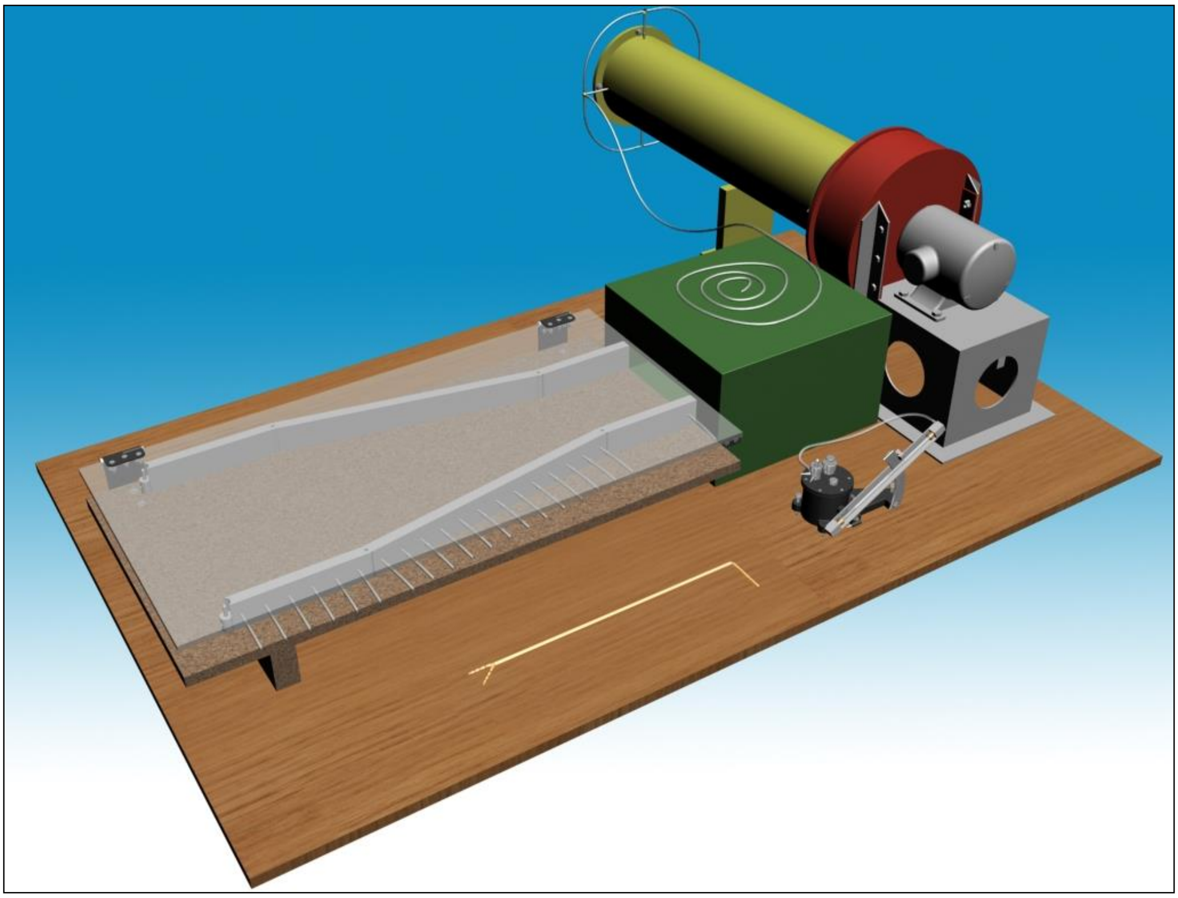

M10
EXPERIMENTAL INVENSTIGATION OF DIFFUSERS AND BORDA-CARNOT TRANSITIONS

1. The aim and practical aspects of the measurement

In engineering practice, liquid and gaseous media are usually transported by pipelines or open channels. Piping systems often include elements that change the direction of flow, split or merge the flow and change the flow cross-section. A pipe that gradually expands in the direction of the flow is called a diffuser (diverging duct), a special case of which is the sudden increase in cross-section (diffuser of an opening angle of 180°), the so-called sudden expansion or Borda-Carnot transition [1].

Increasing the flow cross-section results in a decrease in flow velocity, assuming the fluid is incompressible and fills the pipe completely. This is known as the law of mass conservation (continuity). From a dynamical perspective, the deceleration of fluid particles in a diffuser is caused by a pressure gradient pointing in the streamwise direction. Therefore, the pressure ahead of a fluid particle is always higher than the pressure behind it, meaning the pressure force acts in the opposite direction to the velocity vector. Thus, the fluid slows down in the diffuser. In a frictionless case, the deceleration of the fluid is unrestricted. However, in the presence of friction, a boundary layer forms along the duct wall, and its thickening leads to flow separation. The boundary layer separation can be explained by examining the energetic conditions of the flow in a diffuser. The work required to move a fluid particle from a region of lower pressure to a region of higher pressure is drawn from the particle's kinetic energy, resulting in the deceleration of the fluid. In inviscid flow, this process occurs across the entire cross-section of the channel without difficulty. In viscid flow, fluid particles in the center of the channel decelerate appropriately, but near the wall, in the boundary layer, the kinetic energy of the fluid particles is low, causing them to decelerate significantly or even stop and reverse due to the pressure gradient. Flow separation is indicated by boundary layer thickening and the appearance of recirculation and separation bubbles (see [2] for more information).

The thickening of the boundary layer and the formation of separation bubbles increase dissipative losses, which leads to higher hydraulic resistance in the pipeline system. Consequently, more power is required to move the fluid. In addition to fluid losses, unstable boundary layer separation can cause structural vibrations and noise emission. Furthermore, separated flow in a pipeline can negatively affect the machinery and its associated flow phenomena. For example, if flow fluctuations occur in the air supply system of a furnace burner due to unstable flow separation, the flame and heat source will also fluctuate. Therefore, in hydraulic systems like pipelines and canals, avoiding boundary layer separation is a key consideration. To address this issue, two objectives must be pursued. The first is to become familiar with the characteristics of optimally designed cross-sectional growth from a fluid mechanical perspective. However, it is important to recognize that hydraulically optimal diffuser geometry cannot always be achieved in practical applications. On the other hand, it is essential to understand the impact of manufacturing and operational trade-offs on the flow. This experiment provides an opportunity to explore these practical considerations under laboratory conditions.

Aim of the measurement:

- Investigation of the flow pattern in diffusers and Borda-Carnot transitions using a flow visualization method.
- Determination of the pressure distribution along the channel wall by measurement.
- Determination of the relationship between the flow pattern and the pressure distribution along the wall.
- Calculation of diffuser and Borda-Carnot transition efficiency.

2. Description of the measurement facility

The 3D model and the 2D schematic drawing of the measurement facility is depicted in Fig. 1.

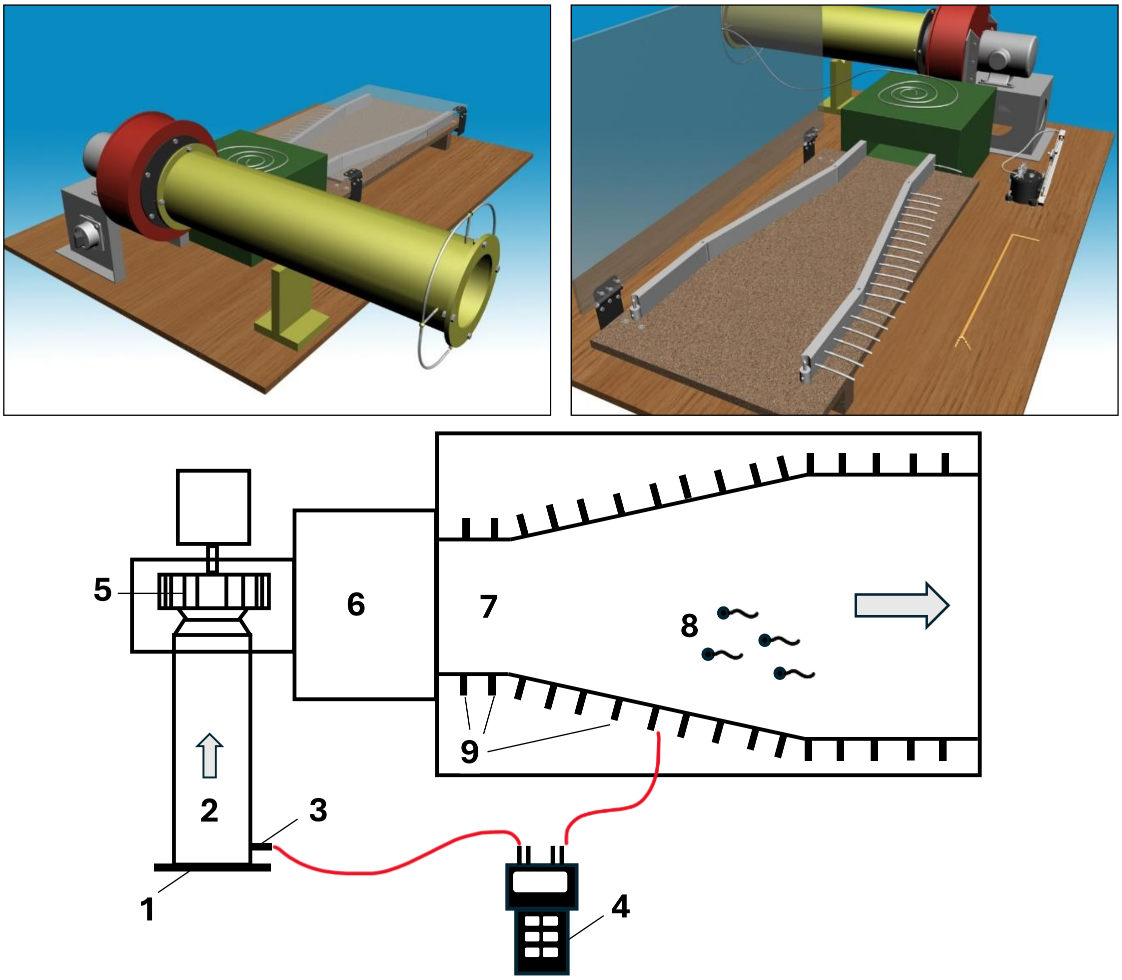

Figure 1 *3D model and 2D schematic drawing of the measurement.*

The measurement facility used to investigate plane channel flows consists of two main parts. The first part is a miniature wind tunnel, which provides a uniform inlet velocity profile, and the second part is an adjustable measuring section. The complete measurement device is shown in Fig. 1. The different sections of the facility are as follows:

1. **Inlet orifice plate**: for measuring the flow rate.
2. **Suction tube**: for introducing the air into the fan.
3. **Pressure measurement point**: which consists of a small pressure tap at the beginning of the suction tube directly downstream of the inlet orifice plate. For the pressure measurement, the tap is connected to the proper tap of the pressure transducer with a thin rubber tube. The volume flow rate can be calculated from the measured pressure.
4. **Two-channel digital manometer**.
5. **Radial fan**: for circulating air, driven by an electric motor.
6. **Settling chamber:** ensuring a uniform outlet velocity profile. The fluid passes through wire gauze and discharges into the measurement section via a converging duct. The purpose of the wire gauze and the converging duct is to straighten the nonuniform velocity profile generated by the fan.

7. **Measurement section**: allows for the assembly of various channel geometries for investigation. The nearly uniform flow from the straightener is directed into the adjustable measurement section. This section is bounded on the bottom by a cork-covered base plate, where flow visualization flags (8) can be inserted into the cork. The top of the channel is made of a transparent plexiglass plate, which can be opened. The sides consist of four sections of varying lengths. By placing the side elements between the base and the top plate, an arbitrary number of diffuser geometries can be formed, starting with the first element fitted to the outlet slot of the flow straightener. The flow pattern is visualized by small flags that turn in the direction of the flow and can be observed through the transparent top plate.

   (Note: The base and top plates form parallel planes, and in every cross-section of the channel, the sidewalls are perpendicular to them. Therefore, as a first approximation, by neglecting the displacement effect of the boundary layer, it can be assumed that fluid particles do not deflect perpendicularly to the bottom and top boundaries. Generally speaking, the flow variables in this direction change at a much slower rate than along the other two dimensions of the measurement section. These characteristics of the setup allow us to investigate relatively simple two-dimensional flows in this facility.)

8. **Flags:** for flow visualization.
9. **Pressure taps:** for measuring the static pressure along the wall of the channel.

Besides the previously described measuring facility, other auxiliary devices are also needed for the measurement (e.g. barometer, thermometer, tape measure etc.) These are also provided in the laboratory.

3. Measurement procedure

The comprehensive examination of the topics outlined in Section 1 would require a significant amount of time. However, within the scope of this laboratory measurement, two basic investigations can be completed:

1. Investigation of symmetrical diffusers with different area ratios thus different setting angles.
2. Investigation of a symmetric Borda-Carnot transition with a given area ratio.

Th area ratio (n_{AR}) is the ratio if the outlet (A_{out}) and the inlet cross-sections (A_{in}) of the diffuser / Borda-Carnot transition:

$$n_{AR} = \frac{A_{out}}{A_{in}} \tag{1}$$

The specific geometries to be examined by the measurement groups are provided in the task assignment document. The following aspects should be examined for each geometry:

3.1) Perform the calibration of the digital manometer!

During the calibration, compare the digital manometer with the Betz manometer. You can also perform the calibration after the measurement.

3.2) Set up the duct section to be tested!

Select the appropriate length of side wall elements from the task description and set up the required cross-sectional area of the diffuser / Borda-Carnot element.

3.3) Measure the differential pressure value at the inlet orifice plate to calculate the volumetric flow rate of air entering the system!

Measure the pressure drop across the inlet orifice plate, i.e., the difference between atmospheric pressure and the pressure at the downstream taps. This will be used to calculate the air flow rate entering the system. The flow resistance varies between different measurement setups, which may affect the fan’s operating point and, consequently, the flow rate of the transported medium. Therefore, it is essential to measure the pressure difference across the inlet element for all arrangements!

3.4) Measure the pressure distribution along the duct wall!

The pressures along the duct wall can be measured using a digital manometer connected to the pressure taps located on the side walls. One tap of the manometer must be connected to the pressure tap at the desired measurement point using a silicone tube. If the other tap is left open, the manometer will display the overpressure or vacuum relative to atmospheric pressure at the measurement point. By measuring the pressures one by one, the pressure distribution along both boundary walls can be obtained. Special attention should be given to determining the pressures at the side wall of the inlet section before the cross-sectional expansion and at the outlet cross-section, as these are critical data for the subsequent evaluation.

3.5) Determine the velocity profiles at the inlet and outlet of the channel!

At the inlet cross-section of the channel, measure the total pressure in the flow relative to atmospheric pressure using a Pitot-type probe with its bore facing the flow. The static pressure, required to determine the velocity, is calculated as the average of the pressures measured at points 2 to 4 on the channel wall, starting from the exit plane. A Pitot-static tube is used to measure the velocity at the outlet cross-section. The measuring points should be positioned 5-10 mm apart at the inlet cross-section and 10-20 mm apart at the outlet cross-section. This exercise is to be performed for one specific measurement setup as outlined in the task description.

3.6) Examine the flow filed using a visualization technique!

The flow field can be observed by inserting flags into the flow by placing pins in the cork covering of the baseboard, attached with a thin thread of soft, fluffy material of a length 30-35 mm. Where the flow pattern varies significantly over a small distance, it is advisable to place the flow direction flags more closely (10-20 mm apart), while in areas with a more uniform flow, they should be spaced farther apart (40-50 mm). The thread should be positioned at a height so that it is approximately at the median plane of the channel. A freehand drawing or photograph of the displayed flow chart should be taken to document the test.

4. Post-processing and evaluation of the results

4.1) Perform the correction of the pressure values measured by the digital manometer based on the calibration of the device!

Prepare the calibration diagram based on the data pairs recorded with the Betz manometer (p_{Betz}) and the digital manometer (p_{dig}). Fit a straight trendline to the data and use its equation to correct all pressure values measured by the digital device.

$$p_{corr} = S \cdot p_{meas} + p_{off} \tag{2}$$

In Eq. (2) p_{meas} [Pa] is the measured pressure value, p_{corr} [Pa] is the corrected pressure value, S [1] is the slope of the calibration line, and p_{off} [Pa] is the offset error of the device. If the devices were zeroed before the measurement, then $p_{off} = 0$.

4.2) Illutrate the different measurements setups!

The report must include a schematic drawing and photos of the measuring device and the different setups. For each diffuser geometry, the diffuser opening angle can be calculated from the set cross-sectional ratios and the side lengths, which should be calculated and indicated for comparison with the literature.

4.3) Calculate the volume flow rate of air entering the system through the inlet orifice!

Provided that the pressure drop at the orifice is given, the volume flow rate can be calculated as:

$$q_{v,op} = \alpha \cdot \varepsilon \cdot \frac{d_{op}^2 \cdot \pi}{4} \cdot \sqrt{\frac{2}{\rho} \Delta p_{op}} \tag{3}$$

In the above formula $q_{v,op}$ [m^3/s] is the volume flow rate through the orifice plate, $\alpha = 0.6$ [1] is the contraction coefficient, $\varepsilon = 1$ [1] is the expansibility factor, d_{op} [m] is the diameter of the orifice plate, ρ [kg/m^3] is the density of air, and Δp_{op} [Pa] is the differential pressure measured across the orifice.

Air density can be calculated from the environmental data, using the ideal gas equation:

$$\rho = \frac{p_0}{RT_0} \tag{4}$$

In Eq. (4) p_0 [Pa] is the atmospheric pressure, $R = 287$ [J/(kg·K)] is the specific gas constant of air, and T_0 [K] is the room temperature.

4.4) Depict the pressure distribution along the channel walls and calculate the efficiency of the diffusers / Borda-Carnot transition!

The interpretation of points 4.4 and 4.5 is aided by Fig. 2. In addition to the velocity field, another very important characteristic of fluid flows is the pressure value prevailing in the flowing medium; changes in pressure can provide insights into changes occurring in the flow pattern. Plot a diagram of the pressure distribution along the channel wall as a function of the distance from the outlet, and evaluate the results of the pressure measurements in writing, along with the conclusions that can be drawn from them!

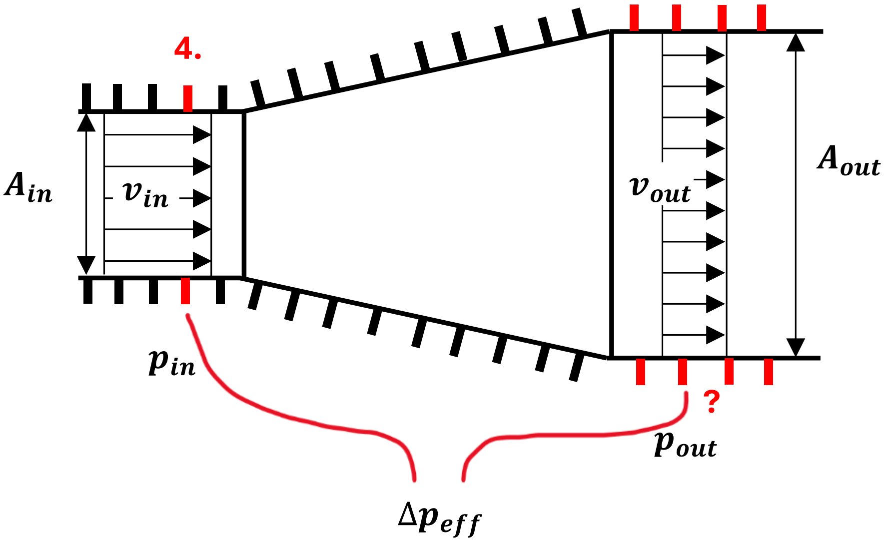

Figure 2 *Variables in the inlet and outlet duct sections.*

In engineering practice, detailed analysis of the flow pattern and pressure measurements is often unnecessary. Instead, it is more useful to introduce integral characteristics that expresses the quality of the flow processes occurring in the expanding section, known as the diffuser efficiency. The diffuser efficiency (η_d) is the ratio of the effective pressure increase ($(p_{out}$-$p_{in})_{eff}$) to the ideal pressure increase ($(p_{out}$-$p_{in})_{id}$) that occurs in the expanding cross-section of the channel:

$$\eta_d = \frac{(p_{out} - p_{in})_{eff}}{(p_{out} - p_{in})_{id}} = \frac{(p_{out} - p_{in})_{eff}}{\frac{\rho}{2}(v_{in}^2 - v_{out}^2)} \qquad (5)$$

In Eq. (5), p_{out} is the static pressure at the "outlet" cross-section of the diffuser, and p_{in} is the static pressure at the "inlet" cross-section of the diffuser. In the present measurement, **the actual pressure on the inlet side is determined from the 4th wall pressure tap from the exit (the average of the pressures measured on both sides)**, thus avoiding errors due to the upstream flow distortion effect of the diffuser. To determine the outlet pressure, it is essential to understand the flow phenomena in the widening channel sections: in the expanding section, the flow velocity decreases due to continuity, causing the static pressure to increase according to Bernoulli's law and reach a maximum. When the expanding section transitions to a straight channel, the pressure begins to decrease again due to wall friction. **The actual pressure at the outlet side will be equal to the maximum wall static pressure (the average of the pressures measured on both sides).**

Due to possible separation in the diffusers, the maximum pressure may not occur right at the end of the expanding section; therefore, it is determined from the pressure distribution diagrams. It is important to note that for diffusers with a larger opening angle, the flow may become asymmetric. Consequently, it is necessary to measure the pressure distribution on both sides of the diffuser/Borda-Carnot element! Plot the diffuser efficiency as a function of the opening angle.

The ideal pressure difference can be calculated from Bernoulli's equation for a frictionless medium, using the average inlet (v_{in}) and outlet (v_{out}) velocities (see equation (5)). These velocities can be determined from the volume flow rate, which is calculated based on the pressure difference measured at the inlet orifice plate:

$$v_{in} = \frac{q_{v,op}}{A_{in}};\ v_{out} = \frac{q_{v,op}}{A_{out}} \tag{6}$$

4.5) Calculate and plot the velocity profiles entering and leaving the channel.!

Determine the velocity distribution at the inlet and outlet cross-sections from the pressures measured with the Pitot-type probe and the Pitot-static tube using Eqs. (7)-(8):

$$v_{in,loc} = \sqrt{\frac{2}{\rho} p_{dyn,in}} = \sqrt{\frac{2}{\rho}(p_t - p_{st})} \tag{7}$$

$$v_{out,loc} = \sqrt{\frac{2}{\rho} p_{dyn,out}} \tag{8}$$

In Eq. (7), $v_{in,loc}$ represents the local velocity measured at the inlet cross-section; $p_{dyn,in}$ is the dynamic pressure at the inlet side, calculated as the difference between the total pressure (p_t) measured by the Pitot-type probe and the average of the wall static pressures (p_{st}) measured at points 2-4 from the exit plane. In equation (8), $v_{out,loc}$ denotes the local velocity measured at the exit cross-section, and $p_{dyn,out}$ is the outlet dynamic pressure measured using the Pitot-static tube.

Calculate the average inlet and outlet velocities from the local velocity values and plot the velocity distribution. Include the average velocity calculated from the local velocities and the average velocity obtained from the measurements at the inlet orifice plate on both the inlet and outlet sides in a common diagram. Additionally, provide a textual analysis of the reasons for any discrepancies observed.

4.6) Illustrate the results of the flow visualization!

Provide and analyze the flow visualization results for each geometry. Based on the position/movement of the cotton threads, try to delineate the location of possible separation zones. Find the relationship between the flow patterns, the wall static pressures and the exit velocity profile.

5. Uncertainty calculations

The measurement uncertainty should be assessed for the calculated diffuser efficiencies. Based on the law of Gaussian error propagation, the total measurement uncertainty of a quantity (δR) depends on the measurement uncertainties of k pieces of independent quantities (δX_k) as follows:

$$\delta R = \sqrt{\sum_{k=1}^{n} \left(\delta X_k \cdot \frac{\partial R}{\partial X_k}\right)^2} \qquad (9)$$

The measurement uncertainty should be calculated for the diffuser efficiency, so: $R = \eta_d$

During the experiment, the following directly measured quantities (X_k) are subjected to measurement error (δX_k):

- Digital manometer pressures: $X_1 = \Delta p$ $\delta X_1 = \delta\, \Delta p = 2$ [Pa]
- Atmospheric pressure: $X_2 = p_0$ $\delta X_2 = \delta p_0 = 100$ [Pa]
- Room temperature: $X_3 = T_0$ $\delta X_3 = \delta T_0 = 1$ [K]

5.1) Substitute the applied formulas to the expression of the η_d diffuser efficiency (Eq. (5)) until it contains only directly measured quantities and known constants!

Show the final expression along with a brief explanation! Hint:

$$\eta_d = \frac{(p_{ki} - p_{be})_{val}}{\frac{\rho}{2}\left(\left(\frac{q_v}{A_{be}}\right)^2 - \left(\frac{q_v}{A_{ki}}\right)^2\right)} \qquad (10)$$

If we substitute $q_v = \alpha\varepsilon \frac{d^2\Pi}{4}\sqrt{\frac{2\Delta p_{mp}}{\rho_{lev}}}$ in Eq. (10), it can be observed that density is cancelled from the derived formula, Thus, the measurement uncertainty depends only on the pressures measured using the digital manometer.

5.2) Calculate the $\partial\eta_d / \partial X_k$ quantities by partially differentiating the above final formula by the directly measured quantities.

Show the partially differentiated equations.

5.3) Calculate the absolute ($\delta\eta_d$) and relative ($\delta\eta_d/\eta_d$) measurement uncertainty of the diffuser efficiency by substituting to the formula of the Gaussian uncertainty propagation.

Plot the absolute errors in form of error bars on the diffuser efficiency versus opening angle diagram. Evaluate the results in writing!

Remarks

Be aware of the following during the measurement:

- Before turning any measurement device on or in general during the lab, make sure that safe working conditions are ensured. The other participants must be warned of the starting of the machines and of any changes that could endanger the members of the lab.
- The atmospheric pressure and room temperature should be recorded before and after every measurement.
- The measurement units and other important factors (e.g. data sampling frequency, date of calibration) of every recorded value of the applied measurement devices should be recorded.
- Type and construction number of the applied measuring instrument should be included in the final report.
- The geometrical parameters to be used in the calculations must be measured.
- Checking and harmonizing of the units of the recorded values with those used in further calculations.
- The manometers should be calibrated.
- The measurement ports of the pressure meter should be carefully connected to the correct pressure ports of the measurement instrumentation. The integrity of the silicone tubes used for connection must be verified before and during the measurement (no holes, slits, etc.).
- If the inlet or outlet tubes are to be assembled with fans, connections should be airtight as escaping/entering air can significantly modify the measurement results.

Before submitting the lab report, it is necessary to check whether its *structure, style and visual appearance* meets the requirements. It is recommended to ask for a *consultation* opportunity from the Measurement Responsible before submission if you have any questions.

Avoiding any suspicion of *plagiarism* in the lab report is crucial. Therefore, any written or visual content (text, images, etc.) derived from another work – including the current measurement guide – must be *properly referenced*. Additionally, ideas taken from other sources should be rephrased in your own words in the lab report to demonstrate your understanding of the material.

References

[1] Lajos Tamás: *Fluid Mechanics basics*. Chapter 10.3.1.: The Borda-Carnot transition & Chapter 10.3.5.: Diffuser. Műegyetemi Kiadó, 2004.

[2] Lajos Tamás: *Fluid Mechanics basics*. Chapter 9.: Boundary layers. Műegyetemi Kiadó, 2004.

Remark: this is a Hungarian book on Fluid Dynamics. The chapter on diffusers supplemented with English comments can be acquired from the Measurement Responsible upon request. It is not mandatory to use this as a reference for the comparison of the measurement results to the literature; other trustworthy sources can be cited alternatively.