MEASUREMENT OF A LIQUID RING VACUUM PUMP

Vacuum pumps are machines that convey gas from a closed space, thereby creating a partial vacuum.

1. Aim of the measurement

We aim to measure the performance curves of an EV 40/80 liquid ring vacuum pump. The independent parameter of the performance curve of a vacuum pump can be one of the following:

p	vacuum pressure,
p_0/p	pressure ratio,
$\frac{p_0-p}{p_0}$	relative vacuum.

Using, e.g., the relative vacuum, the performance curves are the following functions:

$$P_{isothermal} = f_1\left(\frac{p_0-p}{p_0}\right), Q = f_2\left(\frac{p_0-p}{p_0}\right), \eta = f_3\left(\frac{p_0-p}{p_0}\right).$$

2. Theory

Liquid ring vacuum pump

The rotating impeller blades, which are on an eccentrically placed shaft in the cylindrical housing, cause the fluid (water) to rotate and to form a ring in the housing (see Figure 1). This configuration creates periodically changing – increasing and decreasing – volumes enclosed by the water and the impeller blades.

The side where the volumes are increasing is connected to the suction pipe, and the side with the decreasing volumes is connected to the pressure pipe.

The water ring lubricates the impellers and the housing. The temperature of the gas is approximately constant during the compression since the gas is in contact with the liquid ring. Therefore the compression can be assumed to be isothermal. The small temperature rise due to the compression can be further reduced by continually changing the water in the pump.

The isothermal thermodynamic process

If the change in the system is sufficiently slow, then the medium has enough time to maintain thermal equilibrium with it’s environment. This means that the heat transfer between the system and the environment is such that the system’s temperature is the same as the environment’s.
The equation describing the isothermal process of an ideal gas is the following:

$$p_1 v_1 = p_2 v_2 = RT = \text{const.}$$

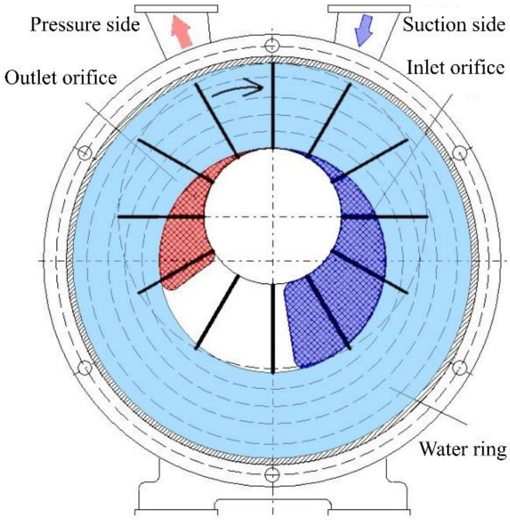

Figure 1. *Schematics of the liquid ring vacuum pump* [1,2]

The isothermal process in a $p - v$ diagram is described by a hyperbole function, and the parameter of this hyperbole is the temperature.

Using subscript 1 for the suction side, and subscript 2 for the pressure side, the specific useful work during the isothermal compression of an ideal gas is the following:

$$W_{1,2} = RT \ln\left(\frac{p_2}{p_1}\right) \left(\frac{J}{kg}\right).$$

We can rewrite this equation using the ideal gas law:

$$W_{1,2} = p_1 v_1 \ \ln\left(\frac{p_2}{p_1}\right) \left(\frac{J}{kg}\right).$$

Using this equation the useful power, using the suction side volumetric flow rate Q_1 is written as follows:

$$P = p_1 Q_1 \ \ln\left(\frac{p_2}{p_1}\right) \left(\frac{J}{s} = W\right).$$

[2] The operation of the machine explained in a video: https://www.youtube.com/watch?v=DEmCy1dwLqo
[3] The operation of the machine explained in another video: https://www.youtube.com/watch?v=Y99ulE85e8Q

3. Description of the measurement rig

The measurement rig can be seen in Figures 1 and 2. A 3-phase asynchronous motor (M) is connected through a clutch (K) to the vacuum pump (Vp). The power driving the electric motor is measured with the multimeter (Mm) using a 3-phase power measuring instrument. The nominal speed of rotation of the electric motor is $n_{nom} = 2900\frac{1}{\text{min}}$.

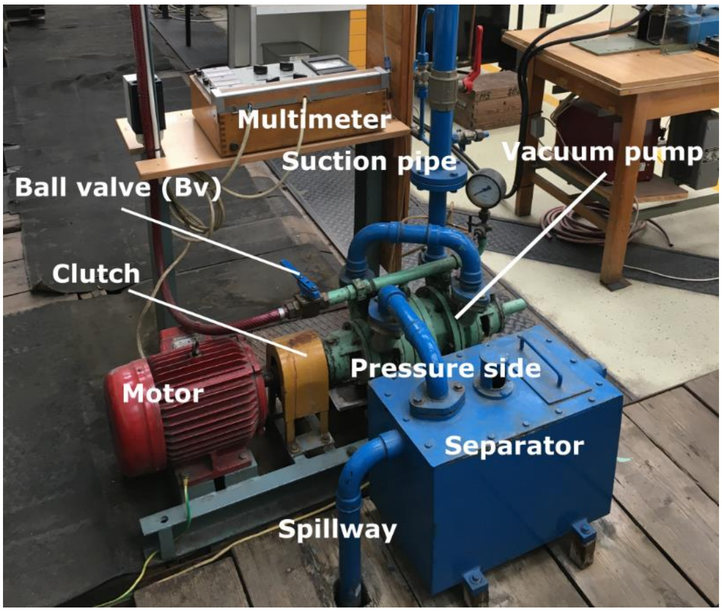

Figure 2. *The measurement rig*

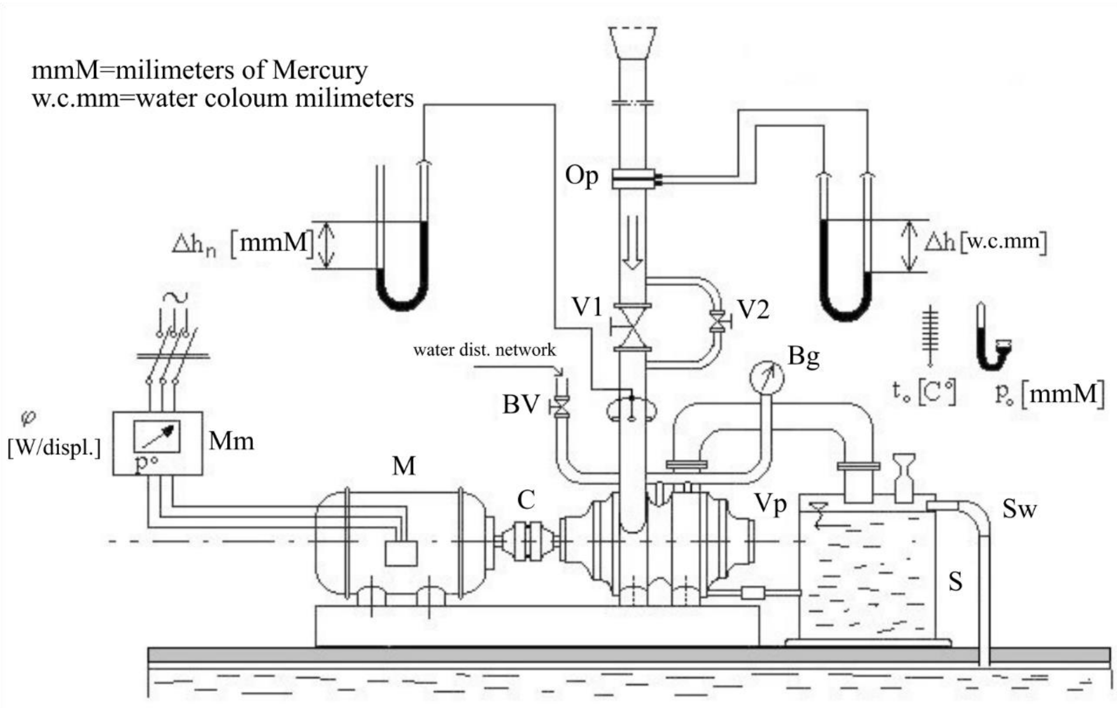

Figure 3. *Schematics of the measurement rig*

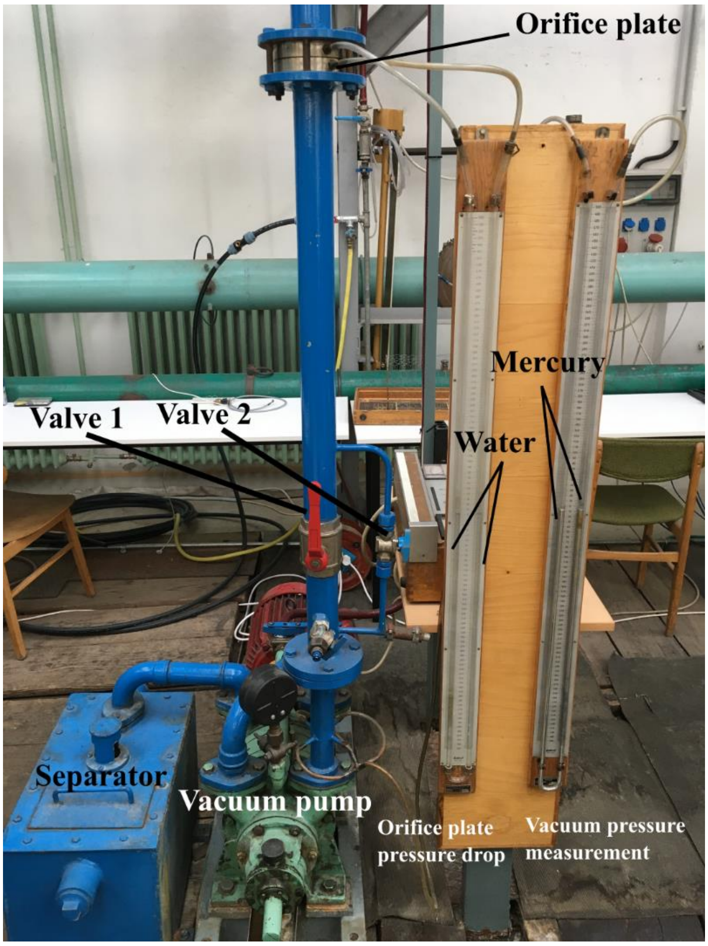

Figure 4. *The location of the pressure gauges and taps*

The volumetric flow rate at the inlet is measured using an orifice plate (Op) with $\beta = \frac{d}{D} = \frac{15}{53}$. The orifice plate is manufactured according to the standard ISO1709/3. Before the orifice plate, the length of the pipe is $l_1 \geq 30D$, and after the orifice plate the distance of the vacuum pump is $l_2 \geq 5D$, which satisfies the requirements of the standard. The pressure drop on the orifice plate $\Delta p(\Delta h)$ is measured with a water column pressure gauge (U-tube manometer), in which the fluid is water. Since the pressure drop on the orifice plate is relatively small, the expansion number is approximately one ($\varepsilon \approx 1$). The pressure in the suction side relative to the ambient pressure is measured with a liquid column gauge (U-tube manometer) filled with mercury. Because the density of mercury is much higher than the density of air ($\rho_{air} \ll \rho_{mercury}$), from the height difference of the liquid columns the pressure difference at the suction side ($p - p_0$) can be calculated directly. The operating point can be set with a ball valve (V1). Reducing the cross-section with the tap decreases the suction side pressure. The ball valve (V2) in the small bypass pipe allows us to adjust the operating point finely. The vacuum pump conveys the ambient air to the separator (S). The spillway (Sw) of the separator passively removes the surplus water from the system.

The water flow to the system aims to provide cooling and to make up for the water loss due to the evaporation and the leakage losses. It is important to note that the pump is sensitive to the pressure of the water supply. Measurements at different p_{supp} pressures result in different η_{max}

maximum efficiencies. The maximum efficiency η_{max} as a function of the water supply pressure p_{supp} can be seen in Figure 5.

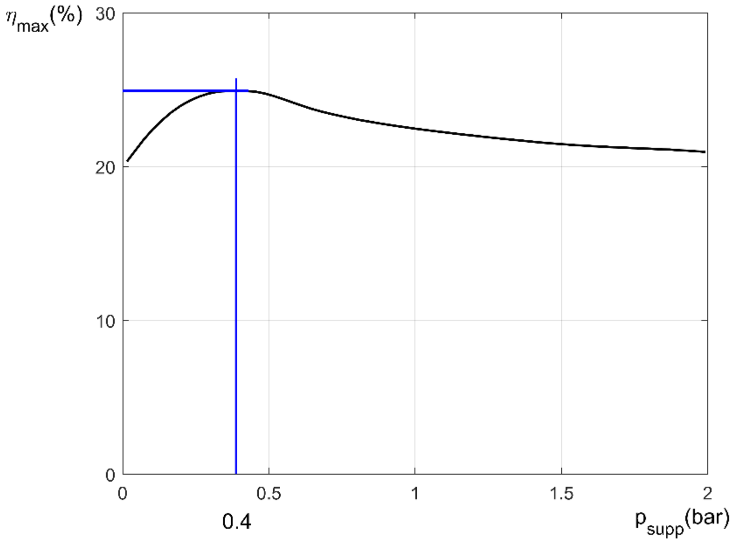

Figure 5 *Maximum efficiency as a function of the water supply pressure*

The maximum efficiency can be reached at $p_{supp} = 0.4\,\mathrm{bar}$ pressure in the case of the current machine. For this reason, we would like to perform the measurements keeping this supply pressure constant. Extensive previous measurement indicate that at higher p_{supp} supply pressure values the relative vacuum and the input power increases, while the volumetric flow rate at the inlet decreases. The p_{supp} pressure can be set by adjusting a ball valve (BV), and it’s value is displayed by a Bourdon gauge (Bg). Performing the measurement at different rotation speeds and plotting the iso-efficiency lines allows a more detailed analysis of the machine. Since the asynchronous electric motor does not allow us to change the speed of rotation, and this would require additional time, the performance curve is measured only at the design speed of rotation.

4. Calculation of the performance curves

4.1. Vacuum pressure (p)

The U-tube manometer (liquid column pressure gauge) directly displays the value of $(p_0 - p)$ in unit millimeters of Mercury. The atmospheric pressure (p_0) needs to be measured only once. Using the atmospheric pressure, p, $\frac{p_0}{p}$, and $\frac{p_0-p}{p_0} = \frac{\Delta h_p \rho_M g}{b \rho_M g} = \frac{\Delta h_p}{b}$ can be calculated. The following equation gives the atmospheric pressure:

$$p_0 = \rho_M g b,$$

where

- $\rho_M = 13600 \frac{kg}{m^3}$ is the density of Mercury,
- $g = 9.81 \frac{m}{s^2}$ is the gravitational acceleration,
- $b\ (meter\ of\ Mercury)$ is the displacement of the Mercury on the barometer.

The atmospheric pressure is displayed by a digital barometer, and from the atmospheric pressure, the height b can be easily calculated.

4.2. Volumetric flow rate (Q)

The volumetric flow rate is given by the formula

$$Q = \alpha \varepsilon \frac{d^2 \pi}{4} \sqrt{\frac{2}{\rho_{air}} \Delta p}\,,$$

In which:

- d = 15 [mm] is the inner diameter of the orifice plate,
- ε = 1 [-] is the expansion number,
- $\rho_{air}\ \left(\frac{kg}{m^3}\right)$ is the density of the air at the ambient temperature $t_0\ (°C)$ (the ambient temperature needs to be measured only once)
- $\Delta p\ (Pa)$ is the pressure drop on the orifice plate, given by the formula $\Delta p = \rho_{water} g \Delta h$,
- $\rho_{water} = 1000\ \left(\frac{kg}{m^3}\right)$ is the density of the water, which is the liquid in the U-tube manometer of the orifice plate,
- $\Delta h (mm)$ is the displacement on the U-tube manometer,
- α (1) is the flow coefficient.

Calculation of the flow coefficient α requires an iterative process, which is described in detail in the centrifugal pump measurement description. A significant difference here is that the fluid in the machine is air, therefore in the formulae the parameters (e.g., kinematic viscosity) of the air need to be substituted. These calculations can be found in the *Fan* measurement description.

4.3. Electric power (P_e) and input power (P_{in})

The electric power of the motor can be calculated from the following formula:

$$P_e = C_e P_e^0,$$

where,

- P_e^0 [°] is the power that can be read from the measuring case in degrees (see Fig. 6),
- C_w = 8 [W/°] is the measurement constant.

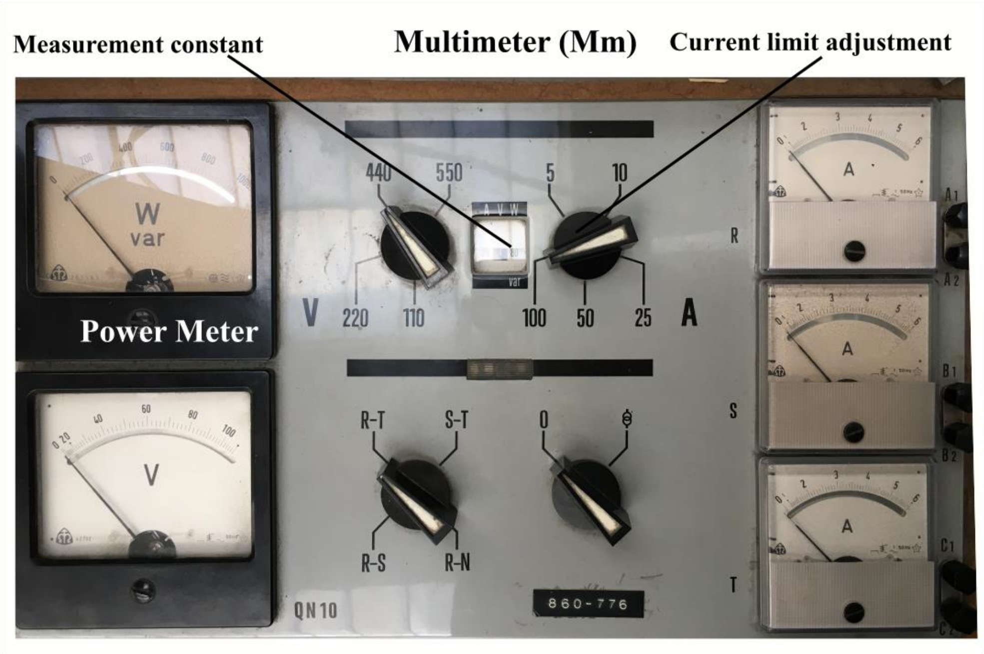

Figure 6. *The Multimeter*

The power supplied to the shaft that drives the vacuum pump, i.e., the input power (P_{in}) can be calculated using Figure 7. Using the load factor x calculated from the diagram, the input power is the following:

$$P_{in} = x\, P_{nomimal},$$

where $P_{nomimal}$ = 5500 (W) is the nominal power of the electric motor.

The ($P_{in} - x$) diagram was obtained by measurements using a balance motor.

4.4. Isothermal power P_{iso}, efficiency (η) I

Assuming isothermal compression (which is reasonable considering the effect of the water ring), the useful isothermal power can be calculated according to the formula discussed in Section 2[3]:

$$P_{iso} = p_0 Q \ \ln\left(\frac{p_0}{p}\right),$$

where

- p_0 és Q are both considered at the inlet,
- p_0 and p are absolute pressures.

The efficiency is given by the formula

$$\eta = \frac{P_{iso}}{P_{in}}.$$

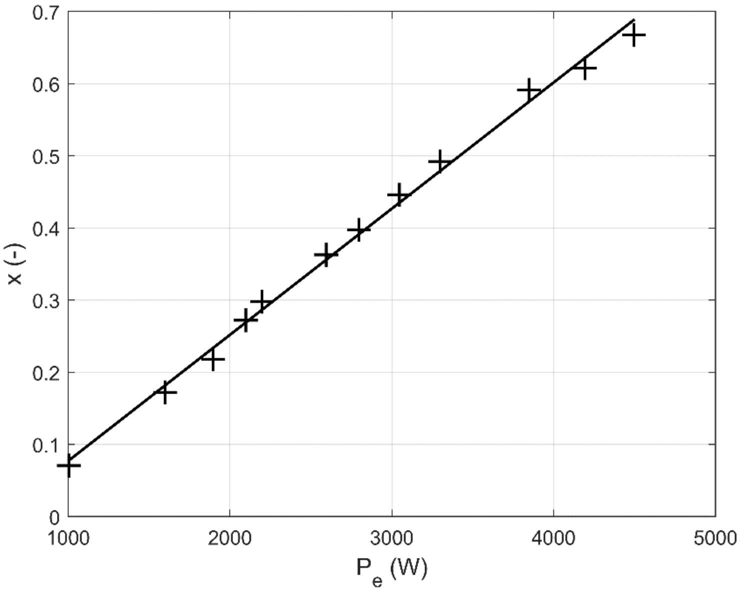

Figure 7 *Electric power –relative power diagram of the electric motor, type VZ 41/2, ID. No. 708.711.*

[3] The derivation of this formula can be found in the Appendix.

5. Data of the measurement rig

Vacuum pump:
- type: EV 40/80 II., liquid ring vacuum pump,
- Q = 50 [m^3/h],
- n = 2900 [1/min],
- t_o = 20 [°C] (reference temperature),
- relative vacuum: 30 ÷ 90 [%].

Electric motor:
- type: VZ 41/2, three phase asynchronous motor,
- n_{nom}= 2880 [1/min],
- P_{nom}= 5500 [W].

Orifice plate:
- d = 15 mm,
- D = 53 mm.

Measuring case:
- Inventory number: 860 – 776.

Digital barometer:
- type: GPB 1300.

6. The measurement

6.1. Preparations

1. The limit of the power meter (Mm) should be set to the maximum value. This is necessary to avoid the potential overload of the machine at the start.
2. Open valve (V1) fully. This permits the spilling of Mercury from the liquid column pressure gauge.
3. Check the pressure gauges.
4. When the machine is already in a steady-state condition, set the limit of the power measuring instrument to the proper value (C_w = 8 (W/degree).
5. Before turning off the machine, open the valve (V1) fully to avoid the spilling of the Mercury from the liquid column pressure gauges.

6.2. The measurement points

With 15 operating points, the performance curves can be approximated satisfactorily. The liquid column pressure gauge (with Mercury) should be used for this. The range 0 and p0 should be divided into 14 equidistant intervals.

The machine at specific operating points can behave ,,uneasily”. This is due to the instability of the water ring. At such operating states, the measured quantities should be averaged over a suitable time.

7. Preparation for the measurement

For the measurements, the following preparations need to be carried out:

- The measurement description should be learned. Each measurement starts with a short test, which aims to check the knowledge of the students.
- The leader of the 4-person measurement group must submit a report from the measurement. The deadline for the report submission is 2 weeks. The measurement report must contain every data about the measurement. The group leader should prepare a table (on a paper or computer), which contains the proper field for the measurement data. The table should contain enough space for at least 15 measurement points.
- At the end of the measurement, the group must submit a verification diagram. This diagram helps us to identify and correct errors during the measurement. The schematics of the verification diagram can be seen in Figure 8. The independent variable, i.e., the one on the x-axis, is in both cases a quantity that is proportional to the relative vacuum. The dependent variable, i.e., the one on the y-axis, is proportional to the input power and with the volumetric flow rate, respectively. The verification diagrams should be made on an A4 millimeter paper or in an Excel sheet on a laptop, and the axes should be adjusted before the measurement.

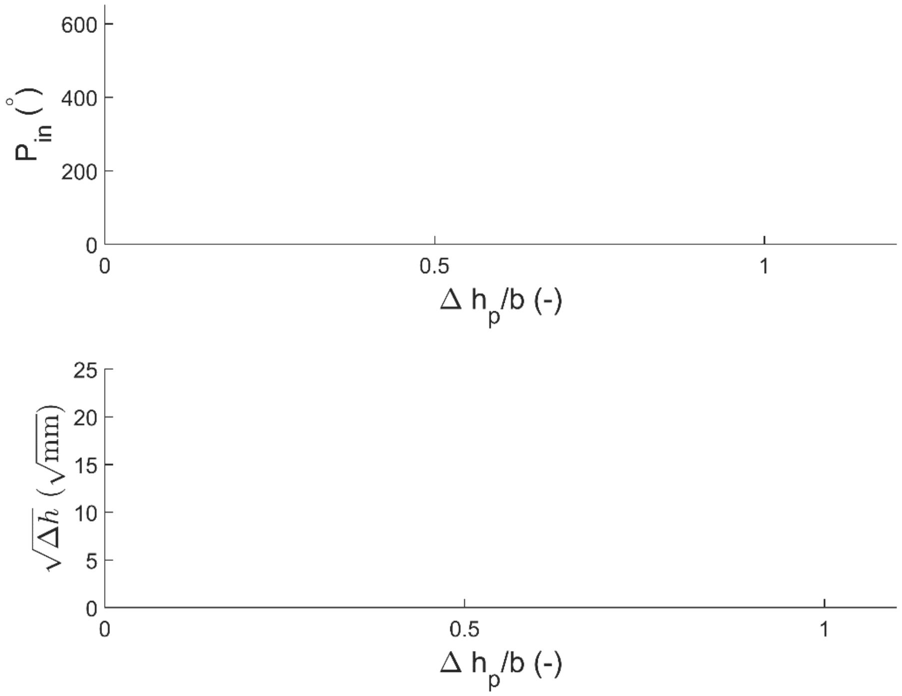

Figure 8. *The verification diagram*

8. Test questions

1. What are the most common performance curves of vacuum pumps? List 3 of them!

2. Describe the schematics of a vacuum pump on a figure! Röviden ismertesse a vízgyűrűs vákuumszivattyúk működési elvét! Rajzoljon ábrát!
3. How do we measure the volumetric flow rate of the vacuum pump? What are the steps of the calculation? Describe them in order!
4. How can we calculate the useful power of the vacuum pump? What quantities do we need to measure for this calculation?
5. Draw the schematics of the measurement rig!
6. Assuming an isothermal process and ideal gas, specify the formula of the useful work of the vacuum pump!
7. At a measurement point, the volumetric flow rate is $Q = 0.006\frac{m^3}{s}$, and the displacement of the U-tube manometer at the pressure side is $390\,mm$. The atmospheric pressure is $1004\,mbar$. Find the useful isothermal work!
8. The useful isothermal power of a vacuum pump is 454 W. The electric power of the machine is 4150 W, The nominal power of the electric motor is 5.5 kW. The formula between electric power and the load factor is the following:

$$x = 1.753 \cdot 10^{-4} \cdot P_e(W) - 0.1153$$

   Find the efficiency of the vacuum pump!
9. What is the formula for the efficiency of the vacuum pump? Describe how the quantities in the formula can be calculated!
10. Plot the efficiency of the vacuum pump as a function of the supply water perssure! What is the significane of this diagam?

9. Problems for the measurement

1. Approximating the $\eta\left(\frac{p_0-p}{p_0}\right)$ function of the vacuum pump with a
   a) third order,
   b) second order

   polynomial, and calculate the parameters of the pump at the optimal performance point($p_{opt}, Q_{opt}, \eta_{opt}$)!

2. Find the isothermal useful power, the volumetric flow rate and the efficiency, if the relative vacuum
   a) 45, 55%;
   b) 70, 80%!

3. The parameters of the air in a tank are the following: $p = 0.35\,bar, T = 27°C$. Find the time during which a vacuum pump conveys air with
   a) V=0,45 m^3 air at temperature T=27 °C,
   b) V=0,8 m^3 air at temperature T=27 °C,

1 bar absolute pressure?

Appendix A – Derivation of the useful isothermal power

The isothermal power for an ideal gas can be calculated with the following formula:

$$P = p_1 Q_1 \ln \frac{p_2}{p_1},$$

where indices „1" and „2" denote the suction and pressure side, respectively. In case of an isothermal process, the following relations hold for the state variables:

$p_1 v_1 = p_2 v_2$, or using the density: $\frac{p_1}{\rho_1} = \frac{p_2}{\rho_2}$.

Rearranging this formula yields

$$\rho_1 = \rho_2 \frac{p_1}{p_2}.$$

The volumetric flow rate at the suction side can be calculated as a function of the volumetric flow rate at the pressure side. This relation is derived from the continuity equation::

$$Q_1 = \frac{\dot{m}}{\rho_1} = \frac{\dot{m}}{p_2} \frac{p_2}{\rho_1} = Q_2 \frac{p_2}{p_1}.$$

Substituting this relation to the formula of the isothermal power results in the following:

$$P = p_1 Q_1 \ln\left(\frac{p_2}{p_1}\right) = p_1 Q_2 \frac{p_2}{p_1} \ln\left(\frac{p_2}{p_1}\right) = p_2 Q_2 \ln\left(\frac{p_2}{p_1}\right).$$

Using the fact that $p_2 = p_0$ is the atmospheric pressure and Q_2 is the volumetric flow rate at the parameters of the ambient air, the formula of the isothermal power is

$$P_{isothermal} = p_0 Q ln \frac{p_0}{p}.$$