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INSTITUTE OF POWER ENGINEERING AND TURBOMACHINERY

INSTRUCTIONS

Laboratory M-5

Measurement of fluid flow – part I

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Purpose of the exercise:

The purpose of the exercise is to learn the basic techniques for measuring the mass flow of humid air in pipelines by: differential pressure devices and speed measurement in cross section of the channel.

1.

In almost every technological process is the flow of a substance. In power station or in the steelworks, flow of liquid or gas occurs at almost everywhere. Amount of flowing substance, like its parameters, impact on operation of an industrial plant. They should, of course, be chosen, that work will be as effective as possible, and the costs as low as possible. But to get them to choose, you need to know their value, which should be measured.

At the laboratory, we will measure **volume or mass flow rate** of humid air flowing through the measuring pipeline. In the case of compressible fluids, i.e. when the density $\rho = f(p, T)$, it is better use the term mass flow rate. For this measure you use some measuring instruments, i.e.:

- ISA orifice with corner taps,
- classical Venturi tube,
- thermoanemometer (hot-wire anemometer),
- Pitot-static (Prandtl) tube,
- turbine (bowl's) anemometer.

Unfortunately, the abundance of methods and measuring instruments used for measuring the mass and volume flow, does not allow a full presentation of the material containing the theoretical basis of the various methods and instruments. In this instruction you will find a lot of theoretical knowledge and the measurement procedure and method of results analysis.

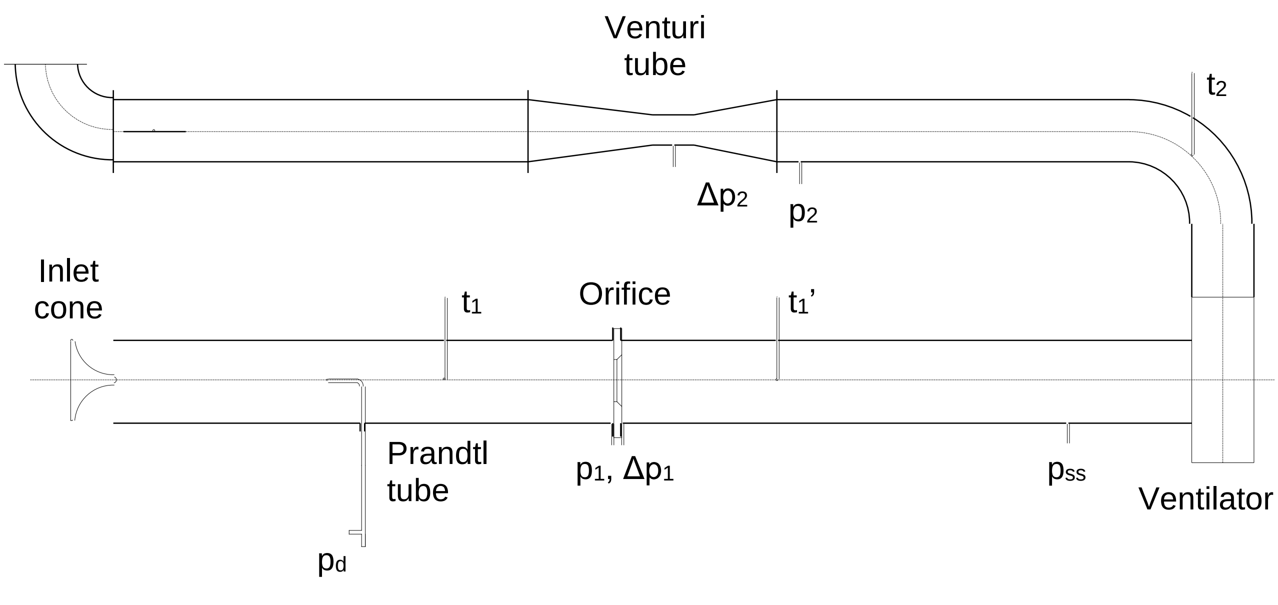

Fig.1 Diagram of the measuring system

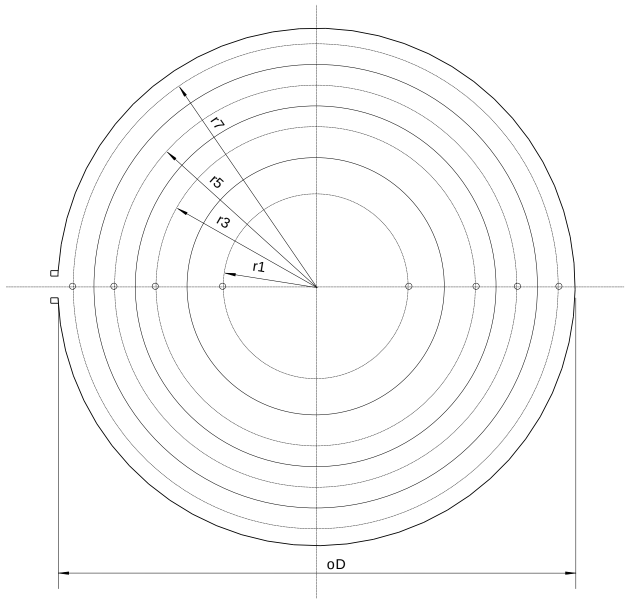

Fig.2 Location of measurement points for hot-wire anemometer measurement

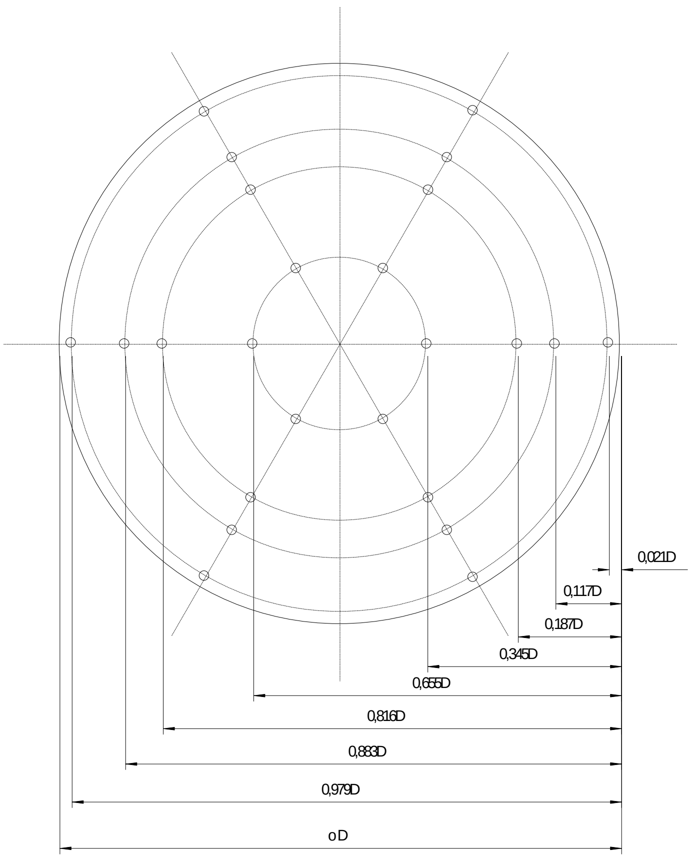

Fig.3 Location of measurement points for Pitot-static (Prandtl) tube measurement

Fig.4 Location of measurement points at the outlet of the pipeline for anemometer measurement

2.

I – ISA orifice

Measured quantities will be: ambient parameters: p_{ot}, t_{ot}, φ_{ot}, static pressure before the orifice h_1, pressure drop across the orifice Δh_1 and the temperature t_1 in the pipeline.

Measurement of ambient pressure

The ambient pressure should be measured using a barometer (mercury). Barometer slider scale indicator set so that the lower edges of the indicator were at the upper point of the meniscus mercury. Ambient pressure calculated from the formula:

$$p_{ot} = l_t \cdot \rho_o [1 - \beta_o \cdot t_{ot}] \cdot 9{,}81 \left[\frac{N}{m^2}\right]$$

l_t [mm] - barometer's mercury level at ambient temperature

ρ_o = 13,595 $\left[\frac{kg}{dm^3}\right]$ - density of mercury at 0 °C

β_o = 0,00018 [$°C^{-1}$] – volume expansion coefficient of mercury

Ambient pressure p_{ot} is measure once during the measurement time. This is the quantity that varies very slowly and changes in a short period of time are unnoticeable on a mercury barometer.

Measurement of ambient temperature

Ambient temperature t_{ot} [°C] should be read on the thermometer placed near the barometer.

Measurement of relative humidity

The relative humidity of the air φ_{ot} [%] should be measure by hair hygrometer located in the Hall of Thermal Machinery (HMC).

Air humidity also does not change very quickly so you just make one measurement.

Table 1. MEASUREMENT RESULTS

l_t [mm]	t_{ot} [°C]	φ_{ot} [%]

Note:
The values of the manometric liquid level with index $(\ )_o$ must be read before taking measurements (before starting the fan).

Flow measurement of humid air

Table 2. MEASUREMENT RESULTS

No.	Air static pressure before the orifice plate [mm]		Differential pressure [mm]		Air temperature in the pipeline [°C]
	h_o	h_1	Δh_o	Δh_1	t_1
1.					
2.					
3.					
4.					
5.					
6.					
average					

Pressure measurements should be made every 2 minutes.

COMPILATION OF THE MEASUREMENT RESULTS

All pressures measured by single arm manometers must be converted using the following formula:

$$p = (h - h_o) \cdot \rho_c \cdot 9{,}81 \text{ [Pa]}$$

Note that the scale on the manometer is in millimeters, and values into the formula must substitute in meters.

where:

h_o – value of the single arm manometer before starting the fan (initial value)

h – value of the single arm manometer during measurement

ρ_c = 0,835 kg/dm^3 - manometric liquid density (ethyl alcohol)

Absolute pressure before the orifice plate

Orifice is in the suction pipeline so ther is underpressure (as absolute pressure).

$$p_1 = p_{ot} - p_{m1} \text{ [Pa]}$$

p_{m1}- manometric pressure of air before the orifice plate (measured)

Density of humid air $\boldsymbol{\rho_1}$

$$\rho_1 = \rho_g + \rho_p$$

The density of dry gas ρ_g should be calculated according to the formula:

$$\rho_g = \rho_n \frac{(p_1 - \varphi \cdot p_p) T_n}{p_n \cdot T_1}$$

p_n = 1,013·10^5 Pa

T_n = 273 K

When reading any values from tables or a graph pay attention to the given units. Check whether the value of the calculated density is the same

where:
ρ_n – density of dry gas at normal conditions p_n, T_n
p_1 – gas static pressure before the orifice plat
p_p – pressure of saturated steam at a temperature t_1 (from physical table or h-s chart)
t_1 – gas temperature in the pipeline

The density of water vapor in the gas

$$\rho_p = \varphi \cdot \rho''$$

ρ'' - density of saturated steam at a temperature t_1 (from physical table)

Calculation according to PN-93/M-53950/01

Discharge coefficient C_1 with corner taps

$$C_1 = 0,5959 + 0,0312\beta_1^{2,1} - 0,1840\beta_1^{8} + 0,0029\beta_1^{2,5} \cdot \left[\frac{10^6}{\mathrm{Re}_D}\right]^{0,75}$$

Re_D – Reynolds number referenced to internal pipeline diameter

$$\mathrm{Re}_D = \frac{\overline{w} \cdot D_s}{\nu}$$

$\overline{w}$ - air flow velocity
ν = 15,06 10^{-6} [m^2/s] - kinematic viscosity coefficient

Expansion coefficient (compressibility) ε_1

$$\varepsilon_1 = 1 - (0,41 + 0,35\beta_1^4)\frac{\Delta p_1}{\chi \cdot p_1}$$

χ - isentropic exponent (choose from the array of air)

This formula can be used only if the condition $\frac{p_1 + \Delta p_1}{p_1} \geq 0,75$

Humid air flow rate calculation:

Differential pressure across an orifice plate

$$\Delta p_1 = (\Delta h_1 - \Delta h_o) \cdot \rho_c \cdot 9,81 \text{ [Pa]}$$

q_m (q_v) - mass (volume) flow rate

$$q_m = \frac{C_1}{\sqrt{1-\beta_1^4}} \cdot \varepsilon_1 \frac{\Pi}{4} d_1^2 \cdot \sqrt{2\Delta p_1 \cdot \rho_1} \quad \left[\frac{\text{kg}}{\text{s}}\right]$$

where:
C_1 - discharge coefficient

order of magnitude as the density under normal conditions.

Reynolds number should be assumed, and then, after the calculation of the flow rate, check that assumption was correct. If not, correct the value of *Re* and repeat the calculation.

Expansion coefficient takes into account a correction, resulting from the assumption that the air density is the same before and behind the orifice

β_1 - diameter ratio of orifice diameter to pipe diameter $\beta_1 = \frac{d_1}{D_s}$

ε_1 - expansion coefficient (compressibility - it corrects errors caused by assuming constant specific volume of fluid; depends on the size and type of orifice)

ρ_1 - gas density $\left[\frac{\text{kg}}{\text{m}^3}\right]$

d_1 = 260,3 mm - internal orifice diameter [m]

D_s = 494 mm - internal suction pipe diameter [m]

LIMITATIONS FOR ORIFICE PLATES

$$15{,}5 \leq d$$

$$50 \leq D \leq 1000$$

$$0{,}2 \leq \beta \leq 0{,}45$$

$$5000 \leq \text{Re}_D \quad \textit{for } \beta \textit{ as abowe}$$

$$10000 \leq \text{Re}_D \; \textit{for} \beta > 0{,}45$$

Values *D* and *d* are given in [mm].

In this case given limitation are filfilled. They give a view in which cases the above method can be used.

II – Classical Venturi tube

Measured quantities will be: ambient parameters: p_{ot}, t_{ot}, φ_{ot}, static pressure in suction pipeline h_{ss}, pressure increase in the fan Δh_s, pressure drop across the Venturi tube Δh_2 and the temperature t_2 behind the fan.

Measurements shall be made in the same way as when measuring ISA orifice

Table 3. MEASUREMENT RESULTS

l_t [mm]	t_{ot} [°C]	φ_{ot} [%]

Flow measurement of humid air

Table 4. MEASUREMENT RESULTS

No.	Static pressure (manometric) in suction pipeline [mm]		Pressure increase in the fan [mm]		Pressure drop across the Venturi tube [mm]		Air temperature [°C]
	h_{sso}	h_{ss}	Δh_{so}	Δh_s	Δh_o	Δh_2	t_2
1.							
2.							
3.							
4.							
5.							
6.							
average							

Pressure measurements should be made every 2 minutes.

COMPILATION OF THE MEASUREMENT RESULTS

Absolute pressure at the Venturi inlet

$$p_2 = \Delta p_s + p_{ss} \text{ [Pa]}$$

p_{ss} - gas absolute pressure at fan inlet (in suction pipeline)
Δp_s - pressure increase in the fan

Density of humid air ρ_2

Measured value h_{ss} indicates underpressure (gauge pressure).

Venturi tube is in the discharge pipeline so

$$\rho_2 = \rho_g + \rho_p$$

ther is overpressure.

The density of dry gas ρ_g should be calculated according to the formula::

$$\rho_g = \rho_n \frac{(p_2 - \varphi \cdot p_p)T_n}{p_n \cdot T_2}$$

p_n=1,013·10^5 Pa

T_n=273 K

When reading any values from tables or a graph pay attention to the given units. Check whether the value of the calculated density is the same order of magnitude as the density under normal conditions.

where:
ρ_n – density of dry gas at normal conditions p_n, T_n
p_2 – gas static pressure at the Venturi inlet
p_p – pressure of saturated steam at a temperature t_2 (from physical table or h-s chart)
t_2 – gas temperature in the pipeline

The density of water vapor in the gas

$$\rho_p = \varphi \cdot \rho''$$

ρ'' - density of saturated steam at a temperature t_2 (from physical table)

Calculation according to PN-93/M-53950/01

Discharge coefficient C_2

$$C_2 = 0{,}985$$

Value C_2 from standards.

Expansion coefficient ε_2

$$\varepsilon_2 = 0{,}999$$

Value ε_2 was read from the tables contained in the standard PN-93/M-53950/01.

Expansion coefficient takes into account a correction resulting from the assumption that the air density is the same before and in the narrowest section of the Venturi tube.

Humid air flow rate calculation:

Differential pressure across a Venturi tube

$$\Delta p_2 = (\Delta h_2 - \Delta h_o) \cdot \rho_c \cdot 9{,}81 \text{ [Pa]}$$

q_m (q_v) - mass (volume) flow rate

$$q_m = \frac{C_2}{\sqrt{1-\beta_2^4}} \cdot \varepsilon_2 \frac{\Pi}{4} d_2^2 \cdot \sqrt{2\Delta p_2 \cdot \rho_2} \quad \left[\frac{\text{kg}}{\text{s}}\right]$$

where:
C_2 - discharge coefficient
β_2 - ratio of the diameter throat of the Venturi to the inside diameter of the pipe $\beta_2 = \frac{d_2}{D_t}$

ε_2 - expansion coefficient
ρ_2 - gas density [kg/m^3]
d_2 = 200 mm - diameter throat of the Venturi tube [m]
D_t = 400 mm - internal discharge pipe diameter [m]

LIMITATIONS FOR VENTURI TUBES

$$200 \le D \le 1200$$
$$0{,}4 \le \beta \le 0{,}7$$
$$2 \cdot 10^5 \le \mathrm{Re}_D \le 2 \cdot 10^6$$

Values D and d are given in [mm].

In this case given limitation are filfilled. They give a view in which cases the above method can be used.

III – Thermoanemometer

Gas flow velocity measurements we make at designated points of the pipeline cross section (due to the construction of the pipeline, measurement is made along one diameter). Measurements must be repeated three times.

Table 5. MEASUREMENT RESULTS

No.	Velocity in the pipeline w_i [m/s]							
	r_{2n-1}	...	...	r_1	r'_1	...	...	r'_{2n-1}
1.								
2.								
3.								
average								

r - radius values indicating measurement points closer to hole in the wall of pipeline
r' - radius values indicating the measurement points behind the longitudinal axis of pipeline

CALCULATION

Average velocity of air stream

$$\overline{w} = \frac{\sum_{i=1}^{2n} w_i}{2n} \quad \left[\frac{m}{s}\right]$$

Air mass flow rate

$$q_m = A \cdot \overline{w} \cdot \rho_1 \quad \left[\frac{kg}{s}\right]$$

In this case, the number of measurement points may be assumed equal 4 at one radius.

IV – Pitot-static (Prandtl) tube

Dynamic pressure are measured at specific points in cross section of the pipeline. Measurements must be repeated three times.

Measurement of air velocity in the pipeline

Table 6. MEASUREMENT RESULTS

No.	Dynamic pressure in the pipeline l_{di} [mm]									Air temp. in the pipeline
	l_o	Place of measurement								
		0,021D	0,117D	0,184D	0,345D	0,655D	0,816D	0,883D	0,979D	
1.										
2.										
3.										
average										

l_o – value indicated by micromanometer before starting the fan (zero state)

CALCULATION

Dynamic pressure in place of measurement

$$p_{di} = c \cdot (l_{di} - l_o) \cdot \rho_c \cdot 9{,}81 \quad \left[\frac{N}{m^2}\right]$$

c – ratio of micromanometer

Distance from the wall of the pipe, in which they are located p_d pressure measuring points, are marked on the Prandtl tube.

Average dynamic pressure in cross section

$$\overline{p}_d = \left[\frac{1}{n}\sum_{i=1}^{n} p_{di}^{0,5}\right]^2$$

Average velocity of air stream

$$\overline{w} = \sqrt{\frac{2}{\rho_1} \cdot \overline{p}_d} \quad \left[\frac{m}{s}\right]$$

Air density assume the same as in the calculation to the ISA orifice.

Air mass flow rate

$$q_m = A \cdot \overline{w} \cdot \rho_1 \quad \left[\frac{kg}{s}\right]$$

V – Bowl's anemometer

Anemometer counter should be reset before making measurements. Perform a series of five measurements of the local velocity at the outlet of the pipeline, (in centre of the pipeline, on the transverse axis close as possible to the inner wall of the pipeline Fig. 4). After placing an anemometer at the measurement point, at the same time turn on the anemometer counter and start the timer. After a predetermined time read the counter value. At the same time read the temperature on the thermometer placed the fan outlet. Measurements repeat three times.

Measurement of air velocity on the pipeline outlet

Table 7. MEASUREMENT RESULTS

Numbers of measurement points	Measure-mnets	Anemometer counter indication Δl $[m]$	Timer indication $\Delta\tau$ $[s]$	Air temperature in pipeline t [^{o}C]
1	I II III			
2	I II III			
3	I II III			
4	I II III			
5	I II III			
Average				

CALCULATION

Air velocity in specific points of pipeline outlet

$$w = \frac{\Delta l}{\Delta \tau} \quad \left[\frac{m}{s}\right]$$

Δl – anemometer counter indication [m]
Δτ – indication of timer [s]

Average air velocity

$$\overline{w} = \frac{\sum_{i=1}^{5} w_i}{5} \quad \left[\frac{m}{s}\right]$$

Air mass flow rate

$$q_m = A \cdot \overline{w} \cdot \rho_o \quad \left[\frac{kg}{s}\right]$$

A – cross section area (the section of use anemometer)

As the diameter of the outlet channel should be taken a diameter of discharge pipeline.

Measurements were taken at the outlet of the pipeline where can be assumed that the density corresponding to the ambient parameters.

VI – Turbine anemometer

Anemometer counter should be reset before making measurements. Perform a measuring series of the local velocity at the outlet of the pipeline, in five measuring points (in centre of the pipeline, on the transverse axis close as possible to the inner wall of the pipeline Fig. 4). After placing an anemometer at the measurement point, wait until you determine the value on the anemometer display. Stop the measurement by pressing the **HOLD** button and save the result by pressing the **MIN / MAX** button. Repeat the procedure for each of the 5 measuring points and then average the the result of these points by pressing the **MULTI AVER** button. All results write to Table 7. The temperature read from the anemometer display, once for each series. Measurements repeat three times.

Measurement of air velocity on the pipeline outlet

Table 8. MEASUREMENT RESULTS

Measuring series n	Numbers of measurement points	Indication of anemometer display w_i $[m/s]$	Average value from measuring serie	Air temperature in pipeline t [°C]
I	1			
	2			
	3			
	4			
	5			
II	1			
	2			
	3			
	4			
	5			
III	1			
	2			
	3			
	4			
	5			
Average				

CALCULATION

Average velocity in particular measurement series

$$\overline{w_n} = \frac{\sum_{i=1}^{5} w_i}{5} \quad \left[\frac{m}{s}\right]$$

n – number of subsequent measuring series

Average air velocity

$$\overline{w} = \frac{\sum_{n=1}^{N} w_n}{N} \quad \left[\frac{m}{s}\right]$$

N – amount of measuring series

Air mass flow rate

$$q_m = A \cdot \overline{w} \cdot \rho_o \quad \left[\frac{kg}{s}\right]$$

A - cross section area (the section of use anemometer)

As the diameter of the outlet channel should be taken a diameter of discharge pipeline.

Measurements were taken at the outlet of the pipeline where can be assumed that the density corresponding to the ambient parameters.

3.

Each measurement and subsequent calculations must be checked. After performing the measurement uncertainty analysis should be carried out. In your case, you should also check the calculated values: with regard to units and the resulting values. The last element of the validation will be calculation the measurement uncertainty, showing the quality of particular measurement methods.

D	0.021	0.117	0.184	0.345	0.655	0.816	0.883	0.979
494	10	58	91	170	324	403	436	484