve 2 and let the tube behind the ball valve 2 lead free into the atmosphere. (There will be no pressure at the manometer 2 and 3).
c) Put the tube into a container with water.
d) Set the pressure to 1 kPa (10 cmH_2O) using the PEEP valve.
e) What happens if the tube is deeper than 10 cm under the water level?

(Always be careful about the ranges of Manometers.)

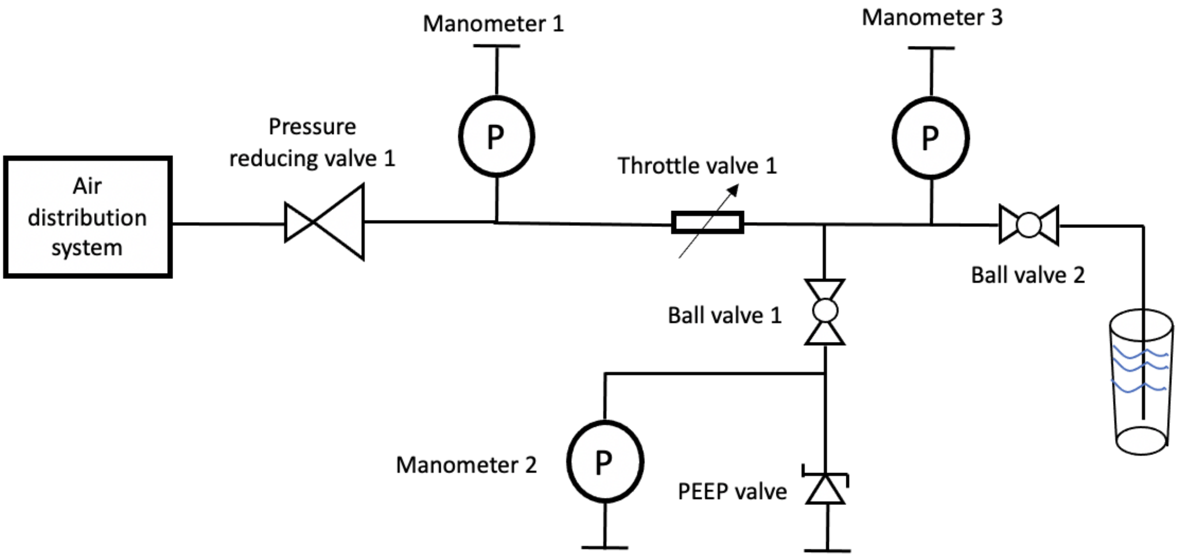

Fig. 36: A scheme of the apparatus

3. Pressure relief valve

a) Make the connection of the apparatus according to the following scheme.
b) Set the pressure to 0.1 Bar.
c) Connect the apparatus to the air distribution system.
d) Check the opening pressure of the pressure relief valve.
e) What happens if you put a throttle valve in front of the pressure relief valve?

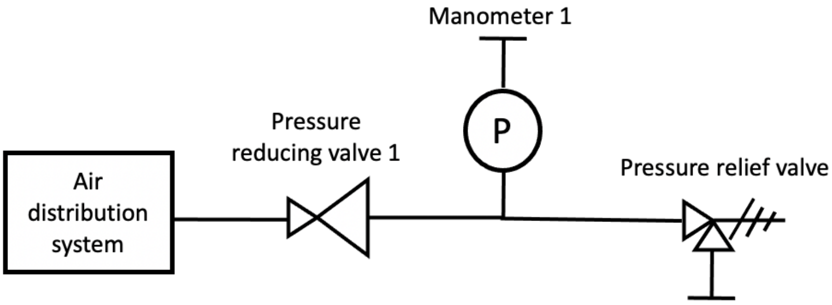

Fig. 37: A scheme of the apparatus

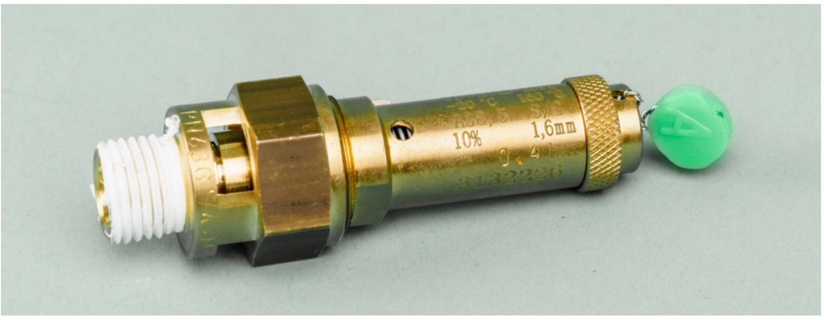

Fig. 38: Pressure relief valve

4. Exspiratory valve

a) Make the connection of the apparatus according to the following scheme.
b) Fully close the throttle valve 1.
c) Connect the apparatus to the air distribution system.
d) Set the pressure at both pressure reducing valves so you will be able to decide what is the conversion characteristic of the expiratory valve:

a) 1:2
b) 1:5
c) 10:1
d) 5:1

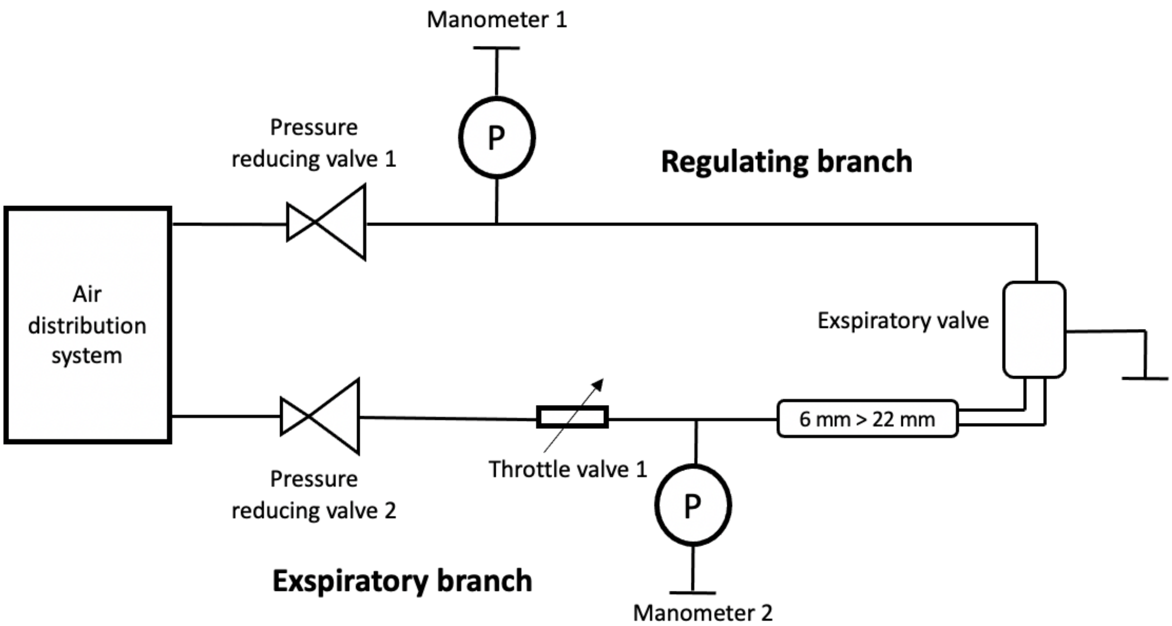

Fig. 39: A scheme of the apparatus

Fig. 40: Exspiratory valves

5. Pressure-flow characteristics of one-way valve in forward bias and reverse bias

a) Make the connection of the apparatus according to the following scheme.
b) Fully close the throttle valve 1.

c) Set the pressure at the pressure reducing valve to 1 Bar.
d) Connect the apparatus to the air distribution system.
e) Adjust the throttle valve 1.
f) Set different flows and write down the measured pressure.
g) Try to connect the one-way valve in reverse bias and try to measure Pressure-flow characteristics.
h) At what pressure you can feel leaking air? **(Be careful! Risk of destruction.)**

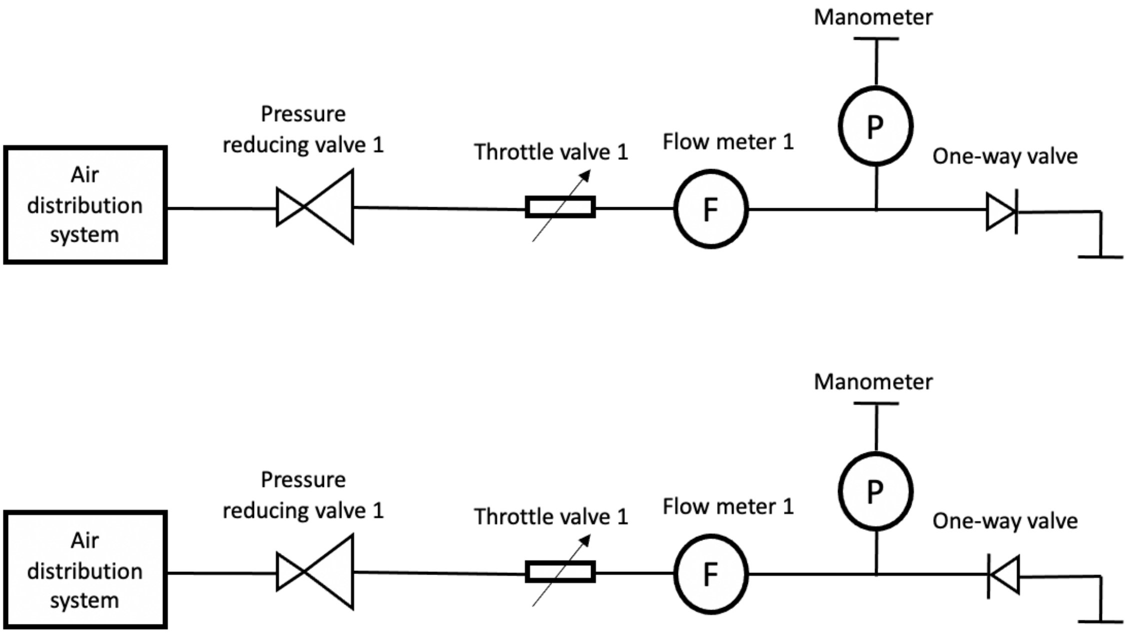

Fig. 41: A scheme of the apparatus

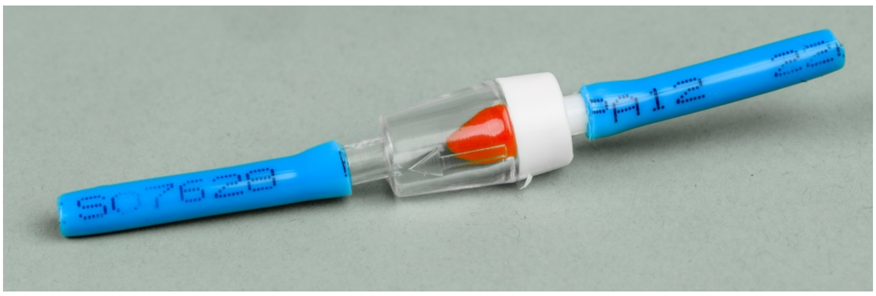

Fig. 42: One-way valve

6. Pressure-flow characteristics of Ambu Bag valve

a) Make the connection of the apparatus according to the following scheme.
b) Set the pressure to maximum of 2 Bar at the pressure reducing valve.
c) Set several different flow rates using the software for controlling the Omega FMA5400 flow controller
d) Do the same but with different Ambu bag valve orientation.
e) What orientation has the biggest resistance?

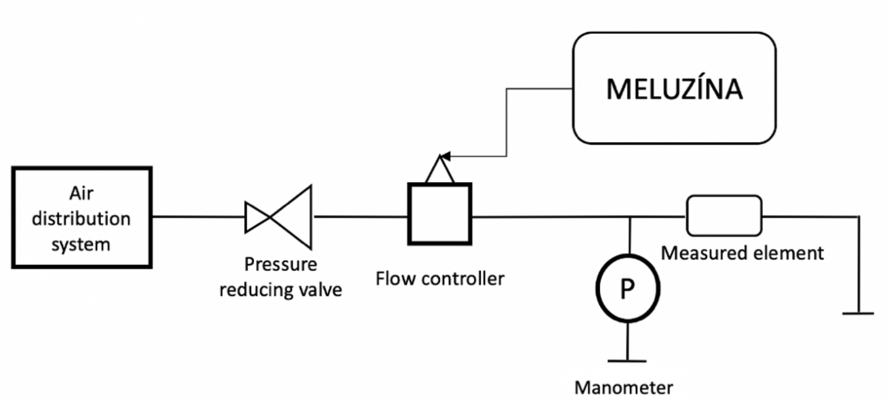

Fig. 43: A scheme of the apparatus for measurement of P-Q of Ambu bag valve

Fig. 44: Ambu Bag valve

Equipment

PNEHYKUR kit
Exspiratory valve
One-way valve
PEEP valves
Water tank
Adapter 6mm-22mm
Ambu bag valve with 3D printed components
Omega FMA5400 flow controller

Reference

Baha Al-Shaikh; Simon Stacey (2013). "Breathing systems". *Essentials of Anaesthetic Equipment*. Elsevier Health Sciences. pp. 55–73. ISBN 0-7020-4954-9.

Christopher., Dickenson, T. (1999). *Valves, piping, and pipelines handbook*(3rd ed.). Oxford, UK: Elsevier Advanced Technology. ISBN 9781856172523. OCLC 41137607.

https://tameson.com/check-valves.html

4.6 Vacuum, suction units in medicine

Goals

a) Experimentally acquaint students with the use of vacuum.
b) Explain to students the place of use of vacuum in health care.
c) To acquaint students with the types of pumps and the size of the vacuum.

Theory

In technical practice, a vacuum is a space in which the gas pressure is lower than at normal atmospheric pressure. The vacuum is created by vacuum pumps and is measured in the usual units using vacuum gauges. A perfect vacuum that would meet the theoretical definition has a zero-pressure value. The lowest laboratory achieved value is 1.33×10^{-11} Pa.

The technical vacuum is divided into several zones, which differ both in the technique of creation and in the field of application.

Tab. 4: Level of vacuum

Level	Pressure (Pa)
Atmospheric pressure	101 325
Under pressure	10 000 – 101 325
Gross vacuum	100 – 10 000
Soft vacuum	0.1 – 100
Heavy vacuum	0.00001 – 0.1

The vacuum is used in mechanical engineering to grip objects, in the food industry for vacuum packaging. A conventional vacuum cleaner reaches about half the atmospheric pressure. Soft vacuum prevents oxidation and is therefore used in electrical engineering (light bulbs) or in mechanical engineering (vacuum heating, melting, welding, soldering). Soft vacuum allows certain types of discharges and is therefore used in electronics (vacuum and X-ray lamps). It is created by mechanical or diffusion pumps and measured by ionization vacuum gauges. Heavy vacuum is mainly used in electronics: screens or semiconductor manufacturing. It no longer requires the use of vacuum-compatible materials and seals.

A vacuum pump is a device that draws air from an enclosed space and acts as a gas pump. It creates a partial vacuum. There are several different pump design solutions. Pumps can be divided according to the physical principle of operation or according to the degree of vacuum they can achieve.

Mechanical pumps displace gas as a liquid pump (piston pump, centrifugal pump, rotary pump). Based on the Bernoulli effect and the entrainment of gas molecules by a stream of liquid or gas, a steam pump (ejector), a water pump or an air pump work. Sorption pumps bind gas molecules: Ionization pumps with a strong electric field bind gas molecule by ionic chemisorption and sorption pumps bind gas to the surface of a substance with a large specific surface area.

The piston pump works like an ordinary pump with a piston and valves. It is structurally simple, but it only allows to achieve a vacuum. In a water pump, liquid flows quickly through one tube, the other tube leads to the pumped space. According to the Bernoulli effect, the pressure at the point of fast flowing liquid is lower than at the point where the liquid flows more slowly, so that the pressure difference draws gas from the second tube and discharges it through the outlet of the first tube. The gas particles in the second tube are "entrained" by the flowing liquid. With them, a pressure reduction of up to 10 Pa can be achieved.

In the cylindrical chamber of the rotary (vane) pump, a cylinder rotates, which on one side is in close contact with the wall of the chamber. There are two baffles in the cylinder slot, which push the springs apart so that they fit snugly against the walls of the chamber. The pump sucks in gas, compresses it and discharges it elsewhere. The two-stage rotary pump can achieve a fine vacuum of up to 10^{-4} hPa pressure. The sorption pump forms the surface of a suitable substance which binds residual gas molecules to each other. Typical examples are getters, metallic glossy coatings on the inside of a flask of vacuum tubes, screens, etc., which maintain a high vacuum inside the flask for a long time. Suitable for pumping in the area of higher pressures.

Vacuum plays an important role in healthcare and life sciences applications. We find vacuum pumps in all major hospitals and in many analytic instruments used in diagnostics and research. In most hospital rooms we find a vacuum connection at the wall delivering vacuum pressure for aspiration. Vacuum is a tool in surgery, anesthesia and during intensive care. The total vacuum system underlies strong medical regulations of quality, certification (e.g. ISO 7396-1) and maintenance. Vacuum is needed for X-rays, suction units, or plasma sterilization.

In hospitals, it is sometimes necessary to create suction. Suction may be used to clear the airway of blood, saliva, or vomit so that a patient may breathe. Suctioning can prevent pulmonary aspiration, which can lead to lung infections. In surgery suction can be used to remove blood from the operated area to allow surgeons to work. Suction devices may be mechanical hand pumps or electrically operated mechanisms. In many hospitals, suction is typically provided by suction regulators, connected to a central medical vacuum supply.

Suction apparatus requires an energy source that generates a sub-atmospheric pressure. This is colloquially referred to as a vacuum source, even though a true (high) vacuum is rarely achieved. In fact, the pressure required is only a maximum of 60 kPa less than the normal environmental pressure. Pipeline suction, of course, is a source of vacuum generated by an electrically powered vacuum pump at a distance from the user. Portable suction apparatus may be battery driven, hand or foot operated, or may make use of compressed gas as a source of energy.

Experiments

1. Air ejector

Vacuum ejector uses high-pressure air as the working fluid. These are commonly used in pneumatic handling equipment when a small vacuum is required to pick up objects since compressed air is often already present to power other parts of the equipment. Air ejectors used to suction liquids directly will produce a fine mist of droplets, this is how airbrushes, and many other spraying systems operate.

a) Connect the air-pressure gun to the air distribution system.
b) Prepare a tube filled with polystyrene.
c) Use an air-pressure gun with appropriate angle to blow the polystyrene out of the tube.

Fig. 45: Air-ejector

2. Under pressure

a) Inflate the balloon.
b) Estimate the volume of the balloon.
c) Put it into the vacuum container.
d) Close the container airtight.
e) Connect the container to the vacuum pump. **(Danger: Never check the vacuum pump by your parts of body!)**
f) Switch on the vacuum pump.
g) Do not exceed 0.4 Bar (-0.6 Bar at the manometer).
h) Calculate the volume of the balloon according to Equation of state.

Fig. 46: Vacuum pump and the apparatus for creating vacuum

Fig. 47: A vacuum container

3. Suction unit

a) Spill the water on the table.
b) Assemble the container with tubing and connect it to the vacuum pump.
c) Suck up the water.

Fig. 48: Vacuum pump and the apparatus for sucking.

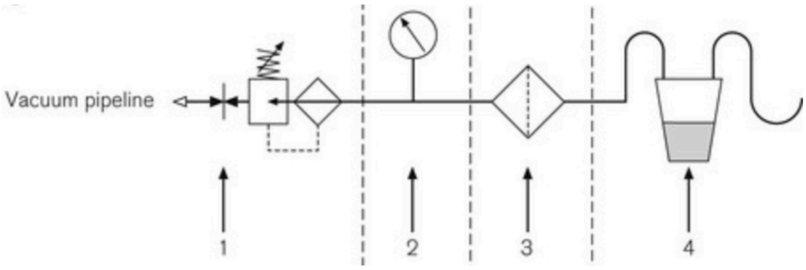

Fig. 49: Suction equipment. (1) vacuum source/regulator; (2) vacuum indicator; (3) filter; (4) collection container.
Source: https://clinicalgate.com/medical-suction-apparatus/

4. The Water-Candle experiment

a) Cover a burning candle with a pitcher so that the candle is in an air-tight room sealed by the water at the ground.
b) After some time, the candle dims and goes out. Just before the candle dies, the water level rises the most. No air bubbles are seen. The water level stays up for many few minutes more.

Oxygen O_2 and paraffin C_nH_{2n+2} react. The burning produces water H_2O and carbon dioxide CO_2. For n=1 we balance the equation as follows:

$$2\,O_2 + CH_4 = CO_2 + 2\,H_2O$$

Because twice as much oxygen is burned than carbon dioxide released, the air volume decreases. The candle heats the air and expands it. This cancels the depletion of the oxygen temporarily and the water level stays down. When the oxygen is depleted, the candle goes out and the air cools. The volume of the air decreases and the water rises. The temporary temperature change delays the rise of the water. Also, the water condensation should be mentioned. While water is initially gas, it condenses and helps to delay the effect.

There are two different effects. Both a chemical and a physical reasoning are needed to explain what we can see.

We see from the balancing equation that two oxygen molecules are replaced by one carbon dioxide molecule. Since CO_2 has one carbon atom more than O_2, it is heavier. Will this not imply that it takes up more volume? It turns out that only the number N of molecules matters. The ideal gas law relates the gas pressure p, the volume V, the temperature T with the number of molecules N as follows:

$$pV = NRT, \qquad (1)$$

The letter R is a constant called the Boltzmann constant. Like any physical law, this is an idealisation and approximation but it is accurate enough for the experiment in question. In the candle experiment, the pressure and temperatures at the beginning and the end are essentially the same. But since the number N of oxygen molecule is replaced by N/2 carbon dioxide molecules, the corresponding volume gets divided by half too. A refinement of the law, the van der Waals equation also incorporates the size of the molecules.

Fig. 50: Water-candle experiment

Fig. 51: A fully assembled water-candle experiment

Equipment

Vacuum pump
Suction unit equipment
Air-pressure gun
Polystyrene
Tube
Candle
Flask
Thermometer
Meluzína
±2 kPa pressure sensor
Water
Holder container
Under pressure container with manometer and tubing
Balloon

Questions

Where would you use the suction unit in healthcare?
Why the candle goes out?

Are the following arguments true?

1. Oxygen is replaced by Carbon dioxide. So, there is the same amount of gas added than taken away. Therefore, heat alone most be responsible for the water level change.

2. Carbon dioxide is absorbed by the water. That's why the oxygen depletion has an effect.

3. The experiment can be explained by physics alone. During the heating stage, air escapes. Afterwards, the air volume decreases and pulls the water up.

4. It can not be that the oxygen depletion is responsible for the water raising, because the water does not rise immediately. The water rises only after the candle dims. If gas would be going away, this would lead to a steady rise of the water level, not the rapid rise at the end, when the candle goes out.

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4.7 Gas blending in medicine

Goals

a) Experimentally acquaint students with various principles of gas mixing.
b) Know the places of use of gas mixing in healthcare.
c) Understand the importance of performance in pneumatic assemblies.

Theory

Gas blending is a process where the mixture of gases for a specific purpose is specified and controlled. It has a big range of applications including scientific and industrial processes, food production and breathing gases.

Gas mixture is usually specified in molar gas fraction: by percentage, parts per thousand or parts per million. Volumetric gas fraction is easily convertible to pressure ratio, following Dalton's law of partial pressures. Partial pressure blending at constant temperature is computationally simple, and pressure measurement is relatively inexpensive. The biggest problem is with maintaining constant temperature during pressure changes. Blending by mass fraction is unaffected by temperature variation during the process but requires accurate measurement of mass or weight.

Partial pressure blending (volumetric blending) must be done at constant temperature for best accuracy, though it is possible to compensate for temperature changes in proportion to the accuracy of the temperature measured before and after each gas is added to the mixture. Partial pressure blending is commonly used for breathing gases for diving. The accuracy required for this application can be achieved by using a pressure gauge which reads accurately to 0.5 bar and allowing the temperature to equilibrate after each gas is added.

Mass fraction blending (gravimetric blending) is relatively unaffected by temperature, and accuracy depends on the accuracy of mass measurement of the constituents. Mass fraction blending is used where great accuracy of the mixture is critical, such as in calibration gases. The method is not suited to moving platforms where the accelerations can cause inaccurate measurement, and therefore is unsuitable for mixing diving gases on vessels.

Gas mixing systems may be mechanical (conventional rotameters) or electronic (electromagnetic solenoids). Gas mixtures must be analyzed either in process or after blending for quality control. This is important for breathing gas mixtures where errors can affect the health and safety of the end user. It is difficult to detect most gases that are likely to be present in diving cylinders because they are colorless, odorless, and tasteless. Electronic sensors exist for some gases, such as oxygen analyzers, helium analyzers, carbon monoxide detectors and carbon dioxide detectors. Oxygen analyzers are commonly found underwater in rebreathers. Oxygen and helium analyzers are often used on the surface during gas blending to determine the percentage of oxygen or helium in a breathing gas mix.

A rotameter is a device that measures the volumetric flow rate of fluid in a closed tube. It belongs to a class of meters called variable-area flowmeters, which measure flow rate by allowing the cross-sectional area the fluid travels through to vary, causing a measurable effect. It consists of a tapered tube, typically made of glass with a small ball (float), inside that is pushed up by the drag force of the flow and pulled down by gravity. The drag force for a given fluid and float cross section is a function of flow speed squared only. A rotameter is a cheap and simple device that requires no external power to measure flow rate. Clear glass is used which is highly resistant to thermal shock and chemical action. The rotameter is calibrated for some type of fluid and it will not work for another if the density or viscosity is different. The position must be vertical because it depends on gravity. Also, the resolution is relatively poor compared to other measurement principles and oscillations of the float can increase the uncertainty of the measurement.

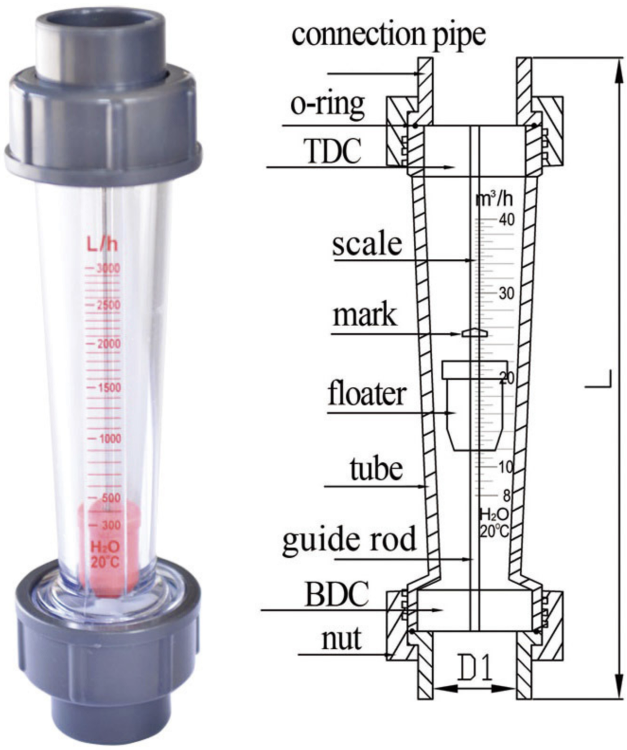

Fig. 52: A typical rotameter

Source: Dr. Alexander Badalyan, University of South Australia
https://instrupedia.wordpress.com/2019/02/16/rotameters/

In hospitals, a typical device, where gas blending is really important, is the anesthetic machine. The anesthetic machine is a medical device used to generate and mix a fresh gas flow of medical gases and inhalational anesthetic agents for the purpose of maintaining anesthesia. The gas mixing and delivery system lets the anesthetist control oxygen fraction, nitrous oxide concentration and the concentration of volatile anesthetic agents. The machine is usually supplied with oxygen (O_2) and nitrous oxide (N_2O). The metered gas is mixed at ambient pressure after the additional anesthetic agents are added by a vaporizer. Then the mixture can be humidified. Air is used to decrease oxygen concentration. In some cases, other gases may also be added to the mixture. These may include carbon dioxide (CO_2), used to stimulate respiration, and helium (He) to reduce resistance to flow.

The machine is commonly used together with a mechanical ventilator, breathing system, suction equipment, and patient monitoring devices. A modern anesthetic machine includes at minimum the following components:

- Connections to oxygen, medical air, and nitrous oxide from the gas distribution system in the hospital (gas cylinders can also be used)
- Pressure regulators to monitor gas pressure in the system and protect the machine components and patient from excessive rises
- Flowmeters such as rotameters for oxygen, air, and nitrous oxide
- Vaporizers to provide accurate dosage control when using volatile anesthetics
- A high-flow oxygen flush, which bypasses the flowmeters and vaporizers to provide pure oxygen at 30–75 L/min
- Systems for monitoring the gases and systems for monitoring the patient's heart rate, ECG, blood pressure, oxygen saturation, end-tidal carbon dioxide and temperature.

Experiments

1. Gas mixing using pressure reducing valves

a) Assemble the apparatus according to the scheme.
b) Fully close both throttle valves and both ball valves.
c) Set the pressure at both pressure reducing valves to 1 Bar.
d) Now fully open both ball valves.
e) Adjust both throttle valves so that the flow is 30 L/min.
f) Change the pressure at the pressure reducing valve 1 between 0.1 to 2 Bar.
g) Discuss the measured values of flow rates from both branches.
h) Is the dependence on the pressure ratio between the branches linear? Exponential?

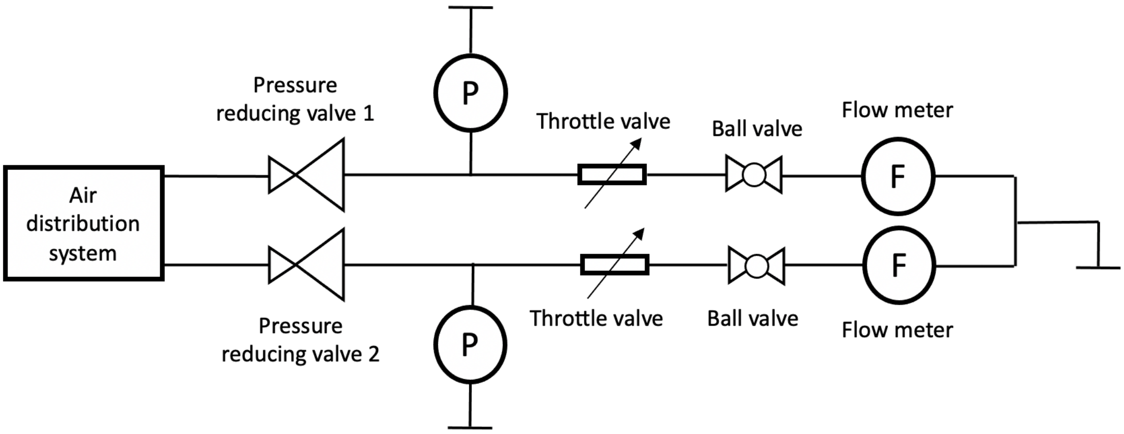

Fig. 53: A scheme of the apparatus

Tab. 5: Gas mixing using pressure reducing valves

Pressure reducing valve 1 [Bar]	Flow 1 [L/min]	Flow 2 [L/min]
0.1		
0.2		
0.3		
0.4		
0.5		
0.6		
0.7		
0.8		
0.9		
1.0		
1.1		
1.2		
1.3		
1.4		
1.5		
1.6		
1.7		
1.8		
1.9		
2.0		

2. Gas mixing using electromagnetic solenoids based on the Pulse Width Modulation (PWM)

a) Basic

a) Assemble the apparatus according to the scheme.
b) Fully close throttle valves 1 and 2.
c) Set the pressure at both pressure reducing valves to 2 Bar.
d) Now open the solenoid 1.

e) Set the flow to 40 L/min using throttle valves 1.
f) Close the solenoid 1.
g) Repeat d) - f) for the second breach.

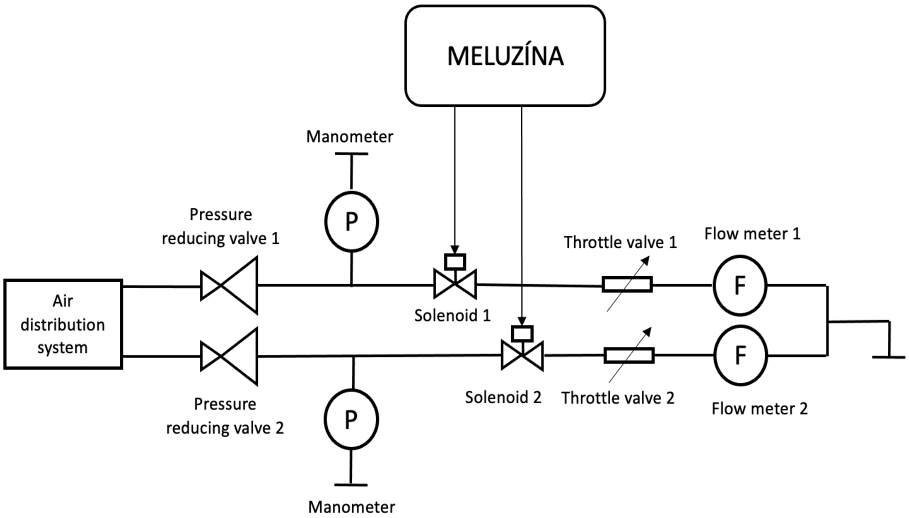

Fig. 54: A scheme of the apparatus

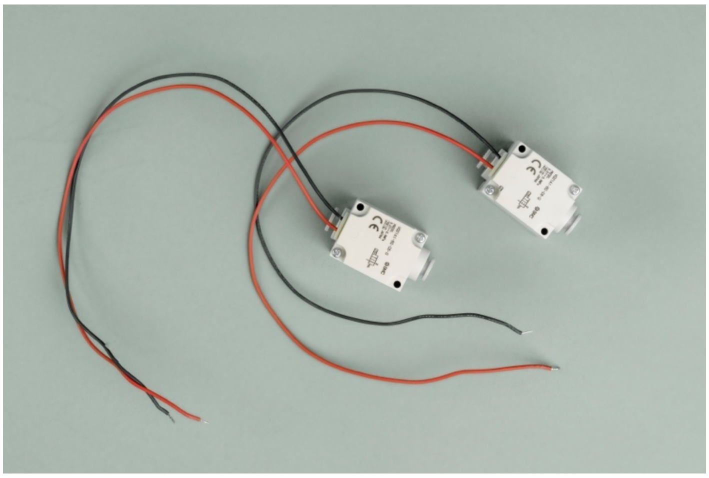

Fig. 55: Fast electromagnetic solenoids

In the application:

a) STEP 1: Open Solenoid valve 1 with step time 100 ms.
b) STEP 2: Open Solenoid valve 2 with step time 100 ms.
c) STEP 3: Open Solenoid valve 1 with step time 100 ms.
d) STEP 4: Open Solenoid valve 2 with step time 100 ms.
e) Set 10 iterations and press Start.
f) Discuss the fluctuating values of flow rates at the flow meters.

b) Advanced

a) Assemble the apparatus according to the scheme.
b) Fully close throttle valves 1 and 2.
c) Fully open throttle valves 3 and 4.
d) Set the pressure at both pressure reducing valves to 2 Bar.
e) Now open the solenoid 1.
f) Set the flow to 40 L/min using throttle valves 1.
g) Set the flow to 30 L/min using throttle valves 3.
h) Close the solenoid 1.
i) Repeat e) - h) for the second breach.

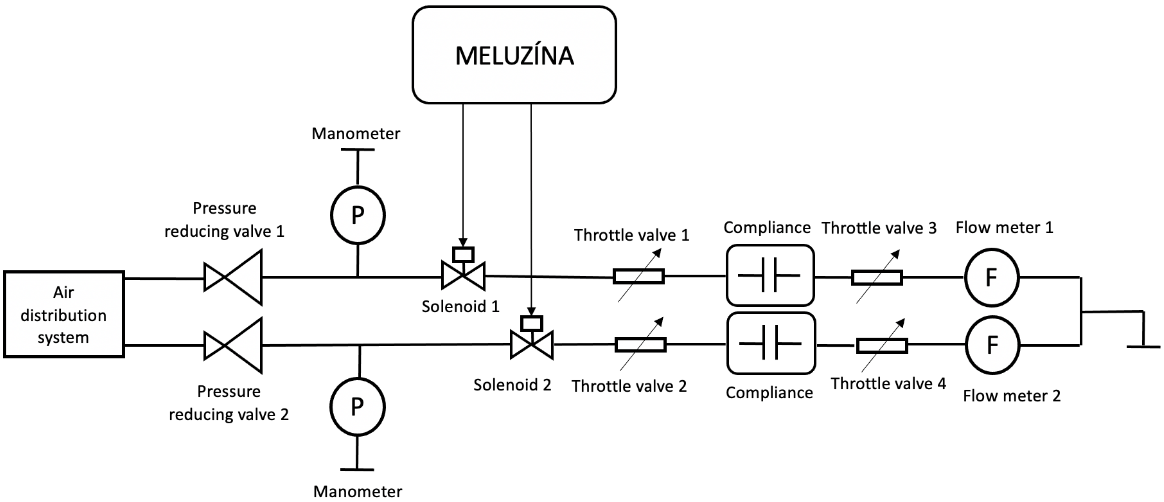

Fig. 56: A scheme of the apparatus

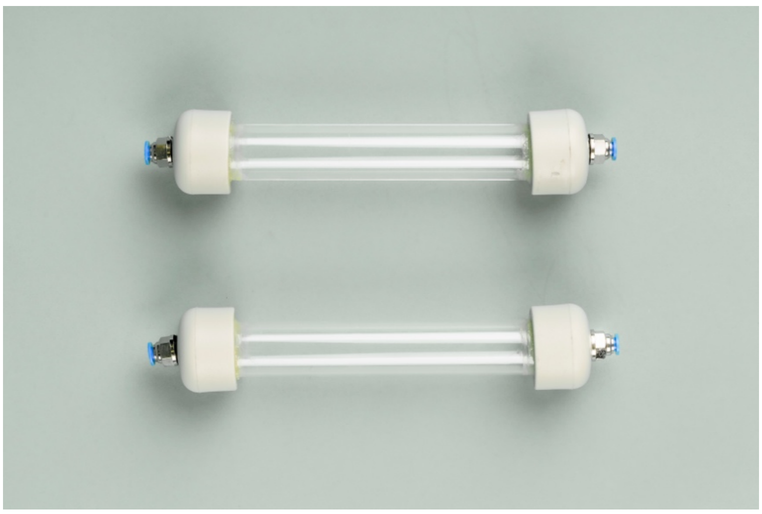

Fig. 57: Compliances

In the application:

a) STEP 1: Open Solenoid valve 1 with step time 50 ms.
b) STEP 2: Open Solenoid valve 2 with step time 50 ms.
c) STEP 3: Open Solenoid valve 1 with step time 50 ms.
d) STEP 4: Open Solenoid valve 2 with step time 50 ms.
e) Set 20 iterations and press Start.
f) Discuss the changes between the Basic and Advanced version of the fluctuating values of flow rates at the flow meters.
g) Based on the knowledge of flows in both branches and step times, try to make a mixture with ratio 1:3 with a total volume of 5 litres and using just 50% flow.

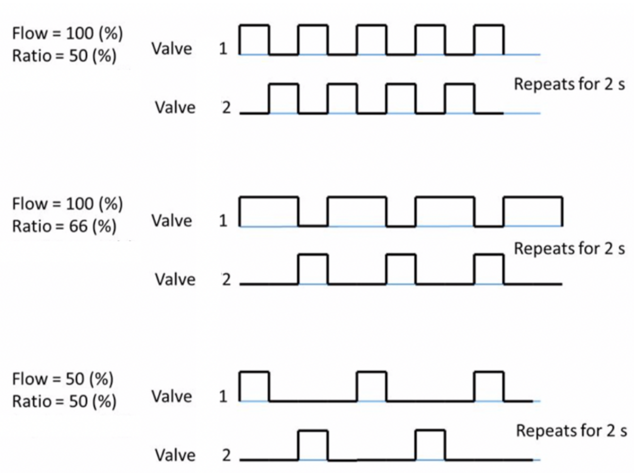

Fig. 58: Gas mixing ratios

3. Gas mixing using rotameters

a) Assemble the apparatus according to the scheme.
b) Adjust the rotameters, so you get the needed mixture.

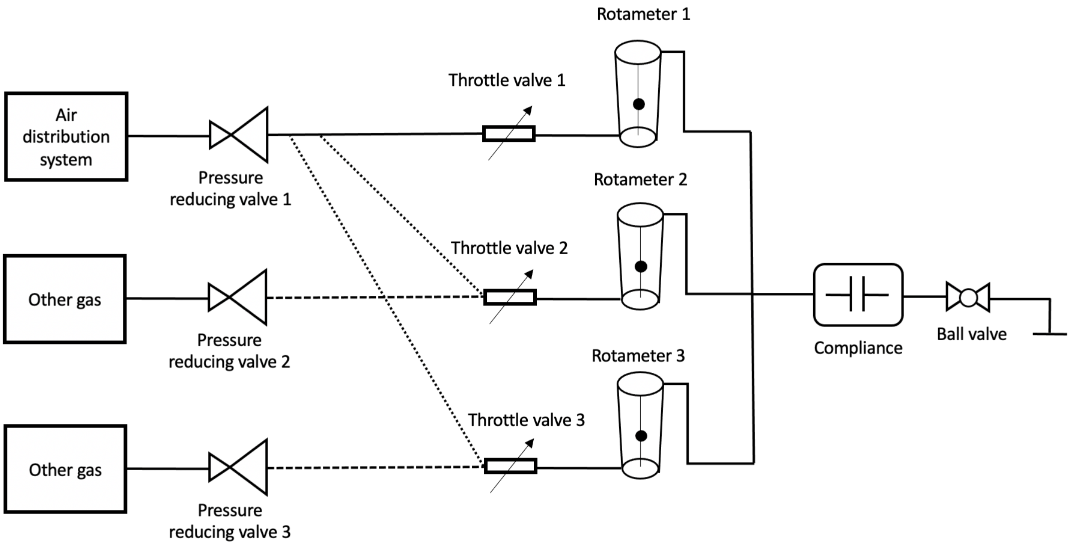

Fig. 59: A scheme of the apparatus

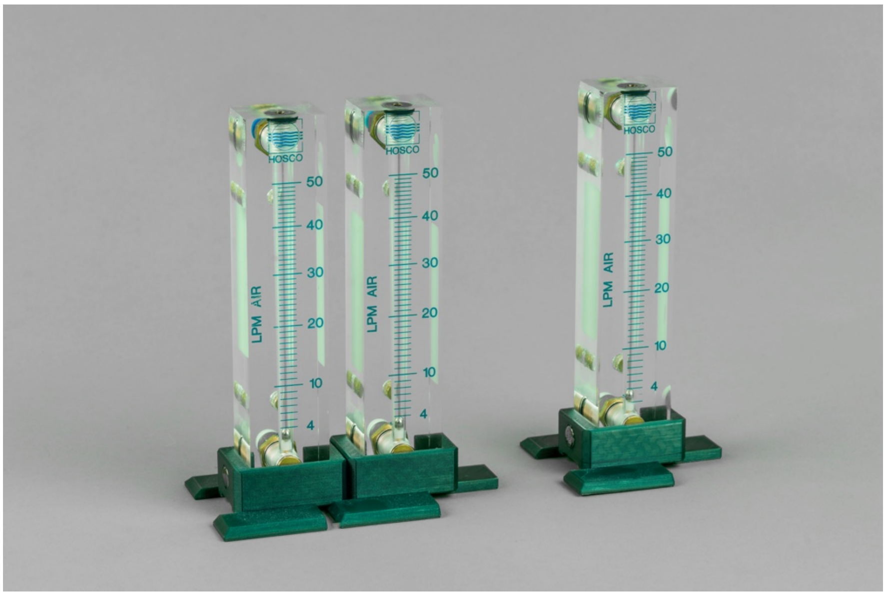

Fig. 60: Rotameters

4. Acoustic power

a) Assemble the apparatus according to the scheme.
b) Do not connect pressure sensors yet (risk of overpressure).
c) Fully close the ball valve and the throttle valve.
d) Connect the apparatus to the air distribution system.
e) Set the pressure on the pressure reducing valve to the lowest value.
f) Fully open the ball valve and partly open the throttle valve.
g) Connect the first pressure sensor.

h) Slowly adjust the pressure by the pressure reducing valve to 8 kPa and watch the pressure on your PC.
i) Set the flow to 10 L/min on the first rotameter using the throttle valve.
j) Connect the second pressure sensor.
k) Are there any changes in flow between rotameters?
l) Are there any changes in pressure in different parts of the apparatus?
m) Change the flow a look at the flow and pressure.

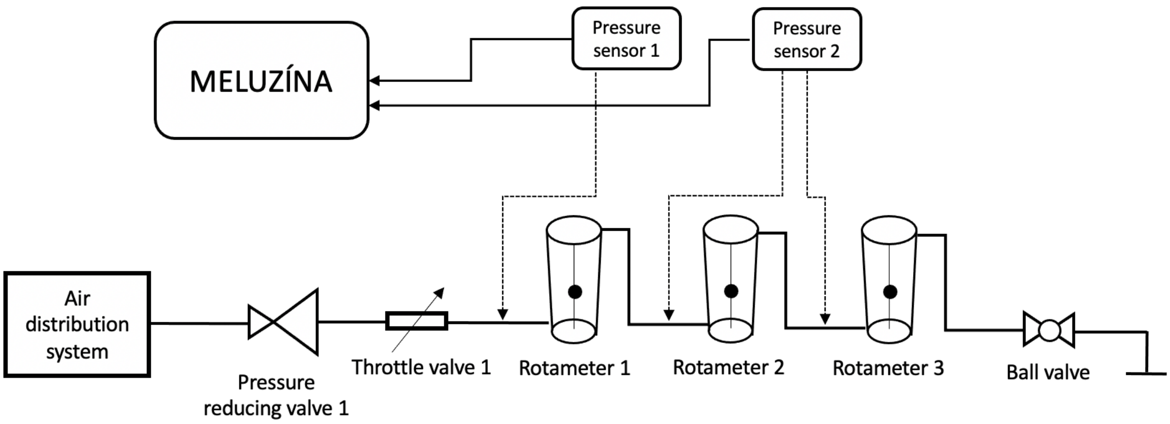

Fig. 61: A scheme of the apparatus

Equipment

Rotameters
Pnehykur kit
Meluzína
Manometers
Flowmeters
Compliances
Fast electromagnetic solenoids

Questions

What is the Electric analogy to Pneumatic compliance?
Why do we use the compliance in the apparatus?
What is the benefit of using these fast solenoids?

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4.8 Humidity, Humidifiers and Nebulizers

Goals

a) To acquaint students with devices designed for humidification of gas mixtures.
d) Explain to students the importance of humidifying the ventilation mixture.
e) Teach students to count air humidity.

Theory

The saturated water vapor curve (Laboratory task No. 3) can be used to design humidifiers or evaporators, where we require a specific value for the content of water vapor or anesthetic substance in the gas.

A nebulizer is an aerosol generating device, i.e. a mixture of small droplets of liquid or small solid particles in an inhaled gas. The nebulizer is used for respiratory diseases, e.g. for the inhalation of mineral water in laryngitis, and in particular for the delivery of drugs (steroids, bronchodilators, e.g. muscle relaxants) to the lower respiratory tract and lungs. The reason is targeted and accurate dosing and minimization of drug waste. Nebulizers are most often pneumatic, based on the Bernoulli effect, or ultrasonic.

Pneumatic nebulizers require a source of compressed gas to function to create an aerosol driving force. The compressed gas flows through a nozzle in which a negative pressure is created. The substance to be administered to the patient is drawn into the gas stream by a negative pressure (Bernoulli effect), where the flow is subsequently broken by a liquid film which is unstable and decomposes into small droplets of fluid due to surface tension. Further downstream of the gas is an obstacle, due to which the fluid droplets are reduced to a size of 1–5 µm. Larger droplets are returned to the tank with the substance due to the obstacle. After passing around the obstruction, droplets of fluid are already delivered to the patient's respiratory gas stream. The determinants of the droplet size of a substance are the characteristics of the substance and the flow rate of the gas and the substance. Increasing the gas flow rate while maintaining the substance flow rate leads to a reduction in the droplet size of the substance and vice versa.

In ultrasonic nebulizers, the fluid is broken into droplets by sound waves. They consist of two basic components: the piezoelectric transducer source and the fan. Piezoelectric transducers convert electrical energy into ultrasonic waves. The frequency of the waves determines the size of the droplets of the substance administered to the patient, with increasing frequency the size of the droplets of the substance decreases, which ranges from 1 to 6 µm. The amplitude of the ultrasonic waves determines the amount of substance that can be delivered by the nebulizer per unit time. As the amplitude of the waves increases, even more substances can be supplied. The ventilator is designed to deliver the resulting aerosol to the patient's respiratory gas.

The most clinically important parameter for evaluating nebulizer function is the dose of the substance delivered to the patient. This is determined by the mass flow from the nebulizer and the size of the droplets formed. The droplet size should be 2–5 µm for airway deposition and 1–2 µm for parenchymal deposition. The finer particles penetrate further (deeper) into the respiratory system.

Experiments

1. Nebulizer

a) Assemble the apparatus according to the diagram.
b) Set the pressure on both pressure reducing valves to 1 Bar.
c) Use throttle valve 1 to set the flow to 40 L/min.
d) Use throttle valve 2 to set the flow to 8 L/min.
e) Simulate human respiration by opening both solenoids simultaneously for 1 second once every 3 seconds.

f) Determine the weight of the box for Silica Gel.
g) Fill the box with dried Silica Gel and weigh it again.
h) Determine the internal volume of the box.
i) Place the filled Box with Silica Gel on one outlet of the nebulizer.
j) Disconnect the air flow after 4 minutes.
k) Determine the density of the silica gel.
l) Determine how much % of water was captured by Silica Gel (measure the loss of water in the nebulizer).

(Silica gel is a material that has a huge moisture absorption capacity. It gradually changes color from orange to green when saturated with water, indicating humidity. The absorption capacity at 80% relative humidity and 25 degrees Celsius is 36.3%. It absorbs moisture up to 36.3% of its weight. Regeneration is carried out by drying at temperatures of 130 - 160 degrees.)

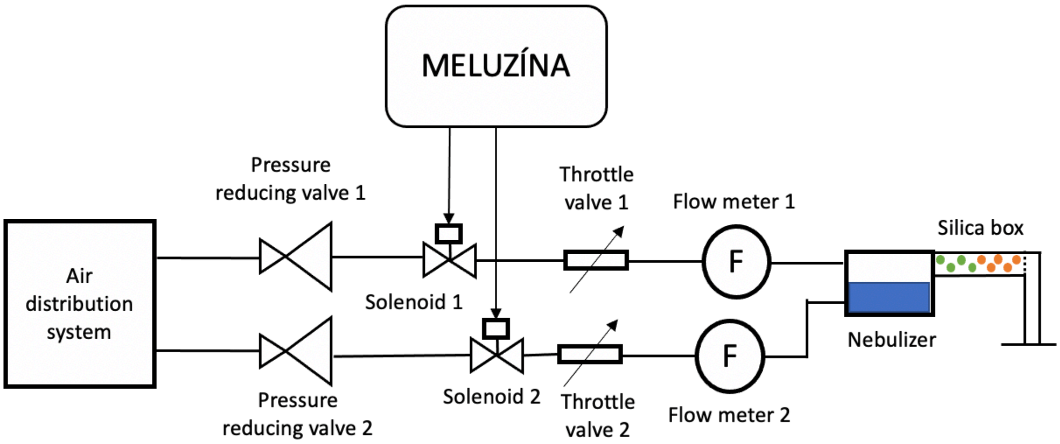

Fig. 62: A scheme of the apparatus for nebulizing

Fig. 63: Nebulizer, silicabox and weighing scale

2. Dose delivered from Nebulizer

a) Repeat a) - e) from the first experiment.
b) After 15 minutes disconnect the flow through the Nebulizer.
c) Determine the speed and the amount of evaporated water from the Nebulizer.

Equipment

Nebulizer with tube
Silica gel
Silica box
Scale

Air distribution system
Flowmeter
Pnehykur kit
Meluzína

Questions

What is the composition of the air (expressed in volume fractions and partial pressures of the components) that has passed through a humidifier filled with water at a temperature of 37 °C? After passing through the humidifier, the temperature of the humidified air will be 37 °C and the water vapor content in it will be the maximum possible.

What is the relative humidity of air that contains water vapor at a partial pressure of 55 kPa at a temperature of 95 ° C?

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4.9 Torricelli's law

Goals

d) Explain Torricelli's law to students.
e) Describe the problem of fluid flow during the outflow from the vessel.
f) Get acquainted with the outflow coefficient.

Theory

Outflow through a hole is an effect in which liquid flows from a tank (vessel, dam tank,..) through the full profile of the hole in the wall or bottom. The hole can be so-called small or large, depending on the relationship between the size of the hole and its depth below the surface. The small hole can be supplemented with a so-called sleeve adapter. Normally, when solving this problem, a steady state is assumed, resp. the constant position of the level (large reservoir, or the inflow into the tank is equal to the outflow from the tank).

The formula can be derived from Bernoulli's equation in pressure form:

$$\frac{1}{2}\rho {v_0}^2 + P_0 + \rho g h_0 = \frac{1}{2}\rho {v_1}^2 + P_1 + \rho g h_1 \ , \tag{1}$$

where ρ is a fluid density at all points in the fluid, v_0 is the fluid flow speed at a point on a streamline, P is the pressure at the chosen point, g is the acceleration due to gravity and h is the elevation of the point above a reference plane.

Assuming that the area of the container is much larger than the hole through which the liquid flows, then the drop in the liquid level can be considered negligible and therefore $v_0 = 0$. Atmospheric pressure can also be considered constant with a small difference in heights, so $P_0 = P_1$.

From Bernoulli's equation it is possible to derive the relation:

$$gh = \frac{v^2}{2} \ , \tag{2}$$

which is called the Torricelli formula. Torricelli's formula or Torricelli's law is a formula for calculating the flow rate of an ideal liquid, which has the form:

$$v = \sqrt{2gh} \ . \tag{3}$$

If we need to determine the liquid flow Q (m³/s) at the outlet of the hole, we start from the equation of continuity. However, it is also necessary to consider the narrowing of the outlet flow (if a narrowing occurs). At that moment, the so-called narrowing factor is implemented:

$$\varepsilon = \frac{S}{S_0}, \tag{4}$$

where S (m²) is the area of the outflow (stream) and S_0 (m²) is the area of the hole at the outlet. Subsequently, we can determine the flow as:

$$Q = S \cdot v = \varepsilon \varphi S_0 \sqrt{2gh}, \tag{5}$$

where φ is speed outflow coefficient.

There is still no reliable method to determine the theoretical speed outflow coefficients, so they are determined empirically, based on detailed measurements in hydraulic laboratories. In addition, their values may vary depending on both the Reynolds number and the position of the hole and its distance from the wall. The typical speed outflow coefficient is 0.97.

The capacity of the outflow through the hole is relatively small, but it can be increased, resp. according to special requirements, adjust by changing the edge of the hole or using a sleeve adapter - a short piece of pipe or fitting (widening, narrowing of the flow) mounted on the hole so that the edge of the hole aligns with the surface of the sleeve adapter.

Experiments

1. Prepare the apparatus

a) Measure the dimensions of the individual parameters.

d = *D* = *h1* = *h* = *H* =

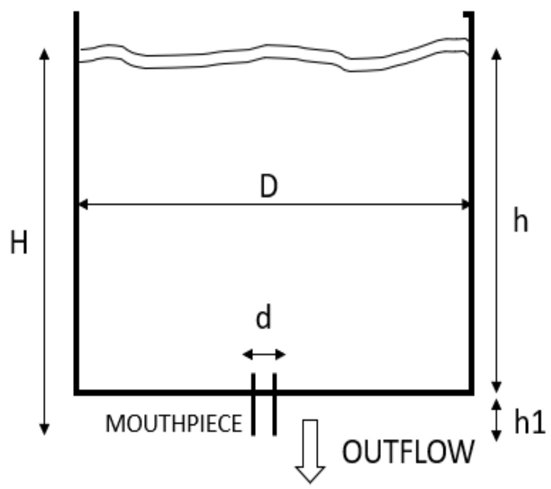

Fig. 64: Diameters of the apparatus

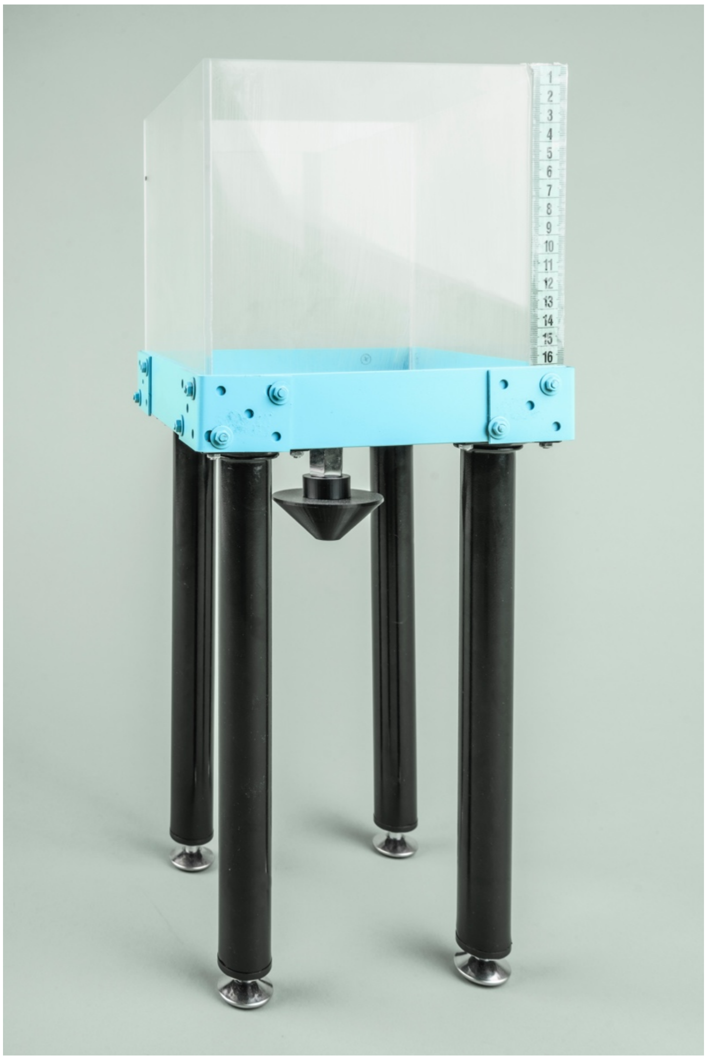

Fig. 65: The apparatus for Torricelli's law demonstration

Fig. 66: Different sleeve adapters

2. Measure the volume flow of water [m³/s] flowing through the small hole

a) Place a beaker (tank) with a marker line under the apparatus.
b) Choose one of the sleeve adapters and connect it from below to the closed ball valve.
c) Fill the container with water so that the *h* level is 15 cm.
d) Release the ball valve.
e) Measure the volume of water that flowed out in 15 seconds.
f) Make five measurements and calculate the mean and sample standard deviation of the flow. (Neglect the level drop in the calculations.)
g) Now do the same with the other sleeve adapters.

Tab. 6: Measured flow out volume in specified time.

Measurement	V [m³]	t [s]	Q [m³/s]
No. 1			
No. 2			
No. 3			
No. 4			
No. 5			

$$\dot{Q}_m = \frac{1}{5}\sum_{i=1}^{5}\dot{Q}_i \tag{6}$$

$$s = \sqrt{\frac{1}{5-1}\cdot\sum_{i=1}^{5}\left(\dot{Q}_1 - \dot{Q}_m\right)^2} \tag{7}$$

3. Determine the outflow coefficient of the hole

Based on the performed measurements, determine the outflow coefficient of the hole which needs to be corrected for the volume flow calculated when the viscosity of the fluid is neglected.

$$\mu = \varepsilon \cdot \varphi = \frac{Q_m}{Q_t} = \frac{Q_m}{S \cdot v} = \frac{Q_m}{\frac{\pi \cdot d^2}{4}\cdot\sqrt{2gH}}\ , \tag{8}$$

where Q_m is the measured outlet volume flow value, Q_t is the theoretical outlet volume flow value, *d* is the diameter of the hole of the sleeve adapter at the outlet and H is the total level height from the upper edge of the water level to the lower part of the sleeve adapter at the outlet.

$\varphi = 0.97$

Compare the outflow coefficients of the sleeve adapters between each other.

4. Derive the dependence of the water level on time when emptying the container

$$d\dot{Q} = \frac{dV}{dt} = \frac{Adh}{dt} = \frac{\pi D^2}{4} \cdot \frac{dh}{dt} = -\mu \frac{\pi d^2}{4} \sqrt{2gh}$$

$$\int_{H_0}^{H} \frac{1}{\sqrt{h}} dh = -\mu \frac{d^2}{D^2} \sqrt{2g} \int_{0}^{t} dt$$

...

...

Result:

$$H_{teor}(t) = \left(\sqrt{H_0} - \frac{\mu d^2 \sqrt{2g}}{2D^2} t\right)^2$$

5. Measure the dependence of the level on time when emptying the container and compare it graphically with the theoretical dependence. (Use the outflow coefficient you find.)

a) Place the apparatus so that the water can drain freely.
b) Choose one of the sleeve adapters and connect it from below to the closed ball valve.
c) Fill the container with water so that the level is 15 cm.
d) Release the ball valve and start the time.
e) Measure the time when the water level reaches 14 cm, 13 cm, 12 cm, ...

Initial water level – $H = h + h_1 =$ ………….. cm

Tab. 7: Measured water level in time.

Water level h [cm]	H = h + h_1 [cm]	H teoretical [cm]	t [s]
15			
14			
13			
12			
11			
10			
9			
8			
7			
6			
5			
4			
3			
2			
1			

Typical result:

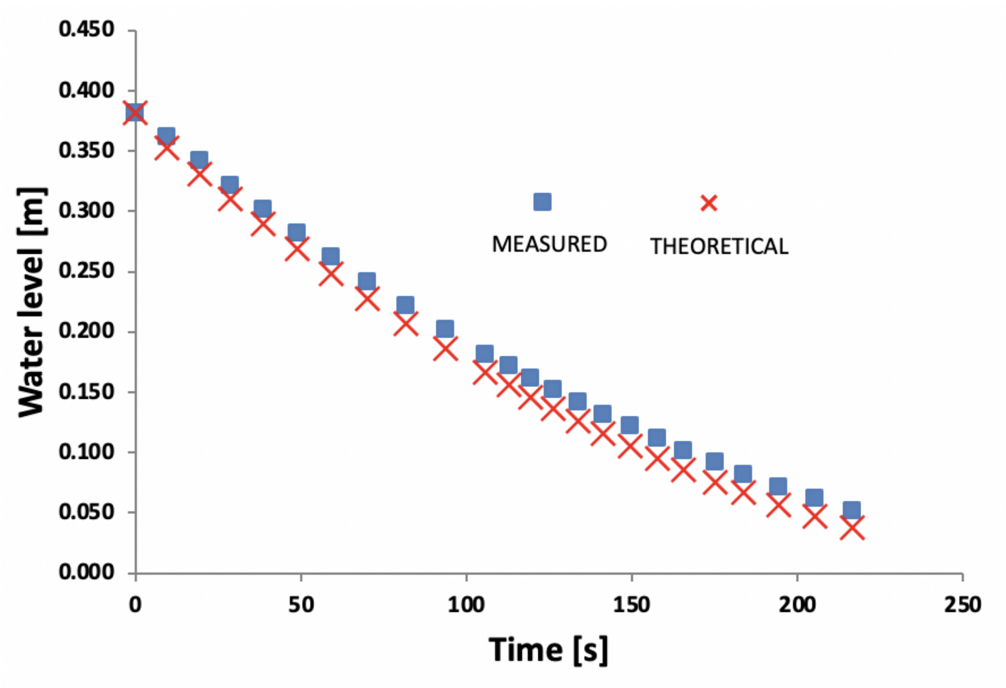

Fig. 67: Dependence of water level on time

Equipment

Water tank
Stand
Ball valve
Meter

Sleeve adapter
Timer
Beaker
Water container

Questions

In which cases will Torricelli's law find application?

Reference

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4.10 Pumps

Goals

a) Experimentally acquaint students with different types of pumps.
b) Explain to students the advantages and disadvantages of each solution.
c) To acquaint students with the places of use of pumps in medicine.

Theory

A pump is a device that moves fluids by mechanical action. Pumps operate by some mechanism (typically reciprocating or rotary) and consume energy to perform mechanical work moving the fluid. Mechanical pumps serve in a wide range of applications such as pumping water from wells, car industry for water-cooling and fuel injection, in the energy industry for pumping oil and natural gas, in air conditioning systems. In the medical industry, pumps are used for biochemical processes in developing and manufacturing medicine, and as artificial replacements for body parts, in particular the artificial heart and penile prosthesis.

Pumps are commonly rated by horsepower, volumetric flow rate, outlet pressure in meters of head, inlet suction in suction meters of head. The head can be simplified as the number of meters the pump can raise a column of water at atmospheric pressure.

There are three basic types of pumps: positive-displacement, centrifugal and axial-flow pumps. In centrifugal pumps the direction of flow of the fluid changes by ninety degrees as it flows over the impeller, while in axial flow pumps the direction of flow is unchanged.

A positive-displacement pump must not operate against a closed valve on the discharge side of the pump, because it has no shutoff head like centrifugal pumps. A positive-displacement pump operating against a closed discharge valve continues to produce flow and the pressure in the discharge line increases until the line bursts, the pump is severely damaged. A relief or safety valve on the discharge side of the positive-displacement pump is therefore necessary.

Gear pump - This is the simplest form of rotary positive-displacement pumps. It consists of two meshed gears that rotate in a closely fitted casing.

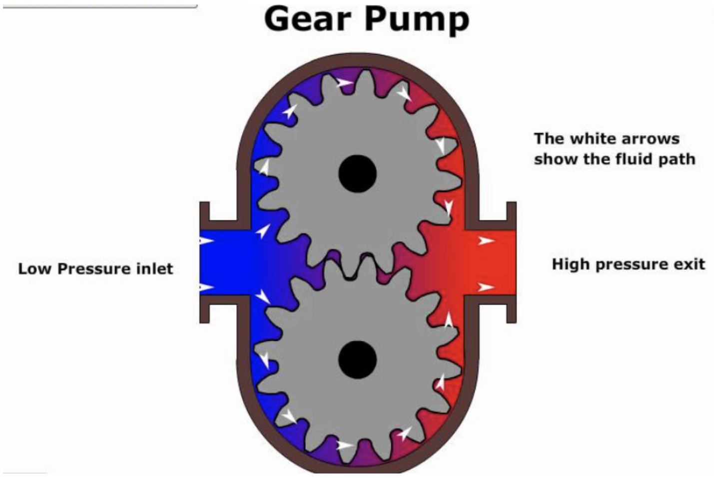

Fig. 68: A principle of gear pump
Source: https://www.youtube.com/watch?v=c6gwU7IHtlo

A peristaltic pump is a type of positive-displacement pump. It contains fluid within a flexible tube fitted inside a circular pump casing. A number of rollers attached to a rotor compresses the flexible tube. As the rotor turns, the part of the tube under compression occludes, forcing the fluid through the tube. Additionally, when the tube opens to its natural state after the passing of the cam it draws fluid into the pump. This process is called peristalsis and is used in many biological systems such as the gastrointestinal tract.

This type of pump is used in healthcare, for example in dialysis or infusion pumps. Peristaltic pumps are often used where very precise dosing is required, as the size of the sample taken is determined by the number of revolutions of the pump with the sucked liquid, which is detected by a sensor in the suction line. The advantage over other types of pumps is the contact of the pumped substance only with the tube, easy cleaning, selectable sampling rate and relative simplicity of construction.

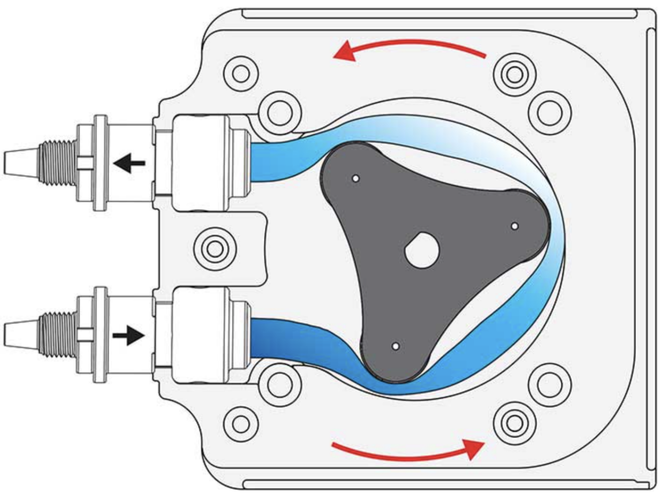
Fig. 69: Peristaltic pump
Source: https://www.pumpsandsystems.com/advantages-peristaltic-pumps-metering-applications

An infusion pump infuses fluids and medication into a patient's circulatory system. Infusion pumps can administer fluids in ways that would be impractically expensive or unreliable if performed manually by nursing staff. For example, they can administer as little as 0.1 mL per hour injections, injections every minute, injections with repeated boluses requested by the patient.

Archimedes' screw or screw pump is a machine used for transferring water from a low-lying body of water into irrigation ditches. Water is pumped by turning a screw-shaped surface inside a pipe. Archimedes screws could produce power if they are driven by flowing fluid instead of lifting fluid.

A piston pump is a type of positive displacement pump where the high-pressure seal reciprocates with the piston. This pump type functions through a piston cup, oscillation mechanism where down-strokes cause pressure differentials, filling of pump chambers, where up-stroke forces the pump fluid out for use. Piston pumps are often used in scenarios requiring high, consistent pressure and in water irrigation or delivery systems.

Diaphragm pump is a device designed for pumping liquids and gases of small volume. The pump consists of a closed vessel separated by a flexible diaphragm. The oscillating motion is transmitted to the membrane, which changes the volume of the space of the closed container. The space under the diaphragm is equipped with a suction and discharge valve, which opens and closes depending on the vacuum or overpressure in the space under the diaphragm.

A hydraulic ram is a cyclic water pump powered by hydropower. It takes in water at one "hydraulic head" (pressure) and flow rate, and outputs water at a higher hydraulic head and lower flow rate. The device uses the water hammer effect to develop pressure that allows a portion of the input water that powers the pump to be lifted to a point higher than where the water originally started.

An axial-flow pump is a common type of pump that essentially consists of a propeller in a pipe. The propeller can be driven directly by a sealed motor in the pipe or by electric motor or petrol/diesel engines mounted to the pipe from the outside.

Centrifugal pumps are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. The fluid enters the pump impeller along or near to the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber (casing), from which it exits.

The performance of a centrifugal pump is presented as characteristic curves in Figure, and is comprised of the following:

- Pumping head versus discharge,
- Brake horsepower (input power) versus discharge, and
- Efficiency versus discharge.

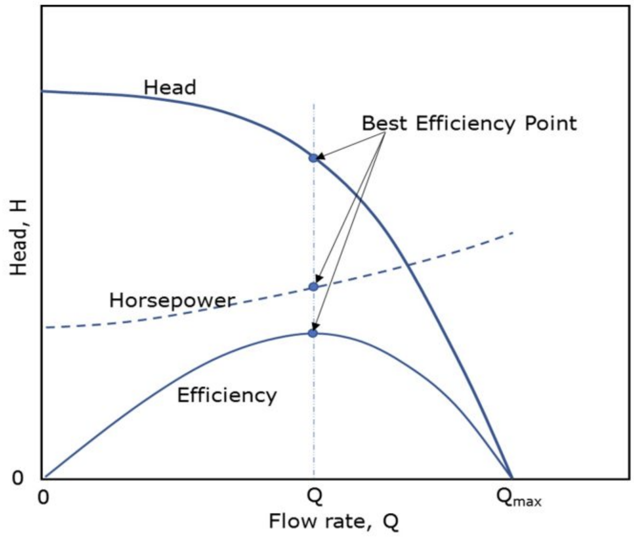

Fig. 70: Typical centrifugal pump performance curves at constant impeller rotation speed.
Source: https://uta.pressbooks.pub/appliedfluidmechanics/chapter/experiment-10/

Experiments

1. **The operational characteristics of two centrifugal pumps when they are configured as a single pump, two pumps in series, and two pumps in parallel.**

a) Each configuration (single pump, two pumps in series, and two pumps in parallel) will be tested at different pump speeds (PWM regulation).
b) For each speed, the globe regulating valve will be set to fully closed, approximately 25%, 50%, 75%, and 100% open.

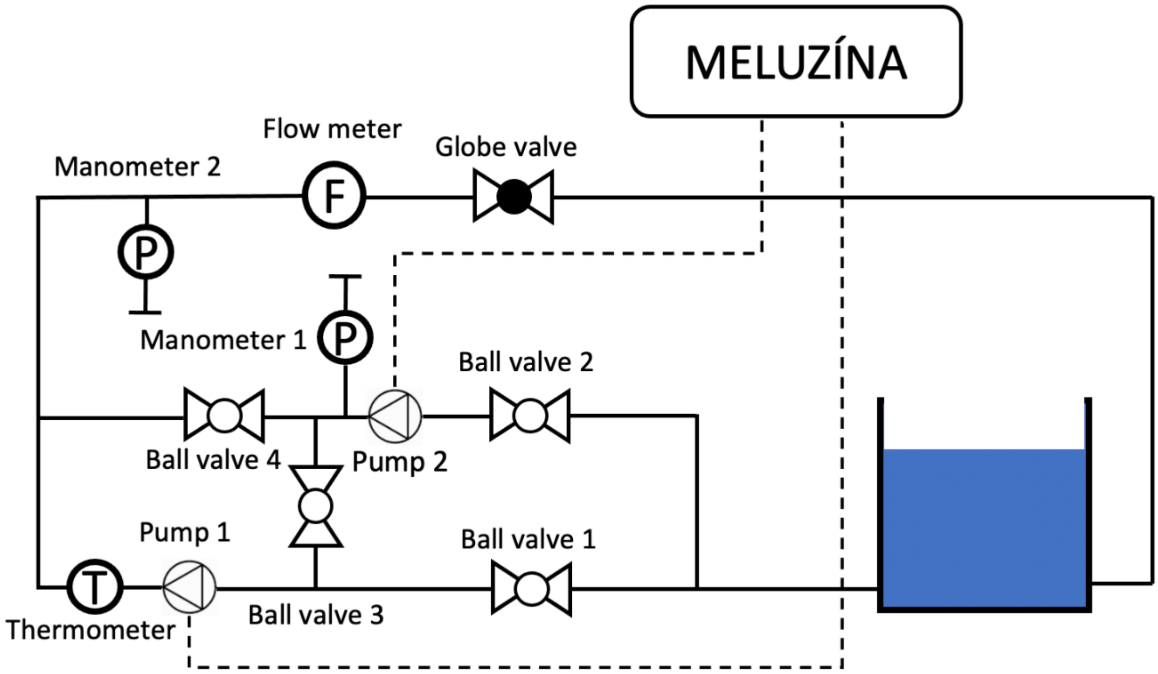

Fig. 71: A scheme of the apparatus

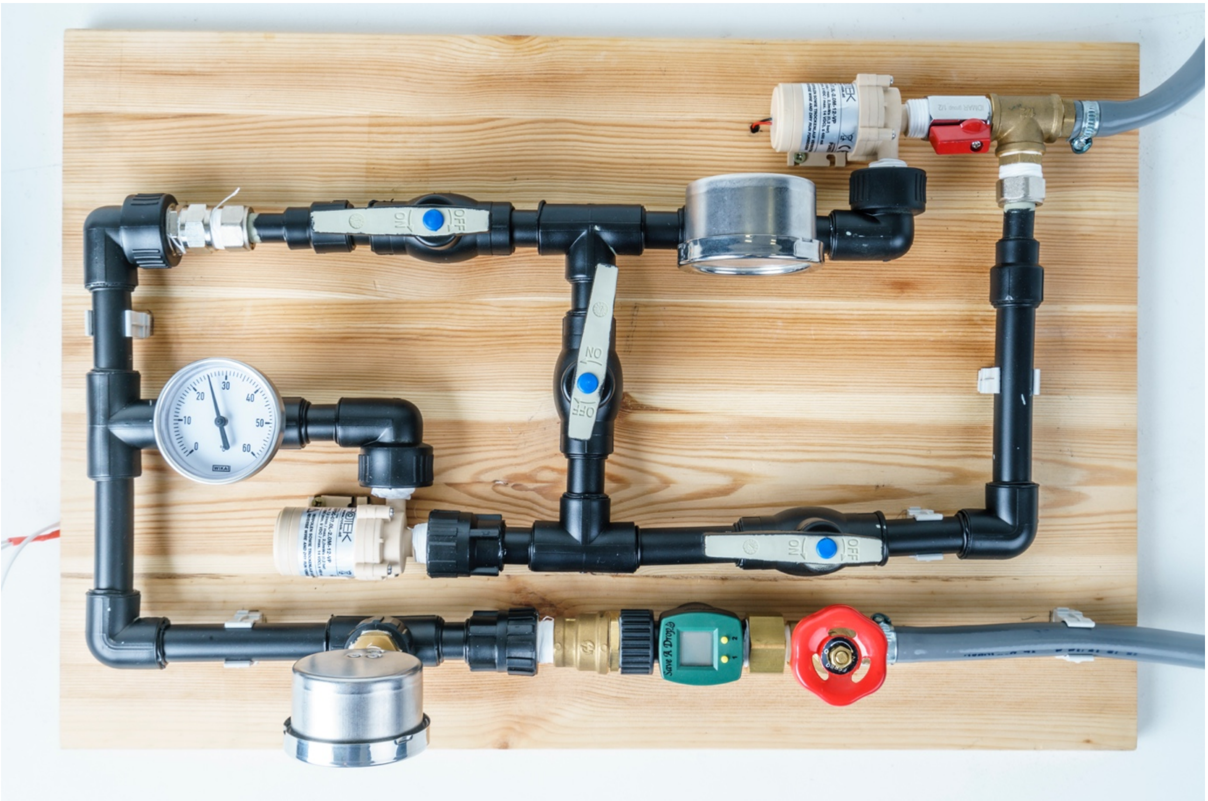

Fig. 72: The apparatus of centrifugal pumps from above view

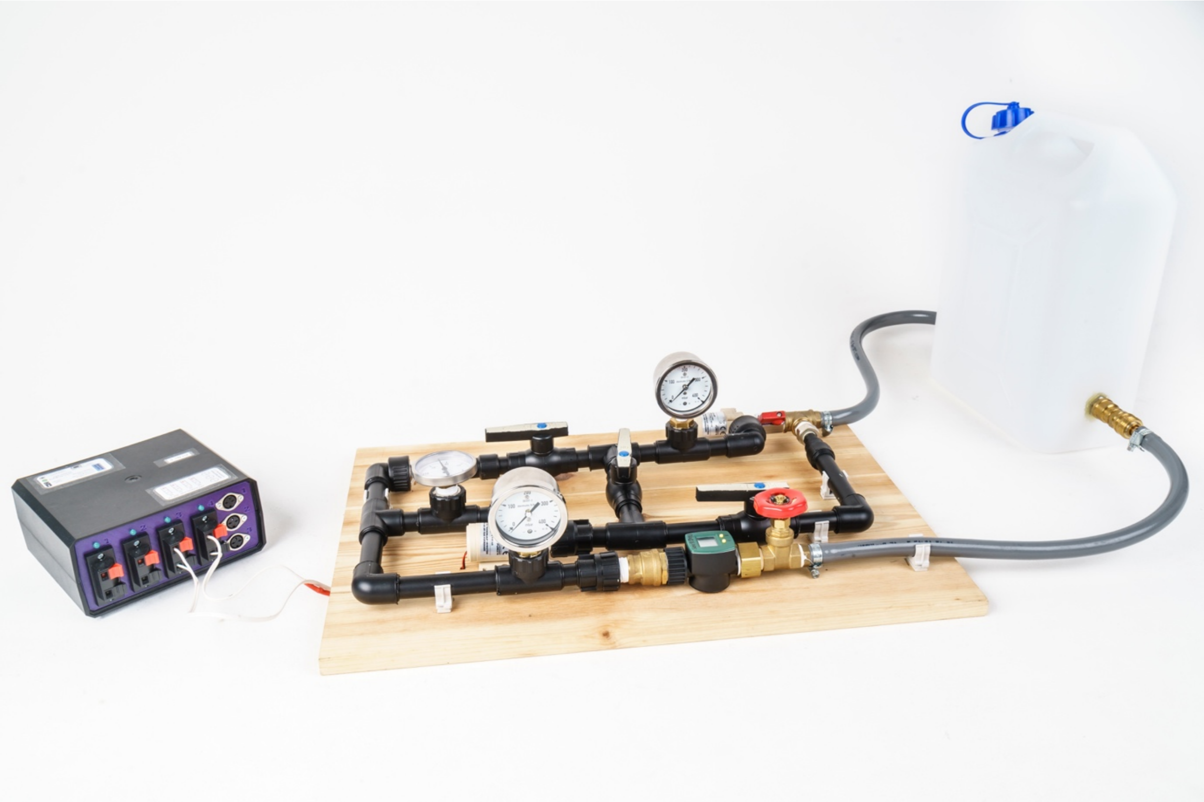

Fig. 73: Fully assembled centrifugal pumps apparatus

1.1 Characteristics of a single pump

a) Set up the ball valves to perform the single pump test.
b) Start pump 1 and set the first speed.
c) Turn the bench regulating valve to the fully closed position.
d) Record the pump 1 inlet pressure (P1) and outlet pressure (P2). (With the regulating valve fully closed, discharge will be zero.)
e) Repeat steps (c) and (d) by setting the regulating globe valve to 25%, 50%, 75%, and 100% open.
f) For each control valve position, measure the flow rate.
g) Increase the speed by changing PWM, and repeat steps (c) to (f) for each speed.

(PWM regulation is possible using the valve cycling application where you change outputs from open to close and back with numerous iterations.)

1.2 Characteristics of two pumps in series

a) Set up the ball valves to perform the two pumps in series.
b) Start pumps 1 and 2.
c) Repeat the steps (c) to (g) from experiment 1.1.

1.3 Characteristics of two pumps in parallel

a) Set up the ball valves to perform the two pumps in parallel.
b) Start pumps 1 and 2.
c) Repeat the steps (c) to (g) from experiment 1.1.

Tab. 8: Measured water level in time

Configuration and speed: Single/serial/parallel and PWM 60/80/100					
Globe valve position (%)	0	25	50	75	100
Volume (L)					
Time (s)					
Inlet pressure (bar) (water level)					
Pump 1 Outlet pressure (bar)					
Pump 2 Outlet pressure (bar)					

2. Peristaltic pump vs Gear pump

a) Connect the apparatus to Meluzína.
b) Put enough water to the water tank.
c) Use the valve cycling application as a power source for the pumps.
d) What type of pump has bigger flow rate?
e) Test the dosing accuracy of the individual pumps by dosing the water by one milliliter. Repeat it for 5 times a discuss the differences.
f) Discuss the benefits of peristaltic pump: accuracy, material, construction, biocompatibility

Fig. 74: Fully assembled apparatus of gear pump versus peristaltic pump

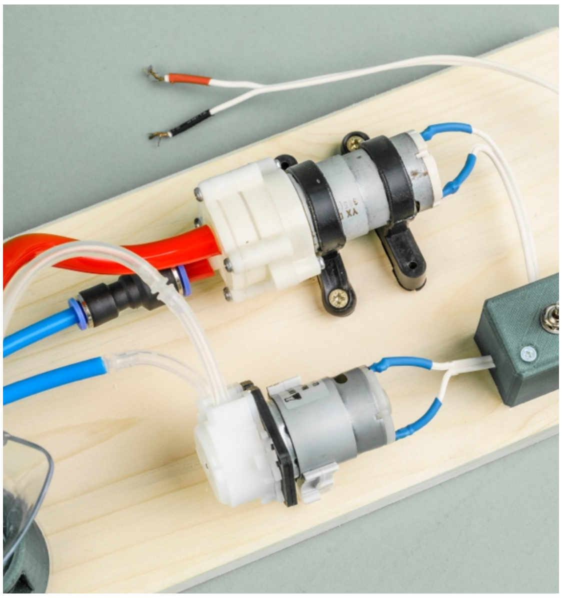

Fig. 75: A detailed view on the water pumps

3. Archimedes' screw

Fig. 76: Archimedes' screw

a) Assemble the Archimedes' screw.
b) Put enough water to the water tank.
c) Use the valve cycling application as a power source for the pumps.
d) Discuss the benefits of this solution – accuracy, maximum achievable discharge level.

Equipment

Meluzína
Archimedes’ screw
Apparatus of gear pump versus peristaltic pump
Centrifugal pumps apparatus

Questions

What type of pump would you use for Extracorporeal membrane oxygenation (ECMO)?
What happens if we connect the pumps in series? in parallel?

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