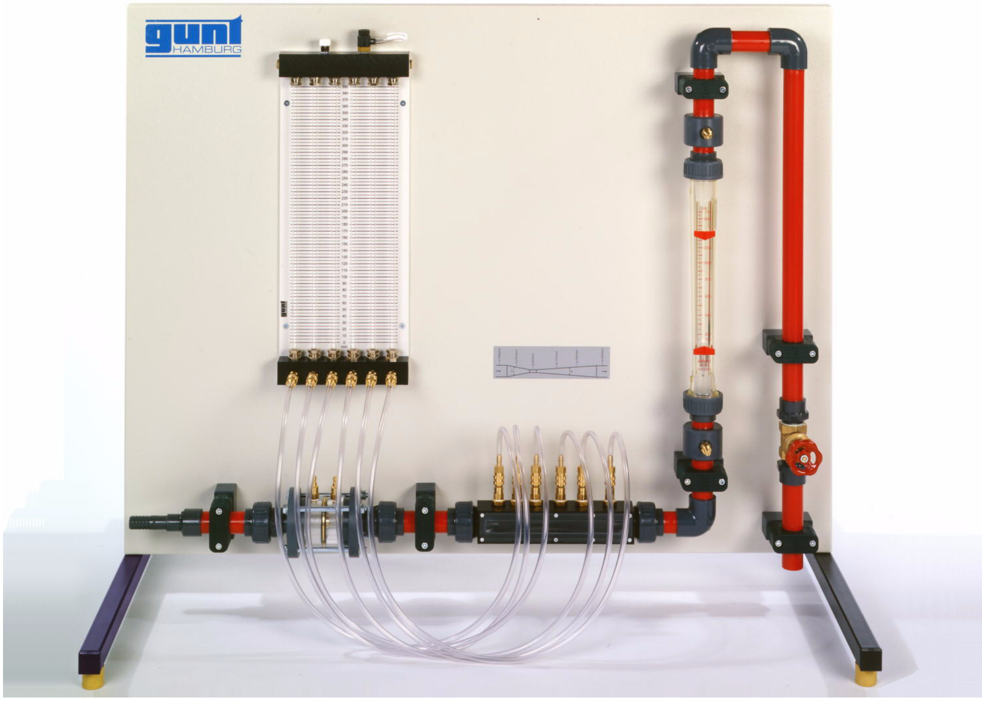
Experiment Instructions

HM 150.13 Methods of Flow Measurement



Experiment Instructions

This manual must be kept by the unit.

Before operating the unit:
- Read this manual.
- All participants must be instructed on handling of the unit and, where appropriate, on the necessary safety precautions.

Version 0.2

Subject to technical alterations

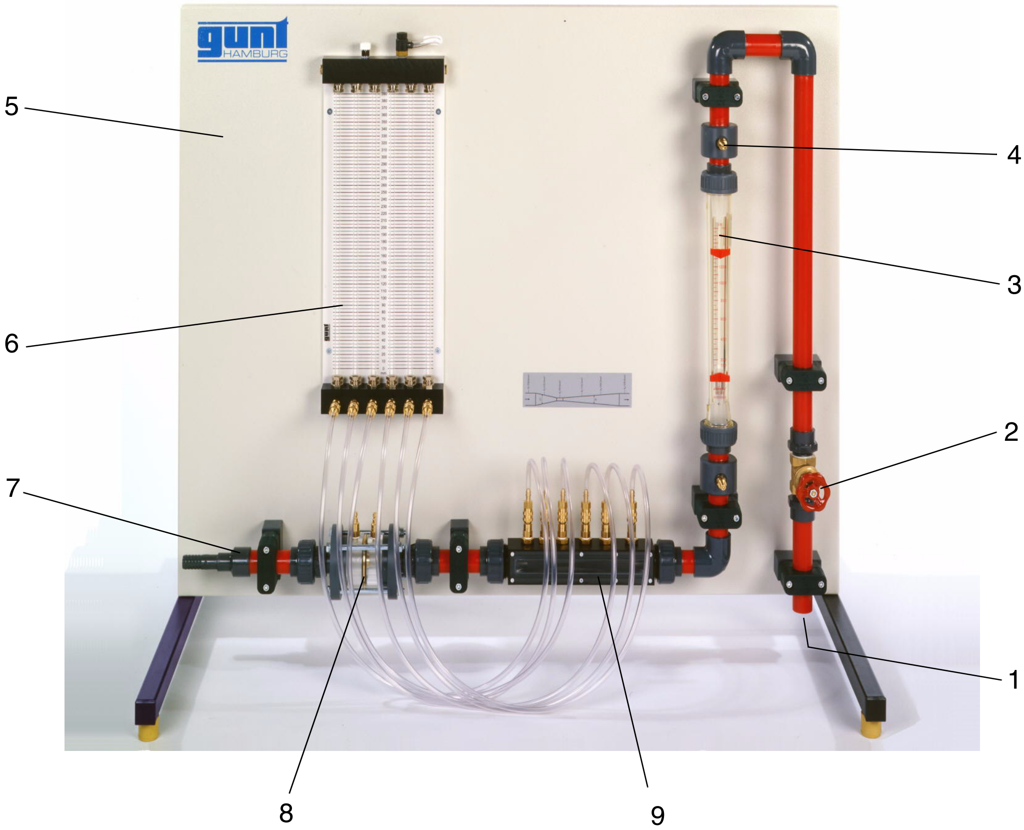
Table of Contents

1 Introduction

The **HM 150.13 Methods of Flow Measurement** unit includes three different flow meters, allowing the following relationships to be investigated experimentally:

- Comparison of different flow meters
- Investigation of relationships between flow and pressure in flow measurement
- Determination of flow coefficients
- Calibration of flow meters

2 Description of the Unit



Pos.	Designation	Pos.	Designation
1	Water outlet	6	Multi-tube manometer
2	Gate valve for inlet	7	Water inlet
3	Rotameter	8	Flow meter with orifice plate, measuring nozzle, or Pitot tube
4	Pressure measurement connections	9	Venturi nozzle
5	Base plate with frame		

Fig. 2.1

The unit comprises a Venturi nozzle (9), an orifice plate, a measuring nozzle and a Pitot tube (8) for flow measurement and a rotameter (3).

The flow rate can be regulated using the gate valve (2).

The pressure losses at the measuring elements can be recorded using pressure connections with rapid action couplings.

The connections are connected to a 6-tube manometer (6), which is fitted with a ventilation valve.

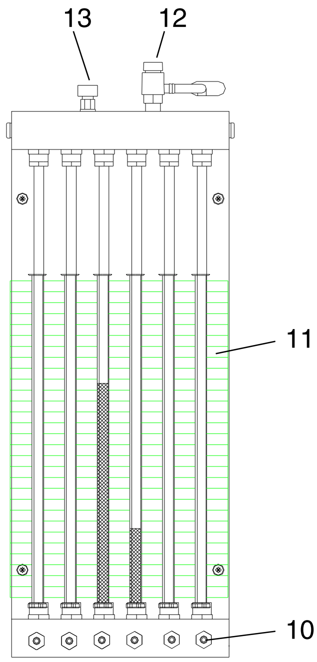
The flow rate can be measured using the **HM 150 Base Module for Experiments in Fluid Mechanics** (volumetric flow measurement).

All components of the experimentation stand are clearly arranged on a base plate with a frame (5).

The unit is designed to be used in conjunction with the **HM 150 Base Module for Experiments in Fluid Mechanics**, which provides the water supply and allows volumetric flow measurement.

3 Basic Principles

3.1 6-Tube Manometer Panel



Pos.	Designation
10	Measuring connections
11	Glass cylinder
12	Ventilation valve
13	Ventilation valve

Fig. 3.1

The 6 tube manometer panel has 6 glass cylinders (11) with a mm scale for measuring the water column (WC). The unit mmWC is often used here. (10mm WS ≙ 1mbar)

- Measuring range 390 mmWC
- All the tubes are connected to one another at the upper end and ventilated by a shared ventilation valve (12). The measuring connections (10) are at the lower end.
- Differential pressure measurements are carried out with the ventilation valve closed (12, 13), relative gauge pressure measurements with the ventilation valve open (12).
  Standard pressure unit: Pascal (Pa)
  $1\,Pa = 1\,N/m^2 = 10^{-5}bar = 0{,}01\,mbar$

3.2 Differential Pressure Measurement

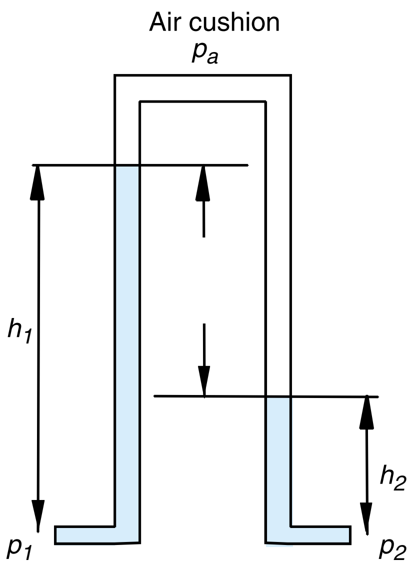


Fig. 3.2

The ventilation valves (12, 13) are closed. Above the two water columns shown there is an air cushion with a pressure of p_a.

This results in the equations below:

$$p_1 = p_a + h_1 \cdot \rho \cdot g \tag{3.1}$$

$$p_2 = p_a + h_2 \cdot \rho \cdot g \tag{3.2}$$

The required differential pressure is

$$\Delta p = p_1 - p_2 = p_a + h_1 \cdot \rho \cdot g - p_a - h_2 \cdot \rho \cdot g \tag{3.3}$$

The pressure p_a cancels out to give

$$\Delta p = \Delta h \cdot \rho \cdot g \text{ mit } \Delta h = h_1 - h_2 \tag{3.4}$$

A zero point adjustment is carried out by adjusting the air pressure p_a.

To ensure the largest possible measuring range, the zero point for the manometer should be in the middle of the scale $\frac{h_{max}}{2}$

$$\frac{h_1 + h_2}{2} = \frac{h_{max}}{2} = \frac{p_1 - p_a + p_2 - p_a}{2 \cdot \rho \cdot g} \tag{3.5}$$

This gives an equation for the air cushion pressure p_a

$$p_a = \frac{p_1 + p_2 - (h_{max} \cdot \rho \cdot g)}{2} \qquad (3.6)$$

The air cushion pressure is adjusted using the ventilation valve (13).

3.3 Relative Pressure Measurement

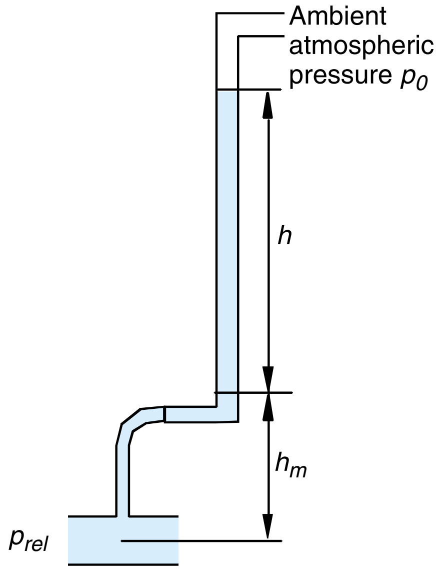


Fig. 3.3

For relative gauge pressure measurements, i.e. measurements in which the pressure is stated relative to the ambient atmospheric pressure p_0, the ventilation valve (13) must be closed. The air cushion pressure p_a is equal to the ambient atmospheric pressure p_0.

In this case, the tube height h_m between the measuring point and the manometer zero point must be taken into account

$$p_{rel} = p_0 + (h + h_m) \cdot \rho \cdot g \qquad (3.7)$$

3.4 Preparing and Performing a Pressure Measurement

- Connect the connecting hoses to one of the two measuring elements and to the 6 tube manometer. The measuring connections are selfclosing.
- Close the ventilation valve (13) on the 6 tube manometer.
- Open the ventilation valve (12) on the 6 tube manometer.
- Start the water inlet (from the HM 150).
- Close the gate valve (2).
- Rinse the 6 tube manometer until no more bubbles are visible.
- Stop the water inlet (from the HM 150).
- Close the ventilation valve (12).
- Open the ventilation valve (13) and adjust the water level in the tube manometer (centre of scale).
- Close the ventilation valve (13) again.
- Carefully open the gate valve (6).
- Carefully open the water inlet (from the HM 150).
- Observe the heights of the water columns in the tubes.
- Adjust the flow rate with the gate valve (6).

3.5 Introduction to Flow Measuring Methods

3.5.1 Rotameter

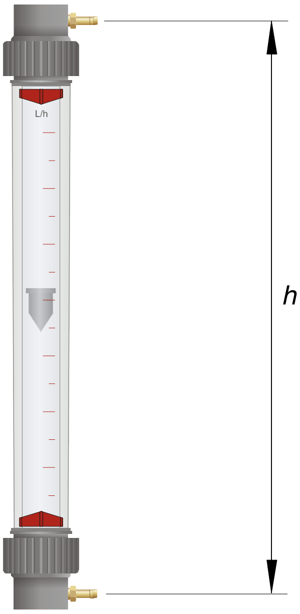


Fig. 3.4

This kind of rotameter consists of a vertical conical measuring section, through which the liquid flows from bottom to top.

A specially shaped float moves freely in the liquid flow and is carried along by the flow due to its flow resistance. This results in equilibrium between the weight of the float on the one hand and its drag and lifting force on the other.

The float adjusts to a particular height in the measuring tube depending on the flow volume. Because of the operating principle, a reliable measuring range on a rotameter never begins at zero, but at ~5% ... 10% of the final measuring value.

Different floats are normally used depending on the medium and the measuring range.

- Standard measuring ranges: ~ 0,0001 ... 100 m^3/h
- Width of measuring range: ~ 1 : 10
- Standard measuring characteristics: linear
- Measuring accuracy: ~± 1 ... 3%
- Pressure loss over measuring tube: ~0,06 ... 0,6 bar

The rotameter used in the HM 150.13 has the following properties:

- Housing made of transparent plastic
- Removable float, stainless steel
- Removable percentage scale, relative to max. flow rate

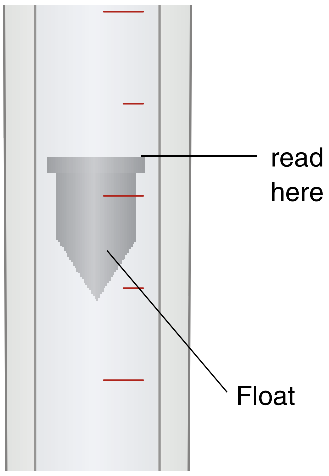


Fig. 3.5

The measured flow rate value is always read at the upper edge of the float.

NOTICE

Air bubbles and other impurities cause measuring inaccuracies. To prevent these, rinse the system at the start of a measurement by fully opening all the valves.

3.5.2 Orifice Plate and Measuring Nozzle

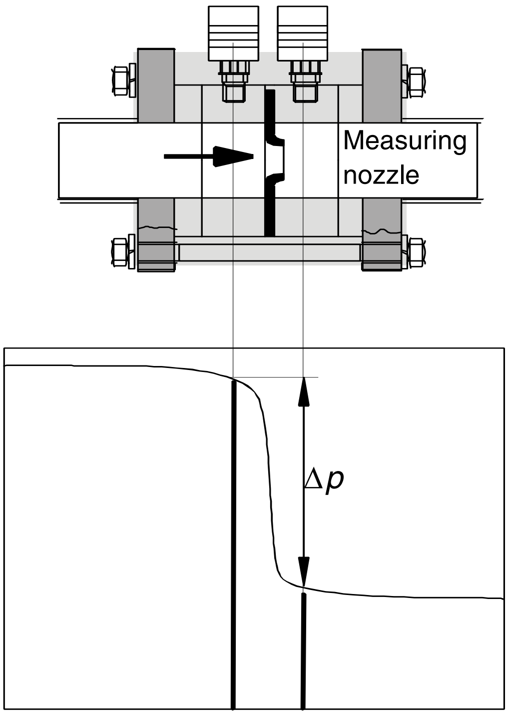


Fig. 3.6

The orifice and nozzle are what is known as the restrictors. They both represent a constriction in a tube. The reduction in cross section results in an increase in the speed of the flowing medium. This is associated with a pressure loss Δp between the normal tube cross section A_D before the inlet and the constricted tube cross section A_d at the orifice or nozzle. This pressure loss Δp is a measure of the volumetric flow.

This type of measurement is extremely accurate, but the orifice or nozzle have a comparatively high flow resistance.

Restrictors are very sensitive to disturbances in the inlet and outlet flow. Elbows, T-pieces, valves, gate valves or similar fittings must therefore be installed sufficiently far away from the restrictor.

$$\dot{V} = \alpha \cdot \varepsilon \cdot A_d \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = k \cdot \sqrt{\Delta p} \quad (3.8)$$

α Flow coefficient, no dimension

ε Expansion coefficient, no dimension (for liquids $\varepsilon = 1$)

ρ Density of medium before orifice / nozzle

NOTICE

Δp must be used in the equation $\dot{V} = k \cdot \sqrt{\Delta p}$ in *mbar.*

- Standard tube diameter:
  ~ Ø 50 ... Ø 1000 mm
- Standard aperture ratios:
  $$m = \frac{A_d}{A_D} = \sim 0{,}1 \dots 0{,}64$$
- Measuring characteristics: Root function

On the **HM 150.13**, the orifice and nozzle are supplied as individual metal discs, which can optionally be inserted into the housing as required.

This housing for the orifice and nozzle is made of Plexiglass to allow observation of the function.

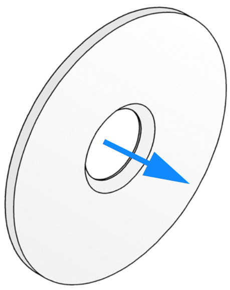


Fig. 3.7

Orifice plate: $$k = 293 \frac{L}{h \cdot \sqrt{mbar}}$$

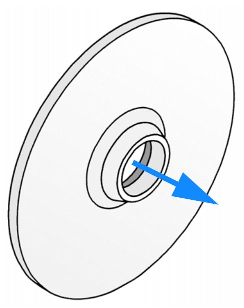


Fig. 3.8

Measurement nozzle. $$k = 231 \frac{L}{h \cdot \sqrt{mbar}}$$

3.5.3 Pitot Tube

The Pitot tube measures both the static (1) and the total pressure (2). The difference between these two values gives the dynamic pressure p_{dyn}.

$$p_{dyn} = p_{tot} - p_{stat} \tag{3.9}$$

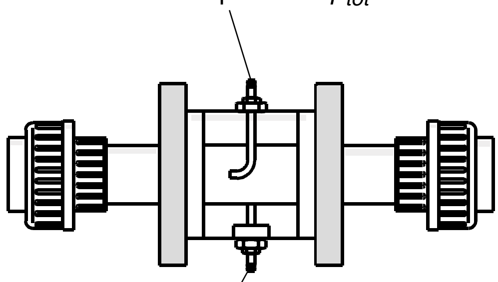


Fig. 3.9 Pitot tube

The dynamic pressure is proportional to the square of the flow speed and can be calculated as follows:

$$p_{dyn} = \frac{\rho}{2} \cdot v^2 \tag{3.10}$$

ρ: Spezific density of water

The flow speed v can be determined from the volumetric flow $\dot{V}$ and the flow cross-section A.

$$v = \frac{\dot{V}}{A} \tag{3.11}$$

The pressure difference can therefore be used to calculate the volumetric flow rate for a given flow cross-section. As a constant distribution of velocity over the flow cross-section is assumed to simplify the calculation, but in reality a significantly lower velocity occurs close to the wall, the volumetric flow rate calculated in this way will be too high. This can be compensated using a correction factor.

For steady turbulent flow in pipes of circular cross-section the average speedv is described by the ratio of the average flow speed v to the maximum flow speed v_{max} in consideration of the correction factor 0,84.

$$\frac{v}{v_{max}} \approx 0{,}84 \qquad (3.12)$$

This yields a average flow speed v.

$$v \approx v_{max} \cdot 0{,}84 \qquad (3.13)$$

The maximum flow speed v_{max} can be determined from the measured differential pressure p_{dyn} and the flow cross-section A.

$$v_{max} = \sqrt{\frac{2 \cdot p_{dyn}}{\rho}} \qquad (3.14)$$

The flow rate $\dot{V}_{cal}$ is calculated from the mean flow speed v and the flow cross-section A.

$$\dot{V}_{cal} \approx A \cdot v_{max} \cdot 0{,}84 \qquad (3.15)$$

The free through-streamed pipe circular cross-section A, is the difference of cross-section of the pass through tube d_1 and the cross-section of pipe for total pressure measurement at Pitot tube d_2.

$$\Delta d = d_1 - d_2 \tag{3.16}$$

$$A = \frac{(\Delta d)^2 \cdot \pi}{4} \tag{3.17}$$

where

$d_1 = \varnothing 17\,\text{mm}$

$d_2 = \varnothing 3\,\text{mm}$

3.5.4 Venturi Nozzle

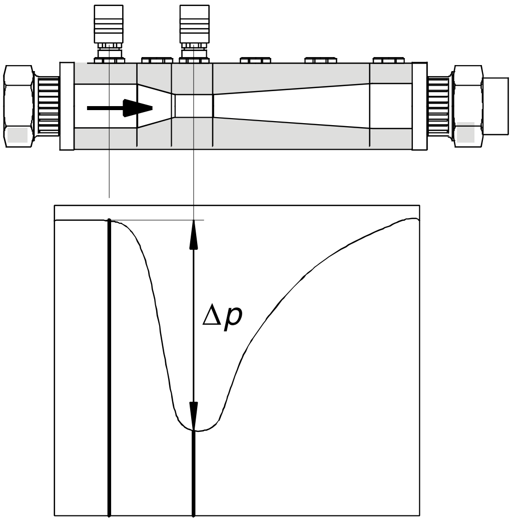


Fig. 3.10 Venturidüse

The Venturi tube is also a throttle device. In this case, the constriction of the tube cross section is split into three different areas. The inlet corresponds to a nozzle, followed by a straight section and finally a diffusor with a defined extension angle φ.

The pressure loss Δp between the normal tube cross section A_D before the inlet and the constricted straight section A_d is significantly less than with the orifice or nozzle.

- Standard tube diameter: ~ Ø 65 ... Ø 500 mm
- Standard aperture ratios: $m = \frac{A_d}{A_D} = \sim 0{,}1 \dots 0{,}6$
- Diffusor extension angle: $\varphi < 30°$
- Measuring characteristics: Root function

To see the construction of the Venturi tube used in the **HM 150.13**, the housing cover is made of Plexiglass.

The pressure conditions in the Venturi tube follow Bernoulli's Law. As for the orifice plate / measuring nozzle, according to this law we can obtain the following relationship between pressure difference Δp (recorded using measuring connections) and volumetric flow $\dot{V}$:

$$\dot{V} = \alpha \cdot \varepsilon \cdot A_d \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = k \cdot \sqrt{\Delta p} \qquad (3.18)$$

α Flow coefficient, no dimension

ε Expansion coefficient, no dimension (for liquids $\varepsilon = 1$)

ρ Density of medium before orifice plate / measuring nozzle

NOTICE

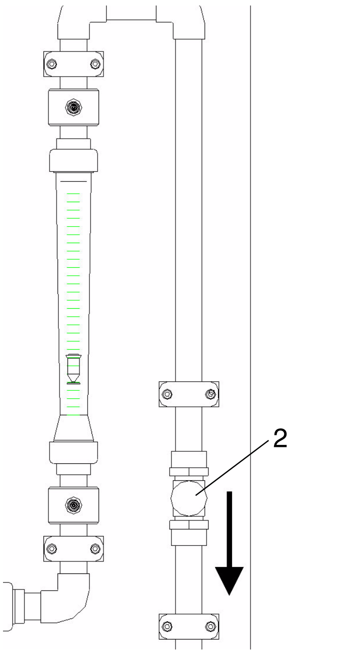
Δp must be used in the equation $\dot{V} = k \cdot \sqrt{\Delta p}$ in *mbar.*

where $k = 132 \frac{\text{L}}{\text{h} \cdot \sqrt{\text{mbar}}}$

4 Experiments

4.1 Calibration of Flow Meters

Example: Rotameter



Pos.	Designation
2	Gate valve for inlet

Fig. 4.1

A flow meter is calibrated by comparing its displayed values with the results obtained from another, accurately verifiable measuring method. By way of example, in the following experiment the rotameter is calibrated using the **HM 150**.

The same procedure can be applied to calibrate the orifice plate / measuring nozzle / Pitot tube or the Venturi nozzle. The volumetric flow measurement is described in the documentation for the **HM 150**.

Performance:

- Prepare the HM 150 and the HM 150.13.
- Switch on the pump on the HM 150.
- Open the gate valve (2) on the HM150.13 and initially set a low flow rate.
- Note the display value on the rotameter in a table (see Tab. 4.1, Page 23).
- Use the HM 150 to perform a volumetric measurement and note the result in the table.
- Repeat the previous steps for at least five further settings of the gate valve (2) on the HM150.13.
- Calculate the difference between the flow values recorded, calculate any error and plot the results in a graph.

4.2 Flow Measurement

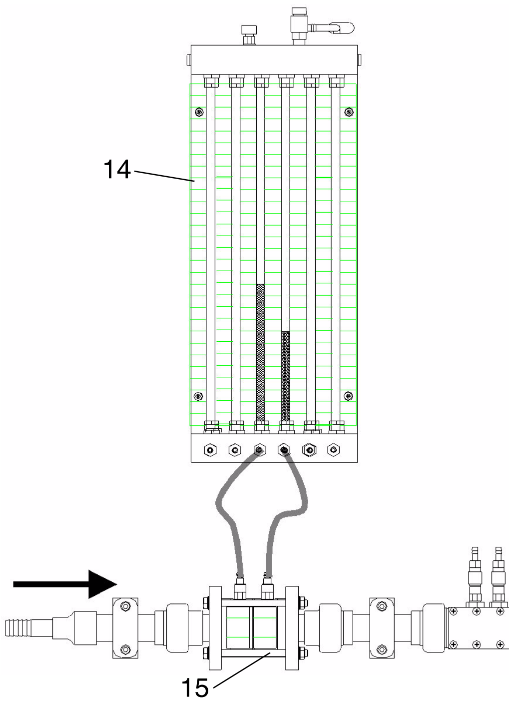
4.2.1 Orifice Plate / Measuring Nozzle

An orifice / nozzle with a volumetric flow $\dot{V}$ running through it results in a pressure loss Δp.

The relationship is:

$$\dot{V} = k \cdot \sqrt{\Delta p} \qquad (4.1)$$

The flow measurement for the orifice plate / mesurig nozzle on the HM 150.13 is carried out using the rotameter calibrated in the previous experiment.



Pos.	Designation
14	Manometer panel
15	Housing

Fig. 4.2

Performance:

Prepare the HM150 and the HM150.13.

- Insert either the orifice disc or the nozzle disc into the housing (15) and fit the housing in the tu
- Connect the pressure connections on the housing to two measuring tubes on the manometer panel (2).
- Prepare the manometer panel (14) for differential pressure measurement.
- Switch on the pump on the HM 150.
- Open the gate valve (2) on the HM 150.13 and initially set a low flow rate.
- Note the volumetric flow $\dot{V}$ displayed on the rotameter in a table (see Tab. 4.1, Page 23).
- Note the differential pressure value on the table.

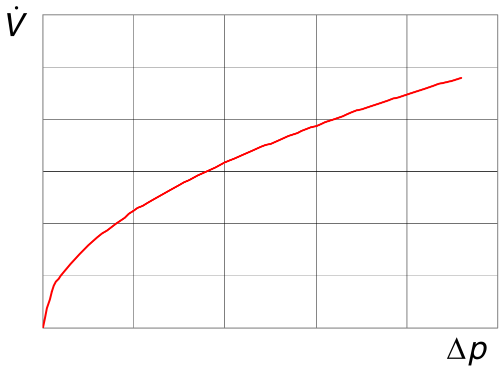


Abb. 4.3

- Repeat the previous steps for further settings of the gate valve (2) on the HM 150.13.
- Plot the flow values recorded against the associated differential pressure values in a graph.

This gives the relationship between pressure loss Δp and volumetric flow $\dot{V}$ as a root function

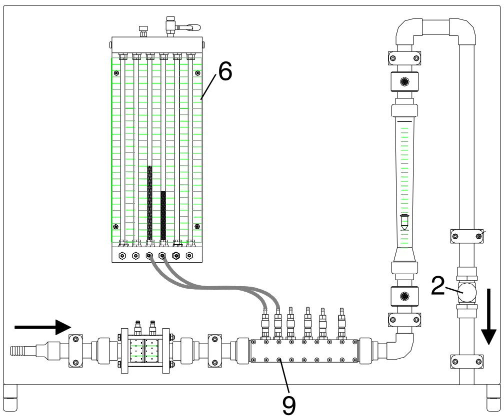
4.2.2 Venturi Nozzle

A Venturi tube with a volumetric flow $\dot{V}$ running through it results in a pressure loss Δp.

The relationship is:

$$\dot{V} = k \cdot \sqrt{\Delta p} \tag{4.2}$$

The flow measurement with the Venturi tube on the HM 150.13 is also carried out using the rotameter calibrated in a previous experiment.



Pos.	Designation
2	Gate valve
6	Manometer panel
9	Venturi nozzle

Fig. 4.4

Performance:

- Prepare the HM 150 and the HM 150.13.
- Connect the pressure connections on the Venturi nozzle (9) to two measuring tubes on the manometer panel (6).
- Prepare the manometer panel (6) for differential pressure measurement.
- Switch on the pump on the HM 150.
- Open the gate valve (2) on the HM150.13 and initially set a low flow rate.
- Note the volumetric flow $\dot{V}$ displayed on the rotameter in a table (see Tab. 4.1, Page 23).
- Note the differential pressure value on the manometer panel in the table.
- Repeat the previous steps for further settings of the gate valve (2) on the HM 150.13.

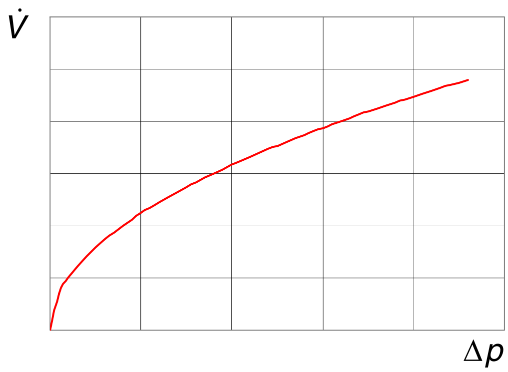


Abb. 4.5

- Plot the flow values recorded against the associated differential pressure values in a graph.

This gives the relationship between pressure loss Δp and volumetric flow $\dot{V}$ as a root function.

4.3 Flow Coefficients

According to Bernoulli's Law, the following applies for a constriction in a tube:

$$\dot{V} = \alpha \cdot \varepsilon \cdot A_d \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} = k \cdot \sqrt{\Delta p} \qquad (4.3)$$

α Flow coefficient, no dimension

ε Expansion coefficient, no dimension (for liquids $\varepsilon = 1$)

ρ Density of medium before constriction (for water $\rho = 1$)

A_d Aperture cross section of restrictor

Flow coefficient:

$$\alpha = \frac{\dot{V}}{A_d \cdot \sqrt{2 \cdot \Delta p}} \qquad (4.4)$$

Aperture ratio:

$$m = \frac{A_d}{A_D} \qquad (4.5)$$

Diameter ratio:

$$\beta = \frac{d}{D} = \sqrt{m} \qquad (4.6)$$

Flow coefficient:

$$C = \alpha \cdot \sqrt{1 - m^2} \qquad (4.7)$$

$$C = \alpha \cdot \sqrt{1 - \beta^4} \qquad (4.8)$$

The values for the volumetric flow $\dot{V}$, the pressure loss Δp and the constricted cross section A_d from the previous measuring tables and the technical data can be used to calculate α and C.

Experiment no.:					
Date:					
Participant:					
Type of experiment:					
Measuring object:					
No.	Pressure loss Δp in mbar	Flow display $\dot{V}$	Measuring volumen HM 150 in L	Measuring time HM 150 in s	Calculated flow from HM 150 in L/s
1					
2					
3					
4					
5					
6					
7					
8					
9					

Tab. 4.1 Measured value table

5 Appendix

5.1 Technical Data

Dimensions

Length	1100 mm
Width	672 mm
Height	900 mm
Weight	approx. 40 kg

Manometer panel for water

6 tubes	390 mm WC

Rotameter max. 1600 L/h

Pipe section

Inner diameter	17 mm

5.2 List of Formula Symbols and Units Used

Symbol	Mathematical/physical quantity	Unit
A_d	Cross-section, smallest	mm
A_D	Cross-section, largest	mm
C	Flow coefficient	
h	Tube height	mm
k	Correction factor	
p	Pressure	Pa, mbar, bar
α	Flow coefficient according to DIN EN ISO 5167	-
φ	Diffusor extension angle	°
Δp	Pressure loss	mbar
ε	Expansion coefficient	1
ρ	Density	kg/m^3
$\dot{V}$	Volumetric flow	L/min

Suffix	Explanation
a	air
max	maximal
rel	relative
tot	total

5.3 Dimensions Restrictors

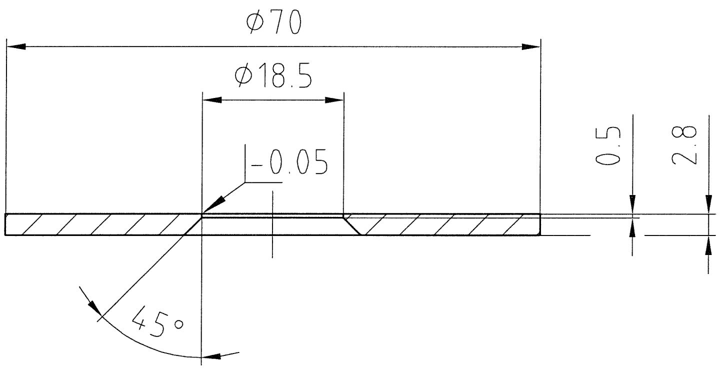


Fig. 5.1 Orifice plate

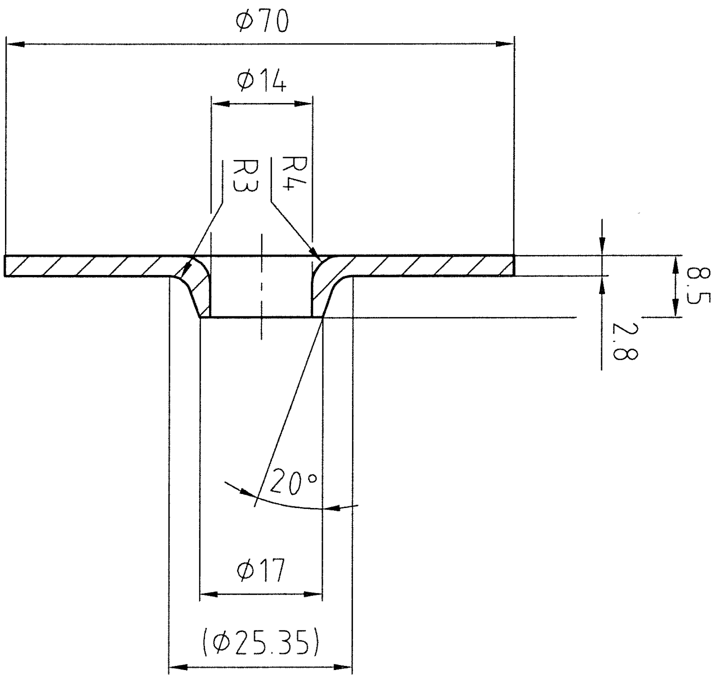


Fig. 5.2 Measuring nozzle

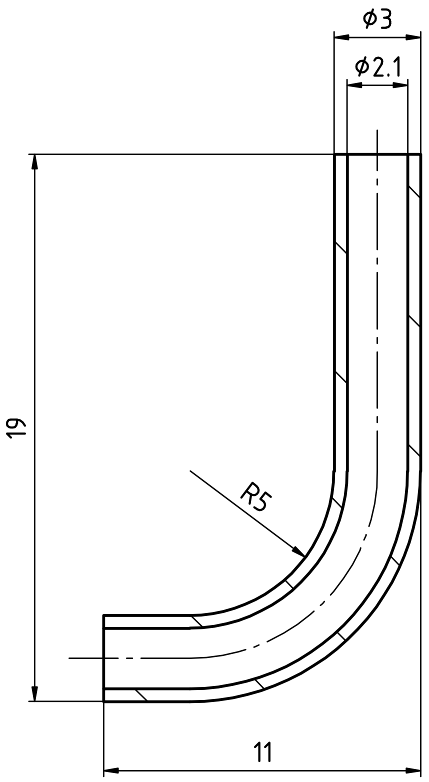


Fig. 5.3 Pitot tube

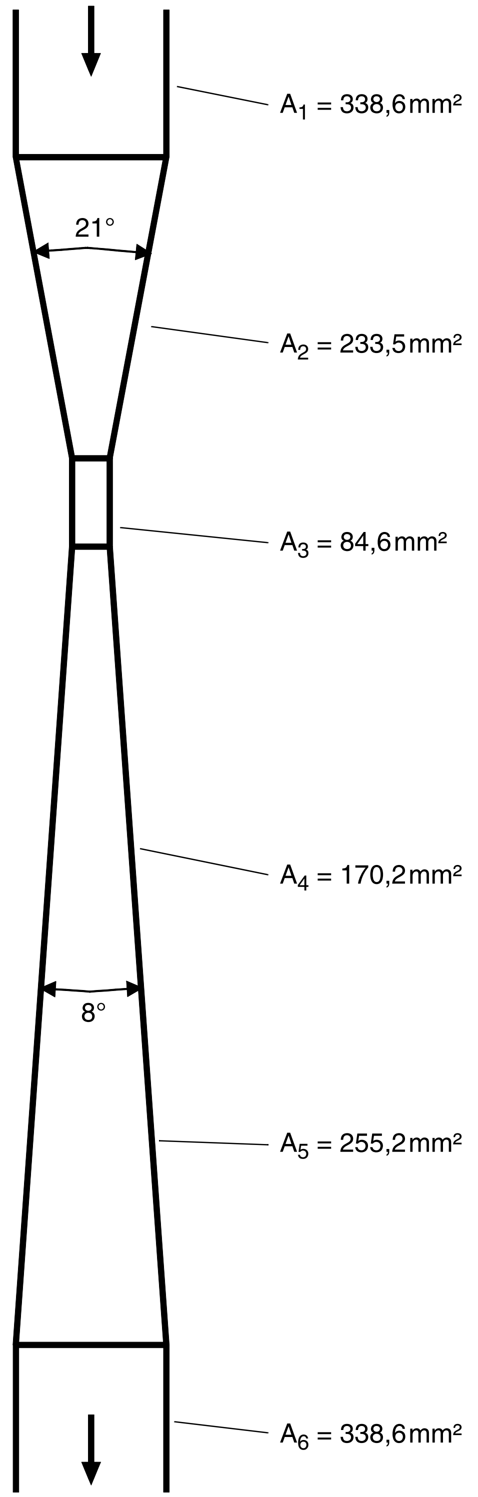


Fig. 5.4 Cross-sections of Venturi nozzle