CHARACTERISTIC CURVES OF A RADIAL FAN
Measurement description
Fluid Machinery

1. Aim of the measurement

The measurement aims to determine the operating characteristic curves of a machine group consisting of a fan and a three-phase asynchronous motor integrated with it (**Section 2**). This means defining the following function relationships:

Δp_{total} = f(Q) - total pressure difference through the fan as a function of flow rate;
Δp_{st} = f(Q) - static pressure difference as a function of flow rate;
η_{MF} = f(Q) - efficiency of the electrical motor-fan aggregate as a function of flow rate.

The aims are also the determination of the velocity distribution (velocity profile) in the suction pipe by Prandtl tube measurement (**Section 3**).

2. Characteristic curves of a radial fan

2.1. Theoretical basics

In the case of fans, instead of the specific work Y per unit mass, the specific work per unit volume, the so-called unit work, the total pressure increase is standard ($\Delta p_{total} = \rho Y$, where ρ is the density of the air.)
Because the change in potential energy can be negligible, the increase in total pressure can be calculated as the change in Bernoulli enthalpy.

$$\Delta p_{\text{total}} = \left(p_2 + \frac{\rho}{2} v_2^2\right) - \left(p_1 + \frac{\rho}{2} v_1^2\right) = p_{2,total} - p_{1,total} \qquad (1)$$

where

- p_1 is the static pressure of the suction side,
- p_2 is the static pressure of the pressure side,
- v_1 is the average velocity of the suction side,
- v_2 is the average velocity of the pressure side.

The specific kinetic energy of the air leaving the fan, the dynamic pressure ($\frac{\rho}{2} v_2^2$) is often not utilized; it is a loss, which justifies the introduction of Δp_{st} static pressure increase.

$$\Delta p_{st} = \Delta p_{total} - \frac{\rho}{2} v_2^2 = p_2 - p_1 - \frac{\rho}{2} v_1^2 \qquad (2)$$

In the laboratory measuring device, the suction and discharge intakes have different A_1 and A_2 cross-sections, so that $v_1 = Q/A_1$ and $v_2 = Q/A_2$ average velocities are also different. Thus, dynamic pressures are not dropped when calculating total pressure. The fan sucks from the outside, where the total pressure is the ambient pressure p_O. It turns into $p_1 + \frac{\rho}{2} v_1^2$ with loss, then in the fan, the total pressure increase with Δp_{total}, i.e., it will be $p_2 + \frac{\rho}{2} v_2^2$. After deducting the pressure pipe, butterfly valve, and the specific kinetic energy of the discharge loss, the (static) pressure is again p_0. The change in static and total pressure along a streamline is shown in Figure 2.1.

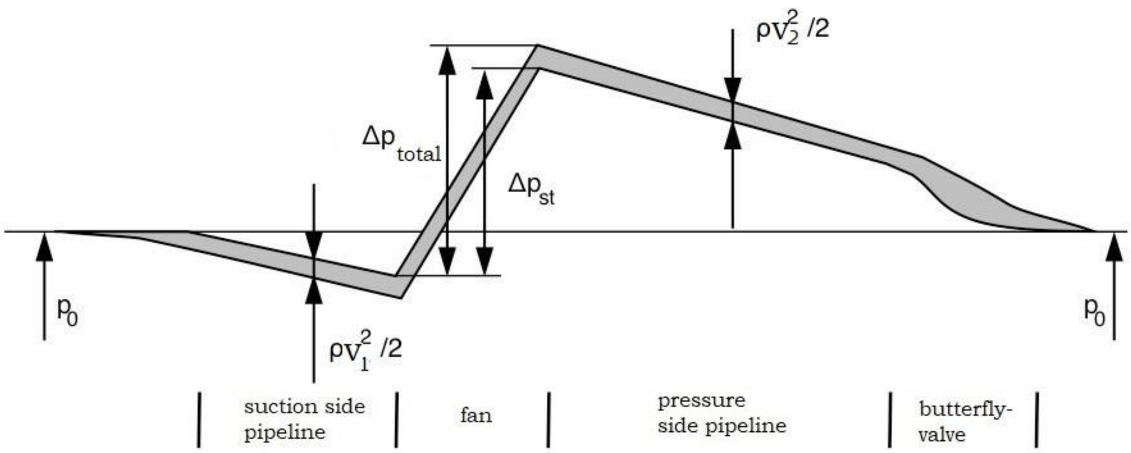


Fig. 2.1: The change in static and total pressure along a streamline

The useful power of a fan is the product of specific work per unit volume (Δp_{total}) and the flow rate (Q), i.e., $P_{useful} = Q\, \Delta p_{total}$.

2.2. Description of the test rig

A sketch of the experimental setup is shown in Figure 2.2.

The radial fan to be measured is marked by "F". This fan is driven by a three-phase asynchronous motor ("M") at n = 1440 / min = 24 / s revolution speed. On the suction and pressure sides, a straight cylindrical tube section is connected to the fan.

The flow rate is measured with a metering orifice ("MO") located at the inlet of the suction pipe, see. Annex 1, Picture 1. The pressure drop caused by the metering orifice was measured with a U-tube manometer.

The various operating points are adjusted using a throttle, which can be achieved by a butterfly valve mounted on the end of the suction pipe, see. Annex 1 Picture 2.). The pressure difference between suction and pressure side is measured with a U-tube, water-filled, Pa-scaled pressure manometer, see Fig. 2.2.

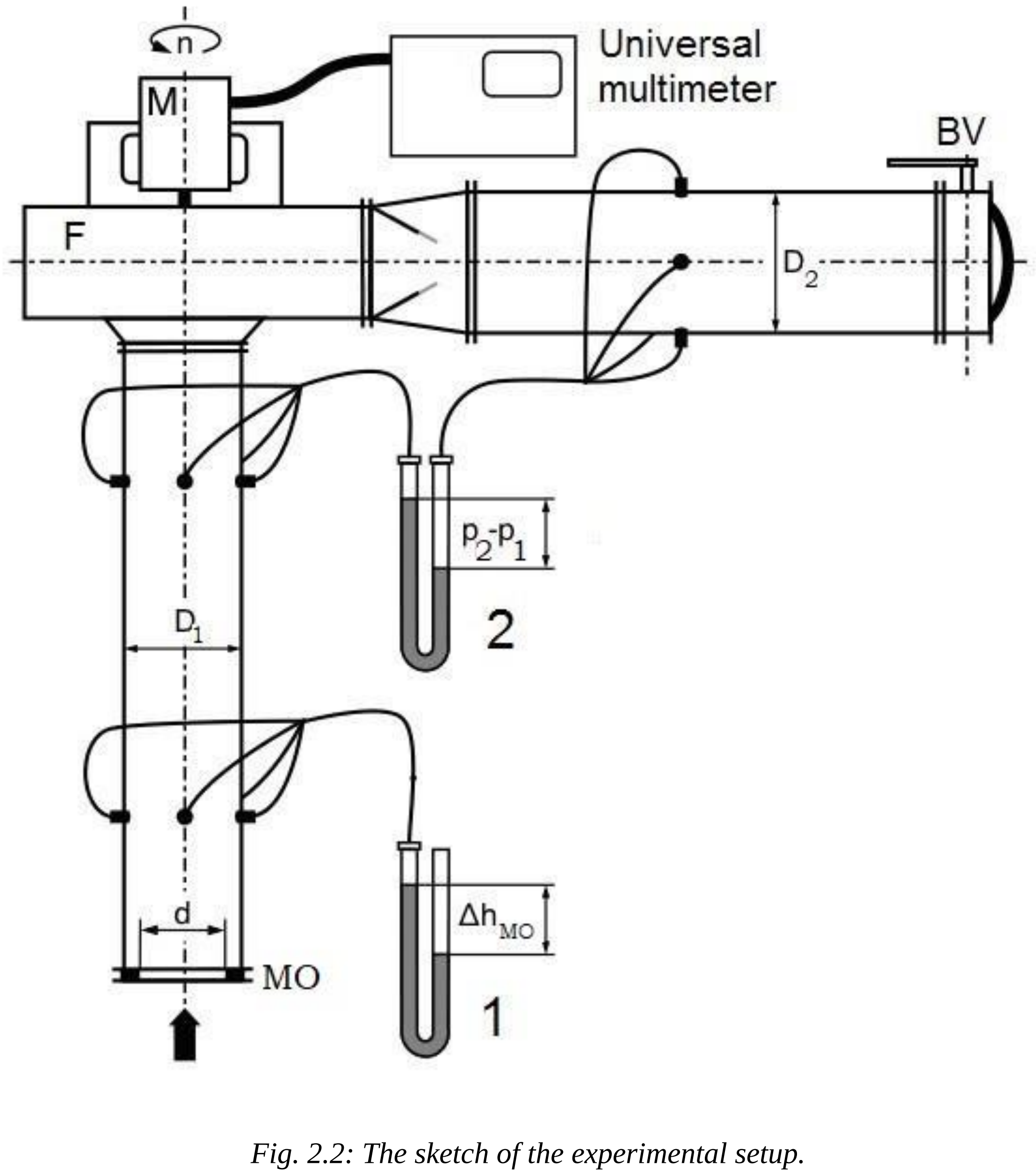


Fig. 2.2: The sketch of the experimental setup.

2.3 Measurement and calculation of quantities on characteristic curves

Revolution number (*n*)

The revolution number at the free end of the motor shaft must be measured with a laser tachometer in each operating condition.

Inlet Power (P_{in})

The inlet power of the engine is measured with an electric power meter (universal multimeter) and can be read directly in kW.

Flow rate (Q)

The flowing medium is air. The volume flow rate can be determined by measuring the pressure drop at the metering orifice (Δp_{MO}).
The pressure before the metering orifice is equal to the atmospheric pressure, the pressure after the "MO" is the average pressure measured on the tap holes located at a distance $0.5 \cdot D_1$ from the inlet.

The flow rate can calculate $Q = \alpha \cdot \varepsilon \frac{d^2 \pi}{4} \sqrt{\frac{2 \Delta p_{mo}}{\rho}}$ (3)

where,

d - the narrowest diameter (*d* = 300 *mm*).

ε - the expansion number; the value due to low pressure drop: $\varepsilon = 1$,

ρ - the density of air, which can be calculated from the atmospheric pressure (p_0) and temperature (T_0) during the measurement according to the ideal gas law $\rho = \frac{p_0}{RT_0}$ where *R=288 J/kg K*.

$\Delta p_{mo} = \rho_{water} \cdot g \cdot \Delta h_{mo}$, where the density of water is 1000 kg/m^3.

In the case of a metering orifice, the flow coefficient $\alpha \approx 0,6$, practically independent of the cross-section. (If the standard installation of the metering orifice is not provided, the flow rate in a cross-section can be determined by measuring the velocity distribution with a Prandtl tube (see Section 3.) But in our case, the actual value of the flow coefficient is $\alpha \approx 0,6$.)

The static and total pressure difference (Δp_{st}, Δp_{total})

The static pressure difference

$$\Delta p_{st} = (p_2 - p_1) - \frac{\rho}{2} v_1^2 \qquad (4)$$

The $(p_2 - p_1)$ pressure difference is measured with a U-tube water-filled differential manometer, the air being used as a pressure transducer. The two legs of the U-tube are connected to the average pressure of 4 to 4 static pressure gauge bores located on the suction and pressure tube. **The manometer scale is Pa!**
To determine the dynamic pressure of the suction side, the v_1 velocity value has to be known; it can be calculated from the flow rate.

The total pressure difference

$$\Delta p_{total} = \Delta p_{st} + \frac{\rho}{2} v_2^2 \quad (5)$$

where the mean velocity of the pressure side is calculated from the continuity equation from v_1 or Q.

The useful power of the fan

$$P_{useful} = Q \cdot \Delta p_{total} \quad (6)$$

The efficiency of fan-motor aggregate

$$\eta = \frac{P_{useful}}{P_{in}} \quad (7)$$

2.4 Starting the measuring equipment

1. The butterfly valve is completely closed.
2. The operating conditions of the manometers are checked
3. Press the start button on the motor switch.
4. When the engine has reached its rated, nominal speed, the electric power meter is switched on.

2.5 Setting of measuring points

We are gradually adjusting the butterfly valve to create various operating states and read the instruments. It is advisable to adjust the butterfly valve to each measuring point so that the root of the Δh_{MO} (i.e., $\Delta h_{MO}^{0,5}$) of the manometer connected to the metering orifice changes in even increments. During the measurement, the quantities directly measured have to be written: $h_{MO,left}$ [mm], $h_{MO,right}$ [mm], $p_{,left}$ [Pa], $p_{,right}$ Pa], P_{in} [kW], n [1/min]. All these values have to be included in the report.

2.6 Preparing for the characteristic curve measurement

a) **Before measuring, we will check the appropriate preparedness in writing by providing the preparation questions at the end of the description. (There will be a short check test before the measurement!)**

b) A table must be prepared (digitally (notebook) or on paper) to record the measurement results.

c) Prepare the coordinate system of control *chart #1* on A4 size graph paper (this can be done digitally).

The following quantities are shown in check diagram 1:

- horizontal axis: $\sqrt{\Delta h_{mo}}$ (as proportional to Q flow rate);
- vertical axis I.: $\Delta p_{fan}=p_2-p_1$;
- vertical axis II.: P_{in} inlet power.

Maximum values for selecting the scale:

$$\left(\sqrt{\Delta h_{m0}}\right)_{\max} = 10\ \sqrt{\text{water coloumn meter.}}$$

$$\left(\Delta p_{fan}\right)_{\max} = 1500\ \text{Pa}$$

$$\left(P_{in}\right)_{\max} = 2000\ \text{W}$$

3. Prandtl tube flow rate measurement

3.1. Principle of measurement

The aim of this measurement: determine the suction velocity distribution by Prandtl tube measurement.

The Prandtl tube measuring device can be seen in Fig.3.1. The Prandtl tube measures only the flow of a single-phase liquid or gas. Liquid or gas must not contain any amount or quality of contamination that could cause clogging of the instrument or build up deposits on its stem that could alter the current pattern. The Prandtl tube should only be used to measure fluid volume at steady-state or slowly variable flow rates.

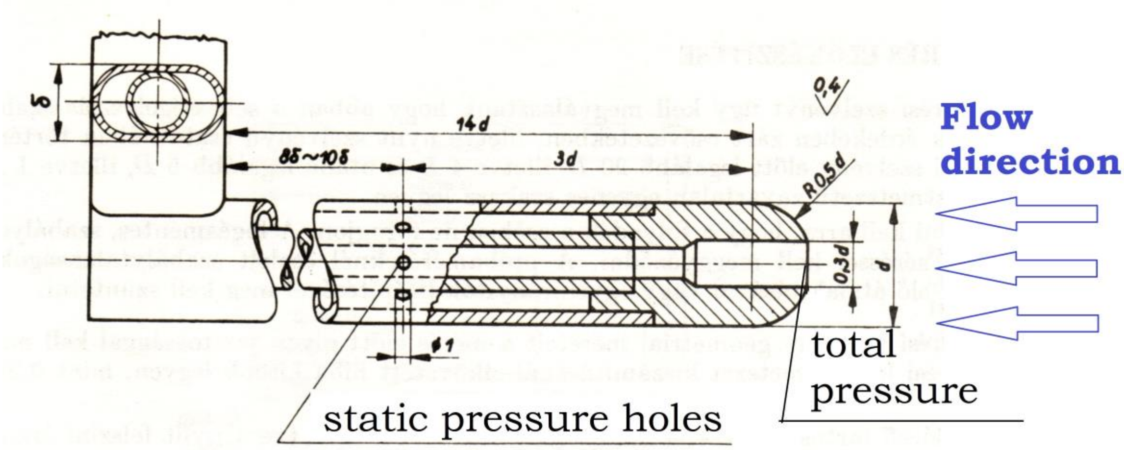


Fig. 3.1.: Relationship of Prandtl hemispherical tube, shape and main dimensions

3.2. Use of Prandtl tube for velocity distribution measurement

The total (or stagnation) pressure (p_{total}) is equal to the sum of the static (p_{static}) and dynamic ($p_d = \frac{\rho}{2} v^2$) pressures of the flow undisturbed by the instrument.

The velocity
$$v = C\sqrt{\frac{2}{\rho}\left(p_{total} - p_{static}\right)} \quad (8)$$

If Reynolds number $\mathrm{Re}_D > 3000$ (see eq. (10)), than C=1. The standard Prandtl tube is less sensitive to the direction of flow, see Fig.3.2.

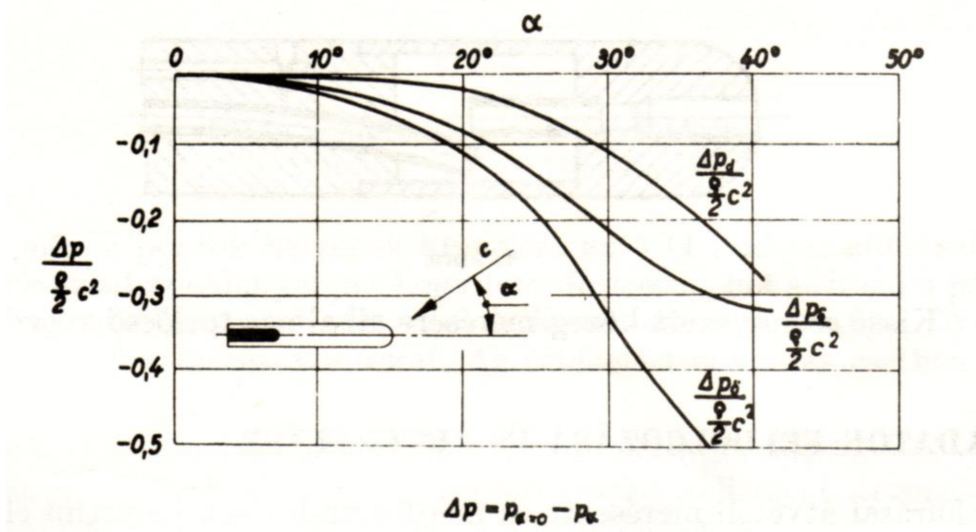


Fig.3.2.: Directional sensitivity of the Prandtl tube. The Prandtl tube can only be used for measurement if $\alpha < 15°$.

3.3. The location of the measurement

For circular pipelines, the velocity distribution has to be determined along at least two diametrically perpendicular diameters. The velocity has to be measured at any number of points (but at least 10 per diameter). The actual distribution of points is given in Section 3.3., as shown in Figure.

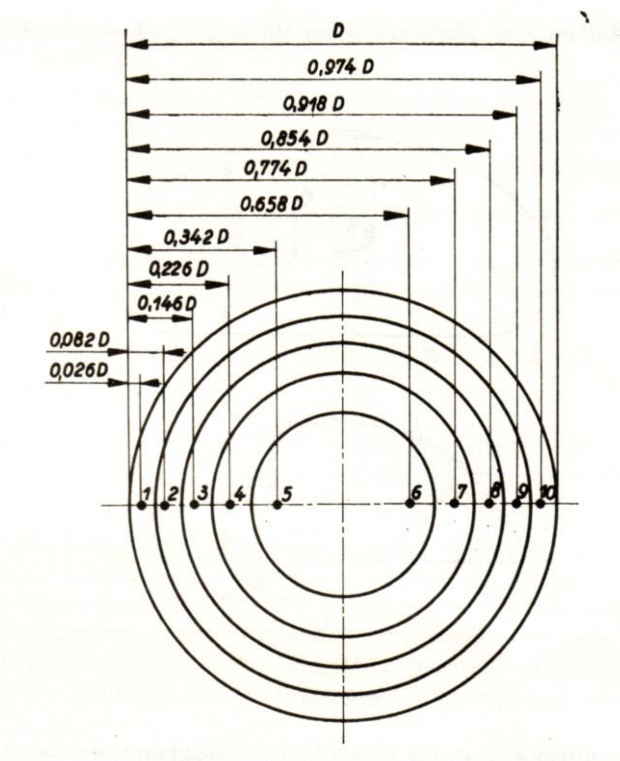


Fig. 3.3.: Example of measuring points

The mean velocity v_{mean} is the arithmetic mean of all measured velocities. With this value, the flow rate can be calculated:

$$q_v = Av_{mean}. \tag{9}$$

3.4. Description of measuring equipment for Prandtl tube measurement

A sketch of the measuring equipment is given in Fig. 3.4. The airflow machine is the fan (F). The device driving this fan is the electric motor M, rated at n = 1440 / min. The measuring arrangement is such that a straight cylindrical tube section is connected to the fan on both the suction and pressure sides. The flow rate is measured with a metering orifice (MO), for details see Section 2.

3.5. Starting the measuring equipment

1. Close the butterfly valve completely.

2. Check that the manometers are in working order, the glass tube of the Rosenmüller micrometer is placed in a vertical position. After the initial pressure, oscillations have subsided, fixed to the inclined position.
3. Press the start button on the motor switch.

3.6. The setup of the measurement points

The Rosenmüller manometer (see. Annex 1 Picture 3.) can be used in the “1: 2” position (i.e., with a tilt angle of 30°) over the entire measuring range. Note: In this case, the „Δl” deviation read in the oblique tube is then half the value of Δh_{MO}.

To determine the flow coefficient (α), the butterfly valve is fixed in the fully open position. After that, the Δh_{MO} values have to read to determine the Q flow rate. The suction tube velocity distribution is then determined using a Prandtl tube. **Before starting the modification of the Prandtl tube, the glass tube of the Rosenmüller micrometer must be set upright!**

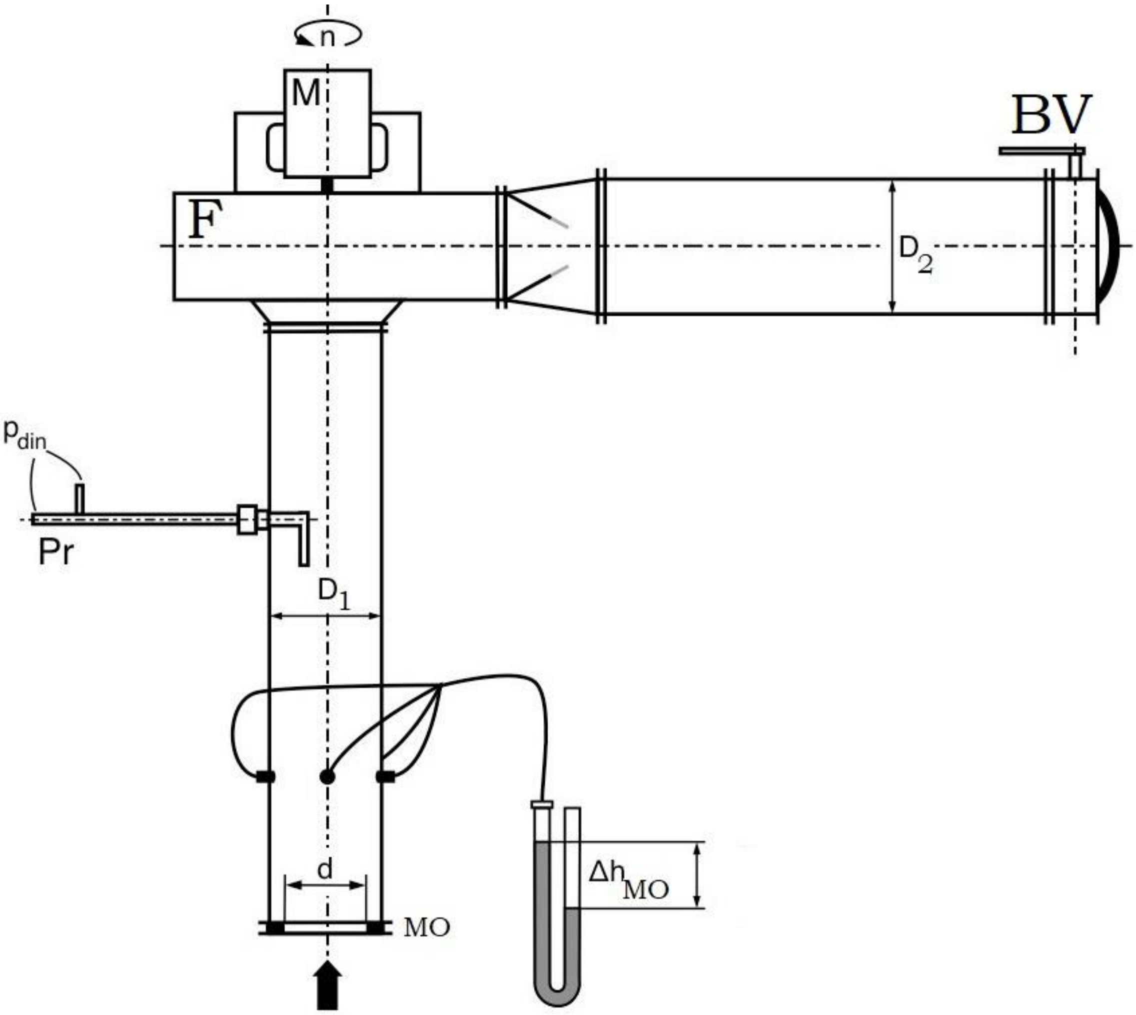


Fig. 3.4.: Sketch of the measuring equipment, instrumentation, Prandtl tube measurement

3.7. Calculation relationships for Prandtl tube measurement

3.7.1. Determination of flow rate using metering orifice, Reynolds number

The flow rate can be calculated using a metering orifice, as described in Section 2.3, by the relation eq. (3). However, it is shown in the next section (Section 3.7.2) that the flow coefficient (α) can be determined by Prandtl tube measurement.
The definition of the Reynolds number:

$$\mathrm{Re}_D = \frac{v_{mean} D_1}{\nu} \ , \tag{10}$$

where ν is the kinematic viscosity at various temperatures, see Table. 3.1.

Kinematic viscosity ν of air at atmospheric pressure (101 325 Pa)			
t ℃	15	20	25
ν m^2/s	$14{,}4\cdot10^{-6}$	$15\cdot10^{-6}$	$15{,}5\cdot10^{-6}$

Table 3.1.

3.7.2. Determination of flow coefficient (α)

To determine the flow coefficient, use the Prandtl tube to determine the average velocity v_{mean} of air flowing through the suction pipe and read the corresponding pressure difference Δp_{MO}. Using that

$$v_{MO} = \alpha\cdot\varepsilon\sqrt{\frac{2\Delta p_{MO}}{\rho}} \quad \text{and} \quad v_{MO} = \left(\frac{D_1}{d}\right)^2\cdot v_{vmean}\ , \qquad (11)$$

the flow coefficient can be calculated by:

$$\alpha = \left(\frac{D_1}{d}\right)^2\cdot\frac{v_{mean}}{\varepsilon\cdot\sqrt{\frac{2\Delta p_{MO}}{\rho}}}\ . \qquad (12)$$

3.7.3. Determining the average velocity

Based on Figure 3.3 and measured at two diameters, we know the value of the velocity at 20 points. From these values, the average velocity can be calculated

$$v_{mean} = \frac{1}{20}\sum_{i=1}^{20} v_i\ . \qquad (13)$$

There are markings on the stem of the Prandtl tube to measure at the right radius.

The pressure difference between the taps of the Prandtl tube is the dynamic pressure ($p_{din} = \frac{\rho}{2}v_i^2$). It is measured with a Rosenmüller manometer, from which („l_i") length values must be read. And local velocities (v_i) can be calculated

$$\frac{\rho}{2}v_i^2 = \rho_{alcohol} g l_i \sin\alpha\ . \qquad (14)$$

The density of the alcohol is 800 kg/m^3, α =30°, and g is the gravity.

3.7.4. Preparing for Prandtl tube measurement

a. Tables must be prepared to record the measurement results (see below for details).
b. **The following quantities are shown in** ***control chart #2*****:**

along one diameter (based on Fig. 3.3.), square root of the "l_i" deviations from horizontal and vertical velocity profile measurements. (Which are directly proportional to the horizontal and vertical velocity profiles.)

The following Table 3.2., the deviation of the micrometer is given in "l_i" [mm alcohol column].

The l_i [mm] values											
	direction	1	2	3	4	5	6	7	8	9	10
1.	horizontal										
2.	vertical										

Table 3.2.

Table for calculating local velocities „v_i [m/s]"

The v_i[m/s] velocities, using eq. (14)											
	direction	1	2	3	4	5	6	7	8	9	10
1.	horizontal										
2.	vertical										

Table 3.3.

Finally, the pressure drop caused by the metering orifice (MO) can be calculated by

$$\Delta p_{mo} = \rho_{water} \cdot g \cdot \Delta h_{mo} = \rho_{water} \cdot g \cdot (h_{left} - h_{right}) \qquad (15)$$

Summary table: average velocity (eq. (13)), differential pressure caused by the metering orifice (eq. (15)), flow coefficient (eq. (12)), Reynolds number (eq. (10))

v_{mean}	Δp_{MO}	α	Re_D
[m/s]	[Pa]	[-]	[-]

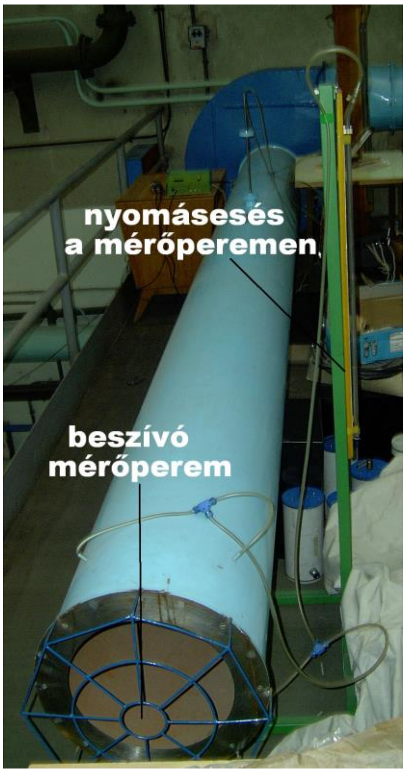
Table 3.4. Summary table of the results.

4. Processing of measurement results

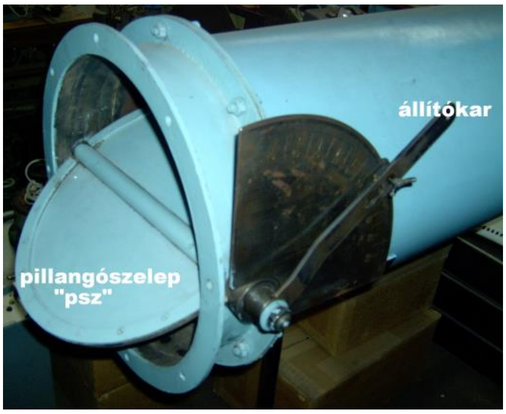
The report shall include the purpose of the measurement, the quantities measured, the calculated characteristic curves, etc. following Chapter 2.
Also, the report shall include the results of the Prandtl tube measurement in Chapter 3, in sections 3.2, 3.3, 3.4. according to the tables (in tabular form), the horizontal and vertical velocity profiles, and the solution of the individual task (see the end of the description).

5. Further specifications of the equipment

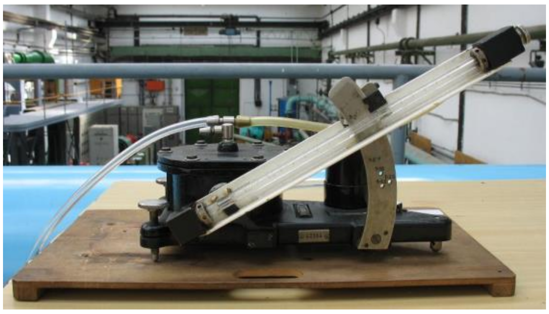
Type of fan: VHF 56,
Type of motor: VZ 222/4
The suction pipe has a diameter of D_1 =378 *mm* and a length of 4800 *mm*.
The pressure pipe has a diameter of D_2 = 400 *mm* and a length of 2000 *mm*.



Picture 1: MO, inlet



Picture 2: Butterfly valve

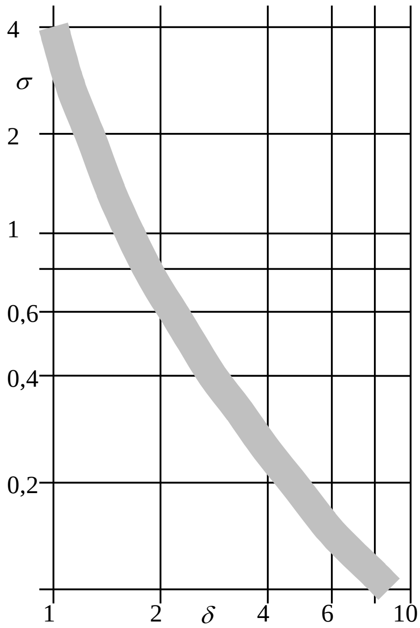


Picture 3: Rosenmüller manometer

The individual task, related to the actual measurement results

Problem #1 a.) and b.)

Calculate and plot the fan speed ($\sigma = \varphi^{1/2}\psi_{total}^{-3/4}$) and diameter ($\delta = \psi_{total}^{1/4}\varphi^{-1/2}$) factor in the enclosed Cordier diagram for optimal fan operation (i.e., where efficiency is maximal) in the case of the measured fan.



$$\varphi = \frac{4Q}{D_2^2 \pi \cdot u_2}; \qquad \psi_{total} = \frac{2\Delta p_{total}}{\rho \cdot u_2^2};$$

where
n, Q, Δp_{total}, ρ are known from the results of the measurement ;
D_2 = 560 mm;
α = 0,6;
$u_2 = D_2 \pi n$.

Problem #2

What circuit (serial or parallel) can be used to form a group of machines that the flow rate have to be

a.) Q = 1 m^3/s and the characteristic curve of the system: $\Delta p_{total} = 2\frac{kPas^2}{m^6} \cdot Q^2$

b.) Q = 2,2 m^3/s and the characteristic curve of the system: $\Delta p_{total} = 0{,}2\frac{kPas^2}{m^6} \cdot Q^2$

Problem #3 a.) and b.)

Select an asynchronous motor (e.g., from an online electric motor catalog) needed to drive the measured fan that operates at the given revolution number and can provide the power absorbed by the machine group. The catalog of the selected electric motor has to be annexed to the report.

Test questions:

1. Define the following dimensionless numbers and write down the quantities in the formulas: φ (volume number), Ψ (pressure number), σ (speed factor) δ (diameter factor)!

2. Draw a linear change in static pressure and total pressure along a flow line as the air flows through the fan. Identify parts of the air transport system!

3. Write down the relationship between the total pressure increase and the static pressure increase when measuring the fans! Name the quantities and units in the formulas!

4. What devices do we use for fan measurement? List at least four and write down the measured quantities and their units!

5. Summarize the Prandtl tube velocity profiles measurement process and the evaluation in a few sentences until the average velocities are determined!

6. What quantities are included in the control charts during fan measurement and Prandtl tube measurement?

7. How to determine the fan flow rate during fan measurement? Write down the relationship and explain the quantities and the units?

8. Sketch the measuring equipment used for the fan measurement!