Experiment Instructions

HM 112 Hydrodynamics Trainer

HM 112	*HYDRODYNAMICS TRAINER*

Experiment Instructions

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Please read and follow the safety regulations before the first installation!

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1 Introduction

The G.U.N.T. **HM 112 Hydrodynamics Trainer** allows experiments for flow and pressure measurement and determination of flow losses and pressure characteristic for pipes and various pipe components. The following topics can be investigated in detail on the experimental unit:

- Various flow and pressure measuring methods
- Function of nozzle, orifice, venturi tube, etc.
- Determination of coefficients of resistance head losses
- Losses due to pipe bends or angles, changes of cross-section and shut-off devices
- Measurement of opening characteristics for shut-off devices

In addition the student gains skills in the preparation and performance of series of experiments, and knowledge of the use of pressure and flow rate measuring equipment.

The experimental unit is fitted with a closed water circuit, which means that it can be used independently of the mains water supply. It can be used in different locations in training, seminar and lecture rooms.

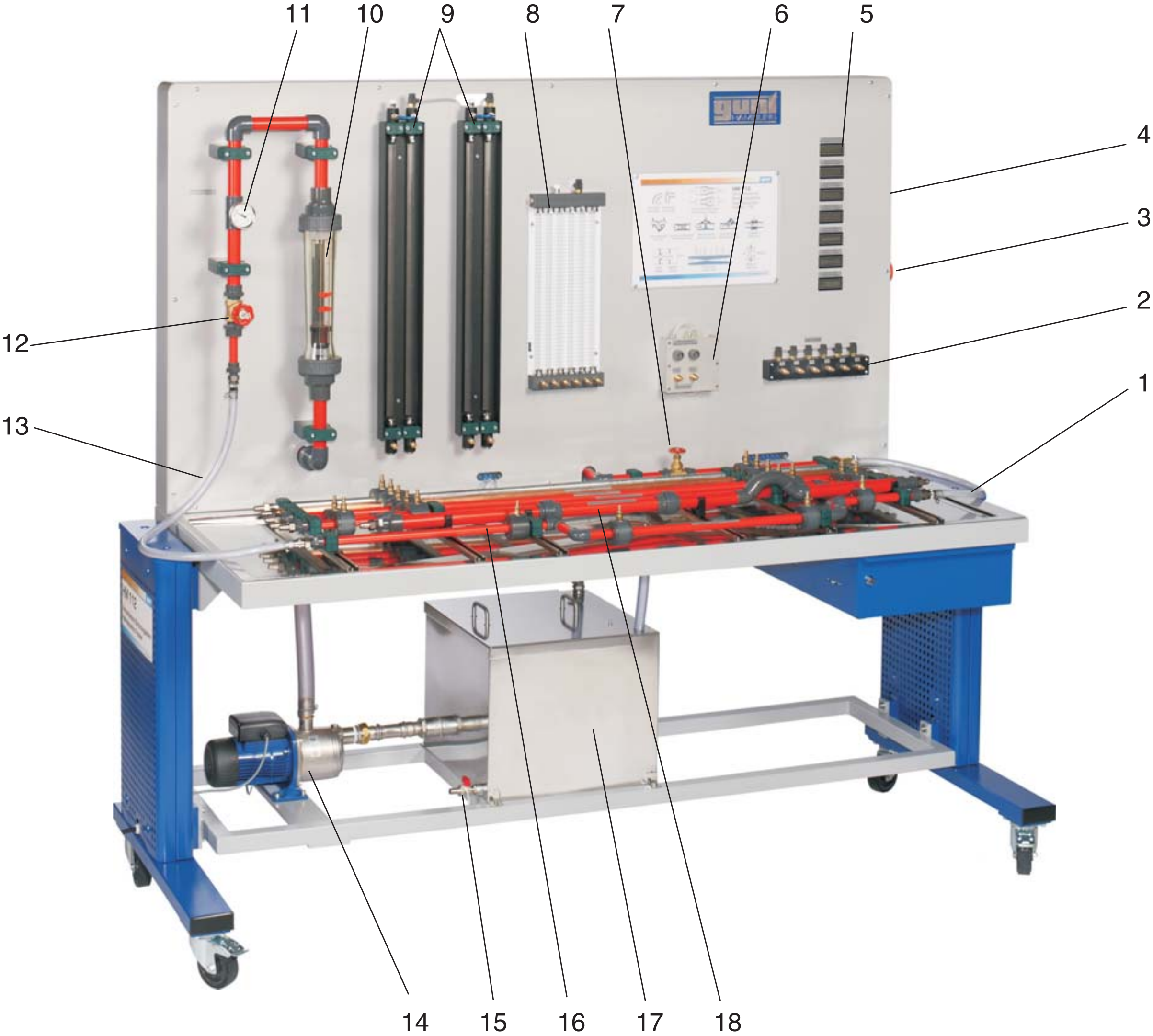
2 Device description

The experimental unit has the following features:

- The entire experimental set-up is clearly laid out on a **laboratory trolley**.
- Four castors make the experimental unit **mobile** and easy to manoeuvre
- Closed water circuit allows operation **independently of the mains water supply**
- Flow rate measurement using a variable-area flow meter with electronic position measuring of the float
- 5 independent **pressure measuring systems** for measurement of differential pressure and head loss
- USB-Multifunction circuit board for **PC data acquisition**
- Disturbance-free **pressure tapping** using annular chambers
- Easy and quick **connection** between measuring points and pressure gauges using hoses with quick action couplings
- Variety of **measuring objects for fluid mechanics**
- Some measuring objects transparent, making **function visible**
- **Seven different fixed** pipe sections
- Pipe sections are **interchangeable**, allowing the use of individual sections
- Easy **pipe section selection** using hoses with quick action couplings

– Standard **measuring length of 1m** for pipe friction measurements

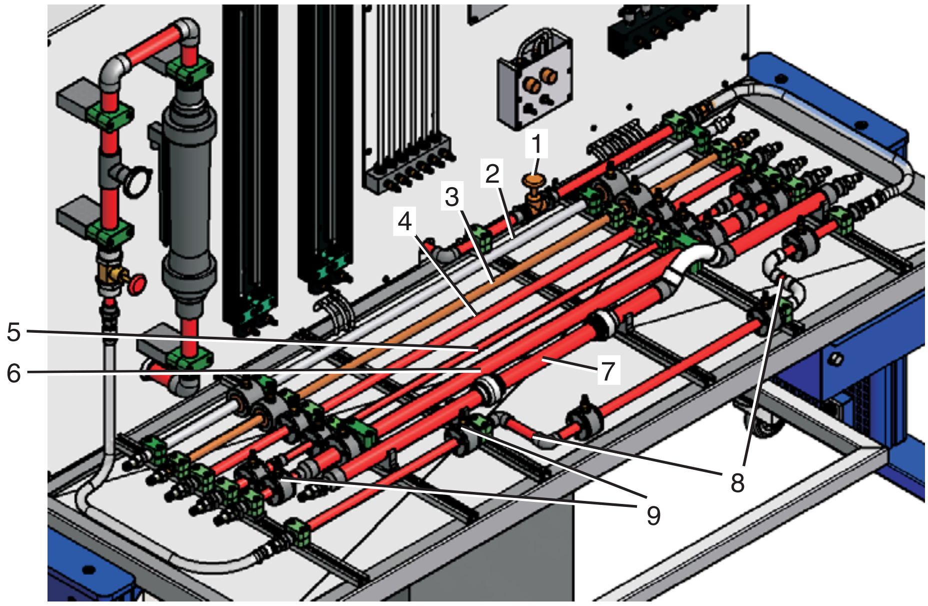
2.1 Experimental unit layout



1 Return hose
2 Electronic pressure sensor
3 Main switch
4 Switch for pump (covered)
5 Digital displays for pressure
6 Differential pressure sensor
7 Return valve
8 Six tube manometer
9 Two tube manometer
10 Rotameter
11 Thermometer
12 reducing valve
13 Feeding hose
14 Pump
15 Drain valve
16 Various measuring sections
17 Water tank
18 Interchangeable measuring objects

2.2 Experimental unit equipment

2.2.1 Fixed pipe sections



1 Return valve with return pipe to water tank
2 Galvanized steel pipe, 1/2"
3 Cu-pipe 18 x 1
4 PVC-pipe 20 x 1.5
5 Cross-section contraction PVC 20-16
6 Cross-section expansion PVC 20 - 32
7 Section for interchangeable measuring objects
8 Pipe bend, pipe angle PVC 20 x 1.5
9 Self closing measuring glands

Fig. 2.3 Arrangement of pipe sections

2.2.2 Measuring objects

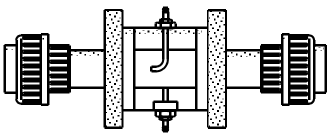


Fig. 2.1 Pitot tube

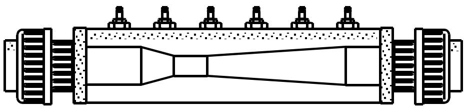


Fig. 2.2 Venturi tube

The measuring objects can be inserted into the measuring section (7) using union nuts. The measuring objects are fitted with annular chambers and hose connections for pressure measurement.

- Slanted seat valve
- Membrane valve
- Ball cock
- Non-return valve
- Dirt trap with filter inserts
- Pitot tube
- Measuring orifice and nozzle
- Venturi tube

2.3 Experimental unit function

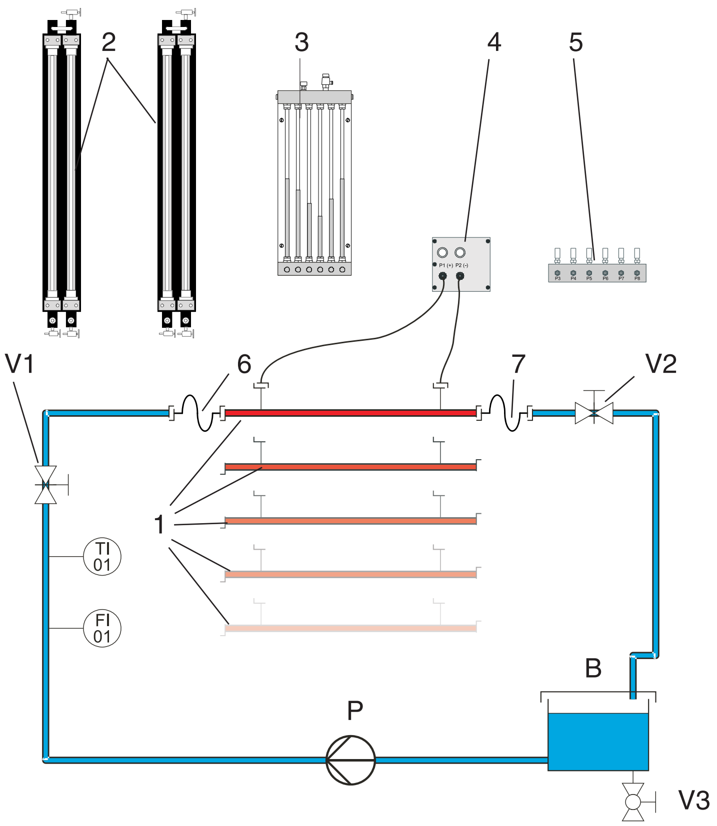
After the pump (P), the water first off all passes the flow rate-/ and temperature measurement (F1 & T1) and the reducing valve (V1). If the hoses are unplugged (6,7), the reducing valve can be used to shut off the water supply. It is also used to adjust the flow rate.

The water is then fed to the selected pipe section (1) via the feeding hose (6).

The pressure is measured at measuring glands at the beginning and end of the measuring section.

Once the water has flowed through the pipe section, it is fed back to the water tank via a second hose (7).

A return valve (V2) can be used to restrict the drain.



1 Measuring sections
2 Two tube manometer
3 Six tube manometer
4 Differential pressure sensor
5 Pressure sensors
6 Feeding hose
7 Return hose

B	Water tank
P	Pump
FI-01	Rotameter
TI-01	Thermometer
V1	Reducing valve
V2	Return valve
V3	Drain valve

Fig. 2.4 Arrangement of pipe sections

2.4 PC data acquisition

This experimental unit is equipped for PC data acquisition. This involves the recording of differential pressure, excess pressure and flow rate by electronic sensors. The sensors output voltage signals from 0-10V. With the exception of the flow rate sensor, which works with a variable resistance at +5 V. The differential pressure (1), and the excess pressures (2) are indicated on digital displays in the switch cabinet.

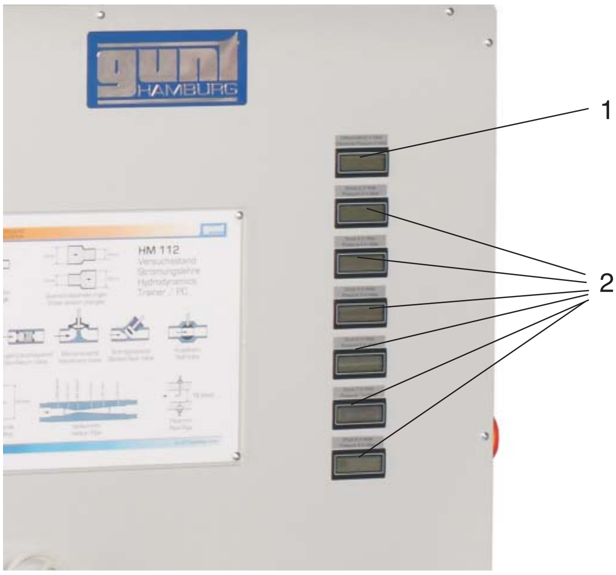


Fig. 2.5 Switch cabinet with digital displays

The signals are displayed on the PC monitor using a visualisation program that runs under Windows ™.

The experimental unit can also be operated **without a PC**.

3 Safety

3.1 Work safety

Always read and observe the following instructions!

DANGER, electric shock!

- The **switch cabinet** is only to be opened by specialist personnel
- Prior to opening the **switch cabinet**, disconnect from the mains
- Protect **switch cabinet and PC** against splashed water, as this can damage components

3.2 Operating safety

CAUTION, store experimental unit in a frost-free location!

Empty the water tank if the unit will not be used for long periods.

CAUTION, do not overload pressure sensors!

The pressure measuring range for the sensors is 0 - 200 mbar.

- Pressures over 600 mbar or negative pressures can damage the pressure sensors. The volumetric flow rates must therefore be restricted using the valves in the inlet and the drain to ensure that this value is not reached.
- Ensure correct polarity when connecting the differential pressure sensor.

4 Software

4.1 Hardware and software installation

The USB cable for the LabView TM application software should be connected and installed in the following order:

– 1.Software installation
Insert CD in drive, run Setup.exe and follow the instructions in the dialog box

– 2. Connect the USB cable

– 3. Start the software application

4.2 Starting the software

After starting the software, the “system diagram” window appears.

The first time you open the software, a language selection window also appears. The language can be changed later using the pull-down menu under “Language” in the menu bar.

Clicking on “Start” in the menu bar allows you to choose between the “system diagram” and “measurement diagram” windows. The menu bar also includes the “EXIT” option for exiting the program.

In the system diagram screen, you can choose the measuring section used in the experimental setup.

Note:

The menu options are context sensitive, i.e. not all options can be selected at all times.

Recording measured values:

- Open the “measurement diagram” window under “Start” in the menu bar.
- Create a new measuring series (“New series”) under “File” in the menu bar.
- If necessary, specify the axes for the diagram. This setting is made using “View” and “choose axis” in the window that is subsequently opened. You can select a maximum of four y-axes and one x-axis.
- You can then record measured data using the record button (Fig. 4.2, 3) or by selecting the “take record” option under “Edit” in the menu bar.
- After recording the measuring series, you can save it to the hard disk or an alternative medium using the “save series” command in the “File” menu.

4.2.1 The “system diagram” window

The system diagram is a clearly arranged representation of the measuring task. The lower button (1) can be used to toggle between different measuring tasks.

– Pipe
– Nozzle/Orifice
– Pitot Tube
– Pipeline Fittings
– Venturi Nozzle

Pressures can be represented as water columns or using a differential pressure gauge. To change the setting, use the “View” option (3) in the menu. The flow, pressures and temperature are displayed online (5).

The “Start” option (2) takes you to the “measurement diagram” option. This window can be used to create the diagrams.

The “Language” option (4) can be used to select one of the four available languages.

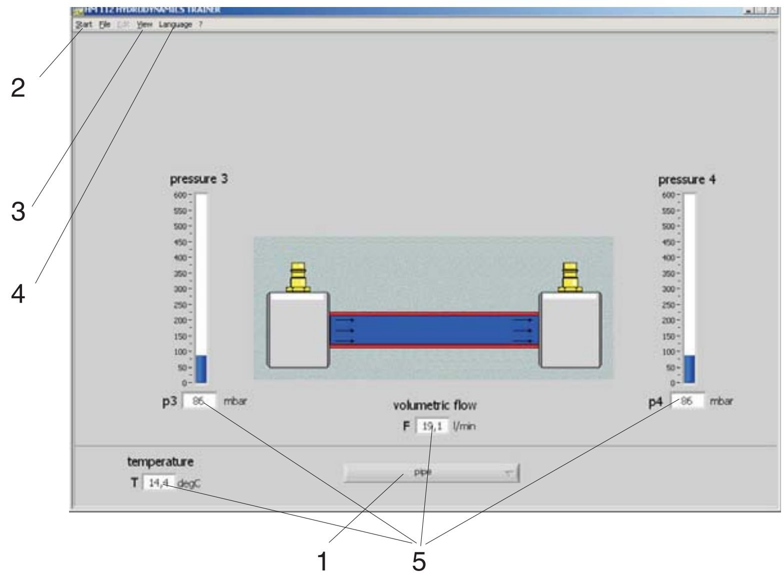


Fig. 4.1 "System diagram" window

4.2.2 The “measurement diagram” window

In the “measurement diagram” window, click on “Start” in the menu bar to record, load and save a curve.

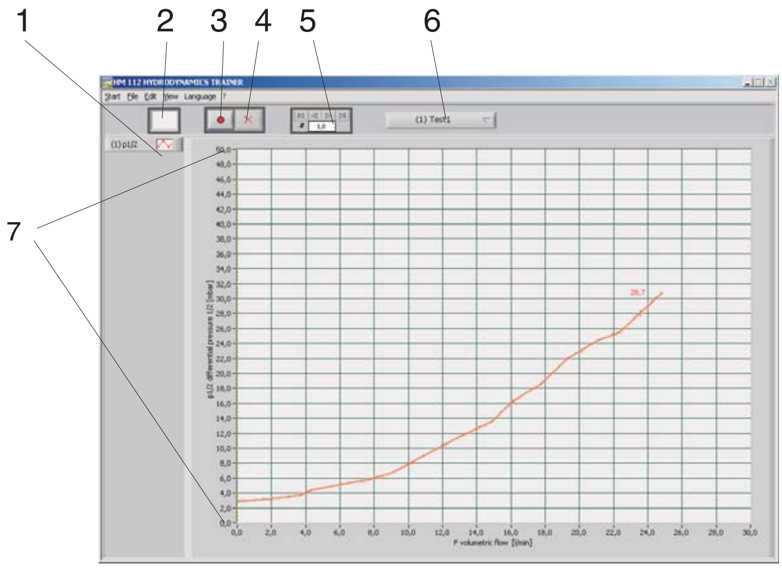


Fig. 4.2 "Measurement diagram" window

The options in this window are only active if a measuring series has actually been loaded or created.

Background / Curve

Left clicking on the buttons for the background (2) and the curve (1) allows you to set the colour of these elements.

Measured value recording

Clicking on the button with the red spot (3) records measured data and adds it to the active data series.

Cursor

The arrow buttons (5) allow the cursor to be moved over the measuring points already recorded. Measured values are displayed at the cursor position.

Delete measured value

The button with the red cross (4) deletes individual measuring points from the active data series. The data record at which the cursor is located will be deleted.

Select active measuring series

In a file containing several measured data series, this button (6) can be used to select the active series. A file can either contain just one or several measuring series. The number of measuring series per file is limited to a maximum of 10.

Scaling

The scaling can be changed by left clicking directly on the limit values.

Measured data can also be recorded and deleted using the menu ("Edit - Take record" or "Edit - Delete record"). The associated abscissa is displayed at the cursor position. Several curves can be plotted in the diagram. A new curve is created using the *"file"* command. The curve can also be saved to a file here. The active curve can be selected using "*select curve"*.

4.2.3 Menu bar structure and commands

- ***Start***
  - ***measurement diagram***

    Opens the window containing x/y graphs for recording, editing and saving measuring series.
  - ***system diagram***

    Opens a window in which the experimental setup and the relevant measured values are displayed online.
  - ***EXIT***

    Exits the program.
- ***File***
  - ***print* window**

    Prints the window on the default printer.
  - ***open file*** (measurement diagram only)

    Opens a previously saved file.
  - ***new series*** (measurement diagram only)

    Creates a new file for at least one data series.

  The following options are only active if a data series is loaded in the “measurement diagram” window.
  - ***save series***

    Saves a measuring series from the working memory to a file (e.g. on the hard disk).
  - ***delete series***

    Deletes a measuring series from the working memory.

- **save all series**

  Saves all measuring series from the working memory to a file.

- ***delete all series***

  Deletes all measuring series from the working memory.

- ***print Graph***

  Outputs the x/y graph on the default printer.

- ***print table***

  Outputs a table for the current measuring series on the default printer.

• ***Edit***

- ***take record***

  Adds a measuring point to the series.

- ***delete record***

  Deletes a measuring point (at the cursor position) from the series.

• ***View***

- ***choose axis*** (“measurement diagram” only)

  Opens a window for selecting the max. 4 y-axes and 1 x-axis.

- ***graph*** (“measurement diagram” only)

  Displays the x/y graph

- ***table*** (“measurement diagram” only)

  Displays the table for the measuring series

- ***pressure*** (“system diagram” only)

  Displays the differential pressure to the ambience

- ***differential pressure*** ("system diagram" only)

  Displays the differential pressure between P1 and P2

- ***Language***

  Allows you to choose one of the four languages

  - ***German***
  - ***English***
  - ***French***
  - ***Spanish***

- ***?***

  - ***About GUNT***

    Information about GUNT

4.2.4 The "Venturi Nozzle" window

The "Venturi Nozzle" window represents the pressure and speed progression along the Venturi Nozzle. This representation clearly illustrates Bernoulli's Law.

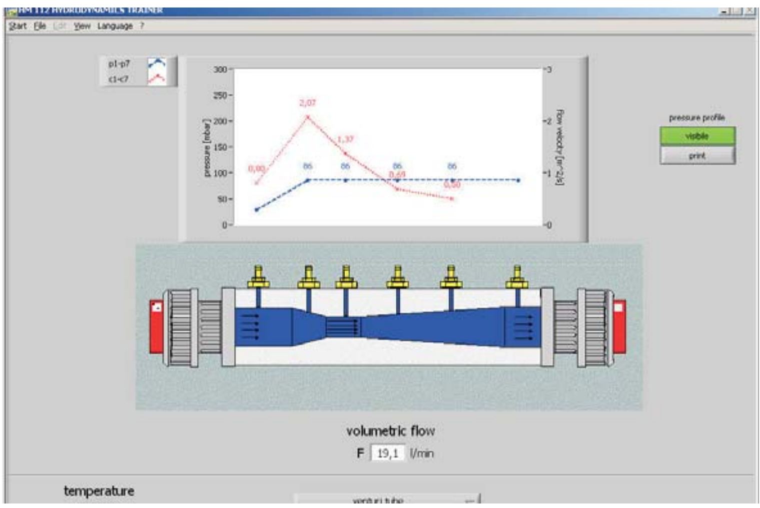


Fig. 4.3 "Venturi Nozzle" window

Basic information on the structure of the measured data file:

Fig. 4.4 File-structure

The measured data file can consist of several measuring series.

Each measuring series has a separate header, which is followed by the measured data records.

A measured data record is the data that is recorded at a specific point in time.

A measuring series contains the data records for several points in time, which are used to plot the curves.

5 Experimental method

Before commencing the experiment:

– Place experimental unit on a flat surface and secure against rolling away (brake).
– Fill up water tank.
– Connect to power supply.

If you intend to work with PC data acquisition, the following steps must also be completed:

– Connect experimental unit and data acquisition card to PC with 37-pin Sub D cable.
– Turn on experimental unit using master switch (digital displays in switch cabinet now show values).
– Switch on PC.
– Start *Windows* TM.
– Open ***GUNT*** program group and start ***HM112*** .

5.1 Leak test

Before starting up the experimental unit and starting any experiments, a leak test should be performed on the experimental unit.

The procedure for this is as follows:

– Check tightness of self closing measuring glands and remove possible particles
– Connect pipe section to feeding and return hose.
– Open return valve.
– Switch on pump.

- Slowly open reducing valve and bleed pipe section.
- Slowly increase pressure by closing the return valve.
- Check all lines, hoses and connections for leaks.
- Repeat procedure for all pipe sections.

5.2 Two tube manometer

The two tube manometer allows both differential pressures and excess pressures to be measured in mm column of water; excess pressures can be converted into absolute pressures taking into account the atmospheric air pressure.

- The measuring range is 0 - 680 mm column of water
- The manometer comprises two glass level tubes (1) with a metal mm scale behind them.
- The two level tubes are connected together at the top and have a common bleed valve (2).
- The differential pressure is measured with the bleed valve closed and the excess pressure with the bleed valve open.
- The measuring points are connected to the bottom of the level tubes using quick action hose couplings (3).
- Each level tube has a drain valve (4) at the bottom.

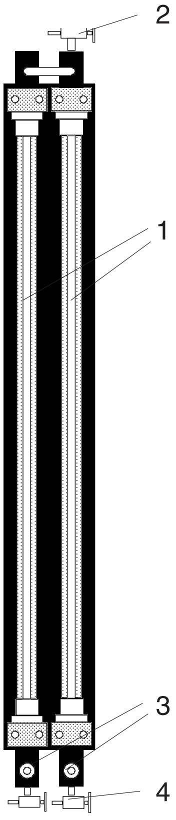


Fig. 5.1 Two tube manometer

5.2.1 Differential pressure measurement

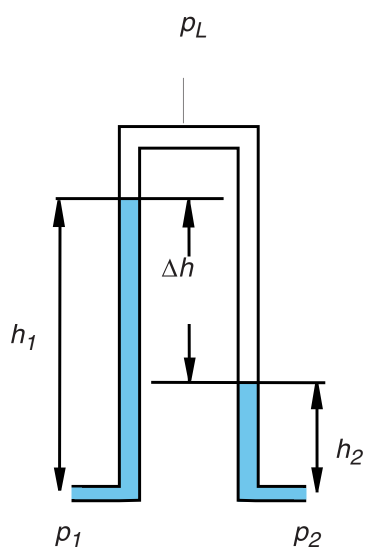


Fig. 5.2 Differential pressure measurement

Here the bleed valve is closed. An air cushion forms over the two columns of water with the pressure p_L. This means that the pressures to be measured p_1 and p_2 are

$$p_1 = p_L + h_1 \rho g$$

$$p_2 = p_L + h_2 \rho g .$$

The differential pressure is then

$$\Delta p = p_1 - p_2 = p_L + h_1 \rho g - p_L - h_2 \rho g.$$

The pressure p_L cancels out and the following is found

$$\Delta p = \Delta h \rho g \quad mit \quad \Delta h = h_1 - h_2 .$$

Using the pressure p_L the zero point for the differential pressure measurement can be adjusted.

For a maximum measuring range it is best to position the zero point or mean value $\frac{h_1 + h_2}{2}$ in the middle of the measuring scale $\frac{h_{max}}{2}$

$$\frac{h_1 + h_2}{2} = \frac{h_{max}}{2} = \frac{p_1 - p_L + p_2 - p_L}{2 \rho g} .$$

The pressure of the air cushion is therefore given as

$$p_L = \frac{p_1 + p_2 - h_{max} \rho g}{2} .$$

The pressure is adjusted using the bleed valve, see also section 5.3.2.

5.2.2 Absolute pressure calculation

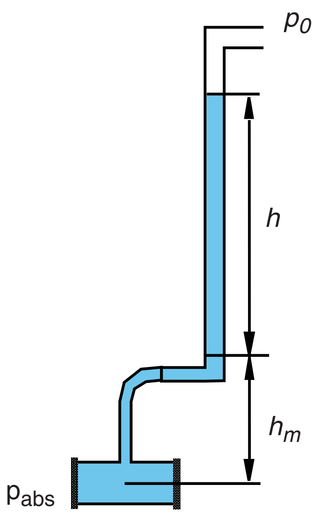


Fig. 5.3 Absolute pressure measurement

To calculate the absolute pressure, the bleed valve is opened and the excess pressure is measured. The pressure p_L corresponds to the atmospheric air pressure p_0.

Here it is also necessary to take into account the height h_m between the measuring point and the zero point on the manometer

$$p_{abs} = p_0 + (h + h_m)\rho g\ .$$

5.3 Manometer connection and operation

– Connect pipe section to feeding and return hose.
– Open return valve.
– Connect manometer to the pipe section to be measured using connecting hoses
– Switch on pump

5.3.1 Bleeding

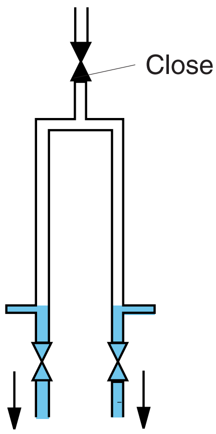


Fig. 5.4 Bleeding step 1

– Close top bleed valve
– Open both bottom drain valves
– Slowly open the reducing valve in the inlet of the pipe section to be measured

Pipe section and connecting hoses are bled by the powerful flow of water.

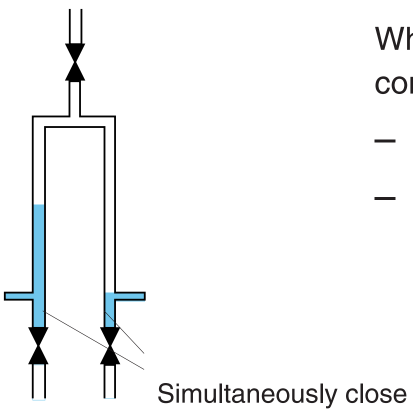


Fig. 5.5 Bleeding step 2

When no more air bubbles are visible in the connecting hoses:

– Close return valve
– Slowly close both bottom drain valves **simultaneously**. Ensure that both columns of water rise evenly and that there is no overflow between the level tubes.

5.3.2 Adjusting the zero point

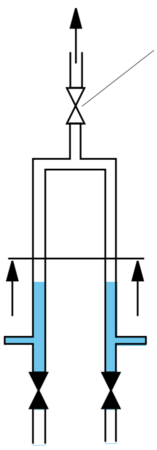


Fig. 5.4 Setting zero point

To ensure the largest possible measuring range, the zero point for the manometer should be in the middle of the scale.

– Close pipe section drain, flow rate is equal to zero.
– Level in the two measuring tubes is the same
– Carefully adjust level to the middle of the scale using the bleed valve.

WARNING! Level can only be adjusted upwards using the bleed valve. If the level is too high, the pipe network must be drained. It is then necessary to bleed the pipe section again before a lower zero point can be set.

5.3.3 Performance of the measurement

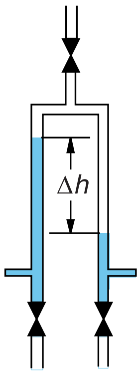


Fig. 5.5 Perform measurement

Set required flow rate using inlet valve. During this process the return valve is fully open. Check this on the flow meter digital display.

Read differential pressure as height difference between the two columns of water.

In case of fluctuating display, estimate mean value. In the case of differential pressure measurements, the key issue is not absolute precision, but reproducible readings.

WARNING! At a large flow rate the differential pressure can increase so much that the water overflows through the top connecting pipe into the measuring tube connected to the lower pressure. If necessary, reset the zero point (see 5.3.2) or use electronic pressure sensors with a greater measuring range.

The differential pressure measurement is always performed with the bleed valve closed.

5.3.4 Ending the measurement

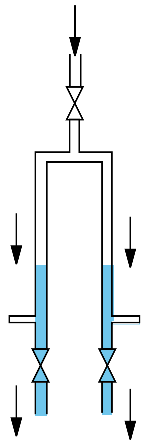


Fig. 5.6 Finish measurement

- Following the conclusion of the measurement, close the return valve
- Switch off pump
- Fully open reducing valve
- Open bleed valve and both drain valves.

Manometer empties and the pipe section is depressurised.

The connecting hoses can now be disconnected and changed.

WARNING!Close unused measuring glands with filler plugs.

5.4 Six tube manometer

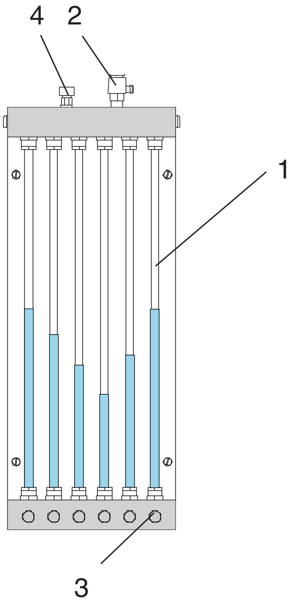


Fig. 5.7 Six tube manometer

The six tube manometer comprises six glass level tubes (1) with a mm scale behind them.

– The measuring range is 390 mm WG.
– All level tubes are connected together at the top and have a common bleed valve (2). The measuring connections (3) are at the bottom.
– The differential pressure is measured with the bleed valve (2 & 4) closed and the excess pressure with the bleed valve (4) open.

The function, connection and operation are identical to the manometer described in 5.2 & 5.3.

5.5 Electronic pressure measurement

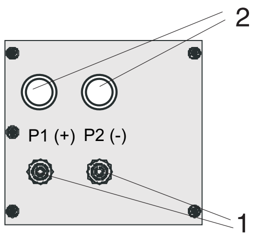


Fig. 5.8 Differential pressure measuring unit

The differential pressure unit has 2 connections, P1 and P2 (1), between which differential pressure up to a maximum of 200 mbar can be measured. The higher pressure must be at P1 and the lower pressure at P2. The valves (2) are used for bleeding.

The excess pressure measuring unit has 6 connections (3) (P3 - P8) for excess pressure from 0 - 600 mbar. The valves (4) are used for bleeding the measuring lines.

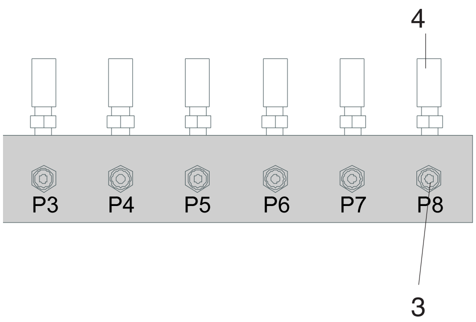


Fig. 5.9 Excess pressure measuring unit

The procedure for bleeding the electronic pressure measuring units is as follows:

- Close all bleed valves
- Connect measuring lines to required connections and the pipe section to be measured.
- Open feeding valve and return valve
- Switch on pump

A powerful jet of water flows through the pipe section and measuring lines.

- Briefly open the bleed valves for the connections used until no more air bubbles are visible in the measuring lines.

WARNING!Never open the bleed valves for unused connections as otherwise water can escape from these connections.

6 Experiments

In this section some experiments are described as examples of the experiments that can be performed with this unit. The range of experiments makes no claim of completeness, but it is intended to serve as a stimulus for your own experiments.

The experimental descriptions are divided into a **section on basic principles** containing the most important calculation formulae, the actual **experimental method** with recording of the measured values and a **comparison between the calculation and the experiment**.

The measured results listed should not be viewed as reference or calibration values for all conditions. Depending of the individual components used and skill, smaller or larger variations can occur.

6.1 Pipe flow with friction

6.1.1 Basic principles

In these experiments, the **pressure loss** p_V or the **head loss** h_V for a flow subject to friction will be determined experimentally.

With **turbulent pipe flow**, where the flow is considered steady at Reynolds' numbers of $Re > 2320$, pressure loss is proportional to the

- length l of the pipe
- Coefficient of pipe friction λ
- Density ρ of flowing medium
- Square of the flow speed v.

In addition, the pressure loss increases as the pipe diameter reduces. It is calculated as follows

$$p_v = \frac{\lambda \cdot l}{2 \cdot d} \rho \cdot v^2$$

The associated head loss h_v is calculated as follows

$$h_v = \frac{\lambda \cdot l}{d} \frac{v^2}{2 \cdot g}$$

In the case of turbulent pipe flow ($Re > 2320$), the pipe friction coefficient λ depends on the pipe roughness k and Reynolds number Re. The pipe roughness k defines the height of the unevenness of the wall in mm. The roughness of the experimental pipes is listed in a table in the appendix. The relationship between Re, λ and k is shown in the diagram based on **Colebrook and Nikuradse**. Here, the wall roughness k is related to the pipe diameter d.

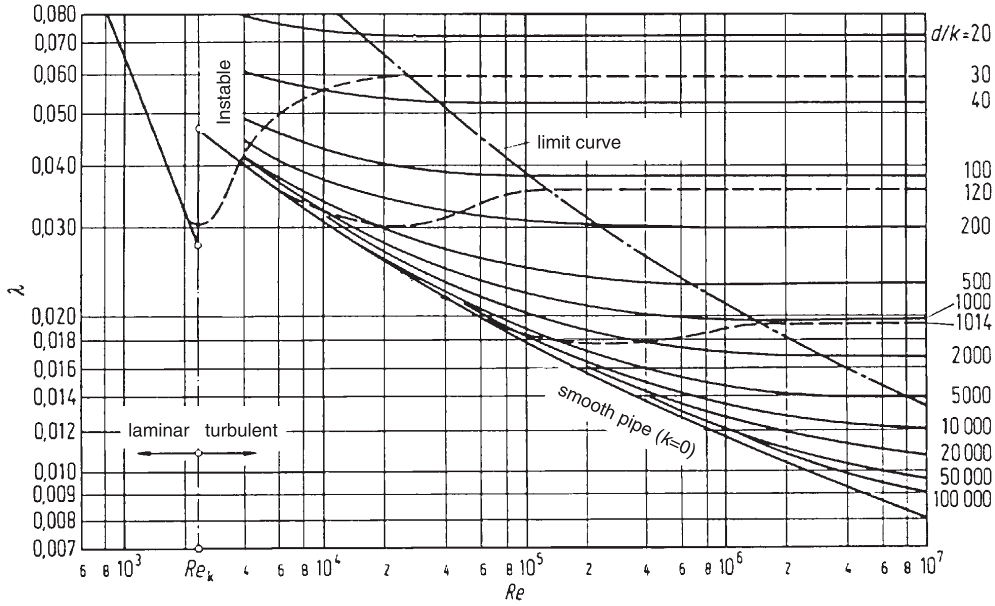


Fig. 6.1 Pipe friction coefficient corresponding to Colebrook and Nikuradse (taken from "Dubbel: Taschenbuch für den Maschinenbau") [Engineering Handbook]

The **Reynolds' number Re** is calculated from the pipe diameter *d*, flow speed *v* and kinematic viscosity ν

$$\mathrm{Re} = \frac{v\,d}{\nu} \ .$$

The kinematic viscosity for water can be taken from table 7.1 as a function of the temperature.

The **flow speed *v*** is calculated from the volumetric flow $\dot{V}$ and the pipe cross-section

$$v = \frac{4\,\dot{V}}{\pi\,d^2} \ .$$

For **hydraulically smooth pipes (*Re* < 65 *d/k*)** and a Reynolds' number in the range of $2320 < Re < 10^5$ the pipe friction coefficient is calculated using the **Blasius** formula

$$\lambda = \frac{0.3164}{\sqrt[4]{\mathrm{Re}}} \ .$$

For **pipes in the transition range to rough pipes (65 *d/k* < *Re* < 1300 *d/k***, the range below the limit curve in the diagram) the pipe friction coefficient is calculated according to **Colebrook**

$$\lambda = \left[2 \ lg\left(\frac{2.51}{\mathrm{Re}\sqrt{\lambda}} + \frac{0.27}{d/k}\right)\right]^{-2} \ .$$

It is an implicit formula that has to be iteratively resolved. First of all estimate λ, place it in the formula and calculate an initial approximation.

This approximation is re-used in the equation to calculate a second approximation.

If the estimated value is taken from the Colebrook and Nikuradse diagram, the initial approximation is generally sufficiently accurate and the values only differ after the 3rd decimal place.

6.1.2 Experimental method

In this experiment, pipes made of different materials (PVC, copper and galvanized steel) are compared. The measuring length is 1000 mm.

The pressure gauge is connected and the measurements are carried out as described in section 5.3.

The flow rate $\dot{V}$ is stated in m³/h.

The displays on the two tube manometer or the differential pressure sensor and rotameter are noted.

Measured results:

Pipe section	Volumetric flow $\dot{V}$ in m³/hin	Differential pressure p_v in mbar	Head loss h_v in mm
2 Galvanized steel, 1/2"	1.2	26	255
3 Cu 18 x 1	1.2	19	220
4 PVC 20 x 1.5	1.2	15	160

6.1.3 Comparison with calculation

Here, the measured head losses are compared with values calculated mathematically. For the calculation, the wall roughness of the pipes used must be known.

Wall roughness of experimental pipes		
Material	Surface	Wall roughness k
Copper pipe, Cu	Technically smooth	0.001 mm
PVC pipe	Technically smooth	0.001 mm
Steel pipe, St	galvanized	0.1 mm

In terms of the kinematic viscosity of the water, for a temperature of 30°C, a value of $\nu = 0.801 \cdot 10^{-6}\ \mathrm{m^2/s}$ is read from table 7.1. This data can be used to calculate the head loss.

Calculation of head loss							
Pipe section	Internal diameter *d* in mm	Volumetric flow		Flow speed in m/s	Reynolds' number *Re*	*d/k*	smooth / rough
		$\dot{V}$ in m³/h	$\dot{V}$ in m³/s				
2 St, gal. 1/2"	16	1.2	$33 \cdot 10^{-5}$	1.66	33159	160	glatt
3 Cu 18 x 1	16	1.2	$33 \cdot 10^{-5}$	1.66	33159	16000	glatt
4 PVC 20 x 1.5	17	1.2	$33 \cdot 10^{-5}$	1.47	31199	17000	glatt

Pipe section	λ calculation according to	Coefficient of pipe friction λ	Calculated head loss h_v in m	Measured head loss h_v in m	Variance
2 St, gal. 1/2"	Colebrook	0.0335	0.253	0.255	+ 0.78 %
3 Cu 18 x 1	Blasius	0.0234	0.217	0.220	+1.36 %
4 PVC 20 x 1.5	Blasius	0.0238	0.154	0.160	+ 3.75%

Taking into account the reading accuracy of $\pm$ 1mm column of water, the concordance between the calculation and the experiment can be rated as good.

6.2 Coefficients of resistance for special pipe components

6.3 Basic principles

Special pipe components and fittings such as pipe bends or elbows, pipe branches, changes in cross-section or also valves and flaps produce additional pressure losses apart from the wall friction losses.

For changes in cross-section and the associated changes in speed, the total pressure loss must take account of the component from Bernoulli's pressure loss (dynamic pressure). The **Bernoulli equation** with loss term is

$$\frac{\rho\, v_1^2}{2} + p_1 + \rho\, g\, z_1 = \frac{\rho\, v_2^2}{2} + p_2 + \rho\, g\, z_2 + \Delta p_v \ .$$

Assuming that the heights z_1 and z_2 are equal, this gives the measurable **total pressure loss**

$$\Delta p_{ges} = p_1 - p_2 = \frac{\rho}{2}(v_2^2 - v_1^2) + \Delta p_v \ .$$

Correspondingly, the **head loss** is then

$$h_{vges} = \frac{1}{2\,g}(v_2^2 - v_1^2) + h_v \ .$$

Unlike the wall friction losses investigated in the previous section, apart from a few special cases the additional flow resistance cannot be calculated exactly.

For the various elements, the literature specifies empirically obtained coefficients of resistance ζ. They can be used to easily calculate the additional pressure losses.

$$p_{vz} = \zeta\, \rho\, \frac{v^2}{2}$$

or for the head loss

$$h_{vz} = \zeta \frac{v^2}{2g}.$$

This means that for the total head loss, we can state that

$$h_{vges} = \frac{1}{2g}(v_2^2 - v_1^2) + \frac{\lambda_1 l_1}{2g}\frac{v_1^2}{d_1} + \frac{\lambda_2 l_2}{2g}\frac{v_2^2}{d_2} + \zeta\frac{v_2^2}{2g}$$

The pipe friction resistance must be determined separately for the sections before and after the change of cross-section. By contrast, the coefficient of resistance is only related to the speed v_2 after the change of cross-section.

If the speeds are equal, there is no dynamic pressure component and a combined pipe friction component is used.

The measured total head loss and the known pipe friction can be used to determine the coefficient of resistance ζ

$$\zeta = \frac{2\,h_{vges}\,g}{v_2^2} - \left[1 - \left(\frac{d_2}{d_1}\right)^4\right] - \left[\lambda_1 \frac{l_1}{d_1}\left(\frac{d_2}{d_1}\right)^4 + \lambda_2 \frac{l_2}{d_2}\right].$$

With no change of cross-section ($d_1/d_2 = 1$), the expression is simplified

$$\zeta = \frac{2\,h_{vges}\,g}{v^2} - \lambda\frac{l}{d}.$$

6.3.1 Pipe elbow

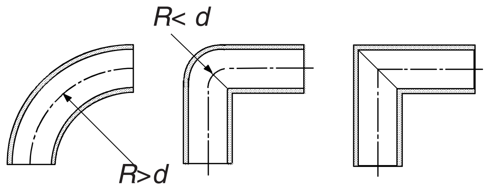


Fig. 6.2 Various pipe elbows

For pipe elbows, the coefficient of resistance ζ depends on the angle of deviation of the flow and the ratio of the elbow radius to the pipe diameter. In addition, the coefficient of resistance is influenced by the shape of the elbow. For this special case of a pipe elbow with 90° deviation, the following diagram is applicable for smooth pipes.

For pipe angles, i.e. elbow radius less than the pipe diameter ($R/d<1$) the coefficients of resistance for knee pieces are approximately applicable.

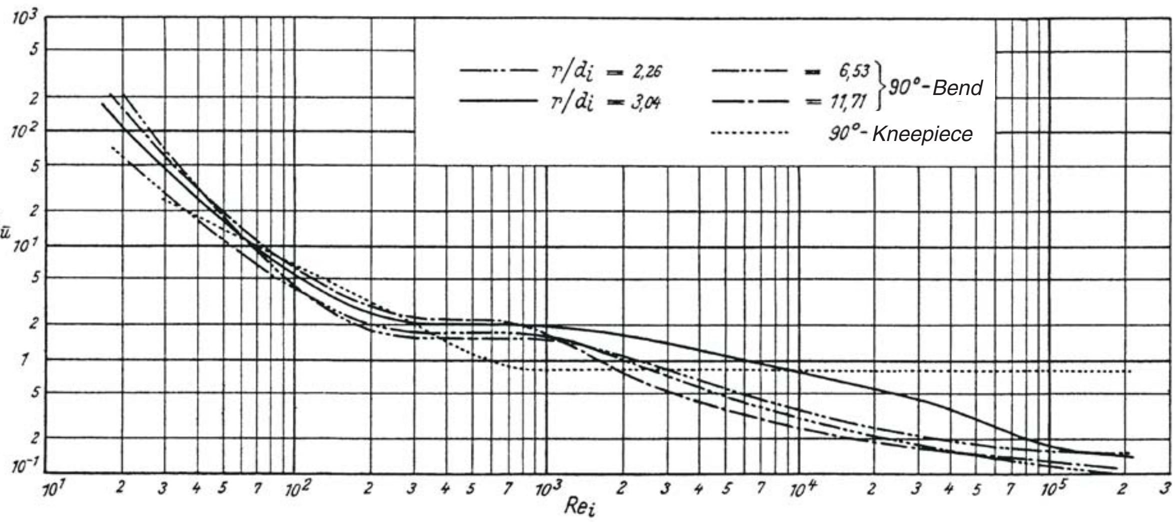


Fig. 6.3 Coefficients of resistance of smooth 90° elbows (VDI Wärmeatlas 10. Aufl. 2006)

For strung-together 90° pipe elbows (offset elbows), as in the case of this trainer, the total resistance value must be calculated using the following formula:

$$\zeta = 2 \cdot 0.7 \cdot \zeta_{90°} \qquad \text{(VDI Wärmeatlas)}$$

6.3.2 Experimental method

Connect double tube manometer to pipe angle measuring glands (pipe section 8) and perform measurement as described in section 5.3. Note the displays on the double tube manometer or on the differential pressure sensor and flow meter.

Repeat the measurement with the pipe bend (pipe section 8).

Measured results:

Pipe elbow	Volumetric flow $\dot{V}$ in m^3/h	Differential pressure Δp_{vges} in mbar	Head loss h_{vges} in mm
2 x Angle 90° PVC 20 x 1.5	1.2	16	163
2 x Bend 90° PVC 20 x 1.5	1.2	9	92

6.3.3 Calculation of coefficients of resistance

The measured values will be used to determine the coefficients of resistance for the pipe angle and bend. As no change of cross-section occurs in this case, the simplified formula for ζ can be used for the calculation

$$\zeta = \frac{2\, h_{vges}\, g}{v^2} - \lambda \frac{l}{d}.$$

For *l*, the pipe length between the measuring connections related to the pipe centre line is used.

In terms of the kinematic viscosity of the water, for a temperature of 12°C, a value of $\nu = 1.227 \cdot 10^{-6}\ m^2 / s$ is read from table 7.1.

Calculation of coefficients of resistance ζ for pipe angle and bend							
Pipe section	Internal diameter d in mm	Length l in mm	Volumetric flow $\dot{V}$ in m^3/h	Volumetric flow $\dot{V}$ in m^3/s	Flow speed v in m/s	Reynolds' number Re	d/k
8 Angle	17	320	1.2	$33 \cdot 10^{-5}$	1.45	20090	17000
8 Bend	17	320	1.2	$33 \cdot 10^{-5}$	1.45	20090	17000

Pipe section	λ calculation according to	Coefficient of pipe friction λ	Measured head loss h_{vges} in m	Coefficient of resistance ζ	Coefficient of resistance $\zeta_{90°}$
8 Angle	Blasius	0.0266	0.163	1.01	0,72
8 Bend	Blasius	0.0266	0.092	0.35	0,25

The coefficient of resistance for one angle corresponds almost with the value read from the diagram (fig. 6.3) for pipe knee piece ($\zeta = 0.78$).

The coefficient of resistance for the bend corresponds with the value read from the diagram (fig. 6.3) of $\zeta = 0.25$ (for $r/d_i = 2.26$ - the ratio is actually at $R/d = 2.35$).

6.3.4 Changes of cross-section

The changes in cross-section available on the experimental unit take the form of continuous expansion or contraction. For a continuous change of cross-section, the coefficients of resistance can be taken from special diagrams (section 7.3). For a discontinuous change in cross-section, the coefficient of resistance can be derived from Bernoulli's equation and the principle of linear momentum.

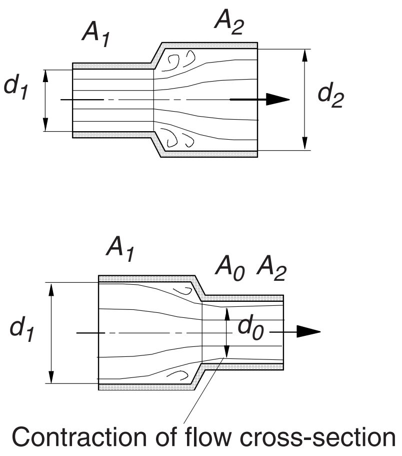


Fig. 6.4 Change of cross-section

For **expansion**

$$\zeta = \left(\frac{A_2}{A_1} - 1\right)^2 = \left(\frac{d_2^{\ 2}}{d_1^{\ 2}} - 1\right)^2 .$$

Accordingly, for **contraction**

$$\zeta = \left(\frac{A_2}{A_0} - 1\right)^2 = \left(\frac{d_2^{\ 2}}{d_0^{\ 2}} - 1\right)^2 .$$

Here, A_0 and d_0 respectively represent the constricted cross-section. As this is normally unknown, the coefficient of resistance for contraction is taken from the following diagram.

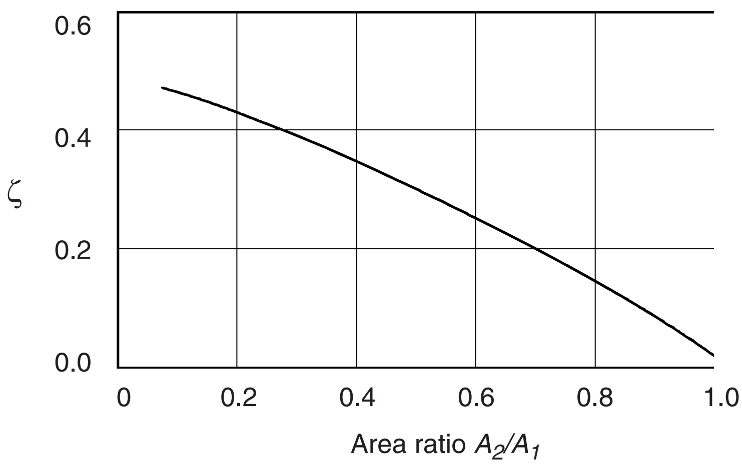


Fig. 6.5 Coefficient of resistance for discontinuous contraction

6.3.5 Experimental method

Connect two tube manometer or differential pressure sensor (P2/1) to continuous expansion of cross-section measuring glands (pipe section 6) and perform measurement as described in section 5.3. Note the displays on the two tube manometer and rotameter. Ensure that the signs are correctly measured.

Repeat the measurement with continuous contraction of cross-section (pipe section 5).

Measured results Pipe section 6: Expansion of cross-section 20 - 32, continuous, d_1=17 mm, d_2=28.6 mm, l=145 mm	
Volumetric flow $\dot{V}$ in m³/h	Head loss h_{vges} in mm
0.7	0
0.9	0
10.8	0
1.2	0
1.8	-15

Measured results Pipe section 5: Contraction of cross-section 20 - 16, continuous, d_1=17 mm, d_2=14.6 mm, l=145 mm	
Volumetric flow $\dot{V}$ in m³/h	Head loss h_{vges} in mm
0.7	+200
0.9	+300
10.8	+415
1.2	+545
1.3	+570

It is interesting that for expansion there is no pressure loss; in fact a pressure gain occurs. The pressure increase caused by the loss of speed outweighs the pressure drop caused by pipe friction, at volume stream of 30 l/min.

6.4 Coefficient of resistance for pipe fittings

The experimental unit has a pipe section, in which various fittings can be installed. In this section, the coefficient of resistance for

- Ball cock
- Slanted seat valve
- Membrane valve
- Dirt trap
- Non-return valve

is determined by measuring the pressure drop.

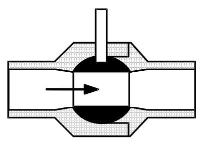


Fig. 6.8 Ball cock

When open, the **ball cock** has a totally smooth and free passage cross-section.

It can therefore be expected to have the lowest pressure losses. Coefficients of resistance falling as low as $\zeta_R = 0.03$ can be reached.

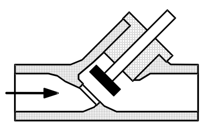


Fig. 6.6 Slanted seat valve

Due to its jagged passage cross-section, the slanted seat valve has a significantly higher coefficient of resistance in the range of $\zeta_R = 1.5 - 2.0$. However, it is still significantly more favourable in terms of the flow than a standard DIN screw-down stop globe valve, in which the flow has to be diverted twice by 90°. Here, a coefficient of resistance of around $\zeta_R = 3.0$ can be expected.

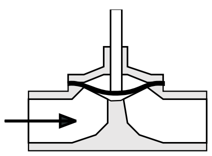


Fig. 6.7 Membrane valve

For the **membrane valve** even high coefficients of resistance ($\zeta_R = 5 - 8.5$) can be expected.

The resistance value for the **dirt trap** depends on the filter insert. The smaller the passage cross-section of the holes, the greater the coefficient of resistance.

Non-return valves are given coefficients of resistance of $\zeta_R = 3.5 - 5.0$ in the literature.

6.4.1 Experimental method

Connect two tube manometer or differential pressure sensor to the measuring glands for the relevant fitting (pipe section 7) and perform measurement as described in section 5.3. Note displays on two tube manometer or sensors and rotameter in a table.

Fitting	Volumetric flow $\dot{V}$ in m^3/h	Differential pressure Δp_{vges} in mbar	Head loss h_{vges} in mm
Ball cock	0.4	0.8	8
Membrane valve	0.4	9	88
Slanted seat valve	0.4	2.8	27
Dirt trap	0.4	50	491
Non-return valve	0.4	5	49

As expected, the ball cock demonstrates a particularly low flow resistance.

The slanted seat valve is not as good as the ball cock but has significantly lower resistance than the membrane valve.

Due to the unfavourable sharp reversal of the direction of flow, the membrane valve demonstrates a particularly high resistance.

However, even higher resistance can be observed on the dirt trap. Nevertheless, this depends greatly on the mesh size of the filter and the level of contamination.

6.4.2 Calculation of coefficients of resistance

The coefficients of resistance for the fittings are now calculated using the following formula

$$\zeta_R = \frac{2\, h_{vges}\, g}{v^2} - \lambda \frac{l}{d}\,.$$

The distance between the measuring connections is used as the length l.

Calculation of coefficients of resistance ζ for fittings

Fitting	Internal diameter d in mm	Length l in mm	Volumetric flow		Flow speed v in m/s	Reynolds' number *Re*	*d/k*
			$\dot{V}$ in m^3/h	$\dot{V}$ in m^3/s			
Ball cock	17	160	0,4	11.6 · 10-5	0.51	7066	17000
Membrane valve	17	160	0,4	11.6 · 10-5	0.51	7066	17000
Slanted seat valve	17	160	0,4	11.6 · 10-5	0.51	7066	17000
Dirt trap	17	160	0,4	11.6 · 10-5	0.51	7066	17000
Non-return valve	17	160	0,4	11.6 · 10-5	0.51	7066	17000

Fitting	λ calculation according to	Coefficient of pipe friction λ	Measured head loss h_{vges} in m	Coefficient of resistance ζ
Ball cock	Blasius	0.035	0.008	0.27
Membrane valve	Blasius	0.035	0.088	6.31
Slanted seat valve	Blasius	0.035	0.027	1.71
Dirt trap	Blasius	0.035	0.491	36.71
Non-return valve	Blasius	0.035	0.049	3.37

The coefficients of resistance given above could be confirmed in the experiment. The coefficient of resistance for the dirt trap depends on the filter insert and the level of contamination.

6.5 Opening characteristics of shut-off devices

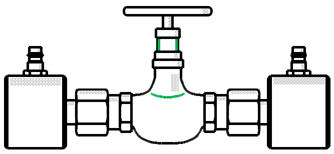


Fig. 6.9 Shut-off device

In this experiment the restricting behaviour of the shut-off devices is demonstrated using the example of the membrane valve.

If shut-off devices are used to set particular volumetric flows in pipe systems, at low opening levels and volumetric flows, considerable attention needs to be paid to good dosing capabilities.

The optimum is a progressive characteristic curve where the opening level rises slowly at first then increasingly quickly. Adjustment of the shut-off device by a particular absolute amount results in a corresponding percentage change in the volumetric flow.

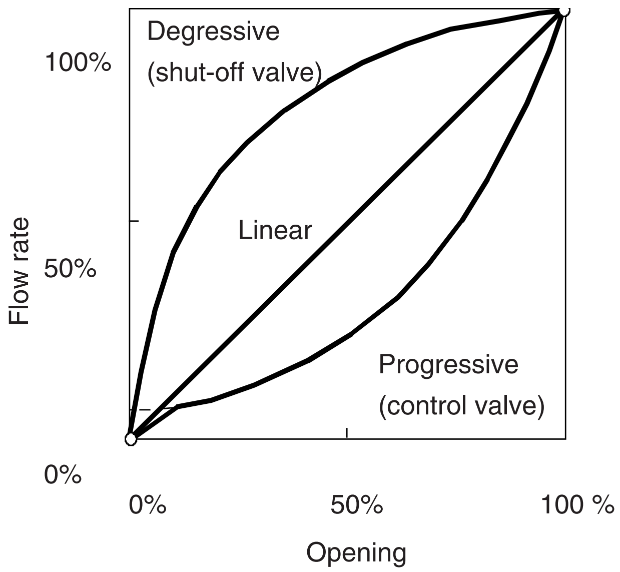


Fig. 6.10 Opening characteristics of valves

For example:

If a valve with a maximum opening of 10 revolutions is opened from 1 to 2 revolutions, i.e. by 10% absolute, and the volumetric flow will show a relative increase of e.g. 30%, e.g. from 1 to 1.3 l/min.

This so-called “equal percentage” characteristic curve is designated as progressive in the adjacent diagram.

Plotted next to it are a linear and a degressive characteristic curve, as occur on typical shut-off devices.

6.5.1 Experimental method

The membrane valve is screwed into pipe section 7 and closed as far as it will go.

Open the valve by 1/4 revolution at a time and note the volumetric flow.

Measured results:

Revolutions	Volumetric flow $\dot{V}$ in m^3/h
0	0
1/4	0
1/2	0.524
3/4	0.752
1	0.953
1-1/4	1.039
1-1/2	1.090
1-3/4	1.102
2	1.113
2-1/4	1.132
2-1/2	1.133
2-3/4	1.170
3	1.181

6.5.2 Evaluation of the experiment

The measured values recorded can be plotted graphically against the opening of the membrane valve.

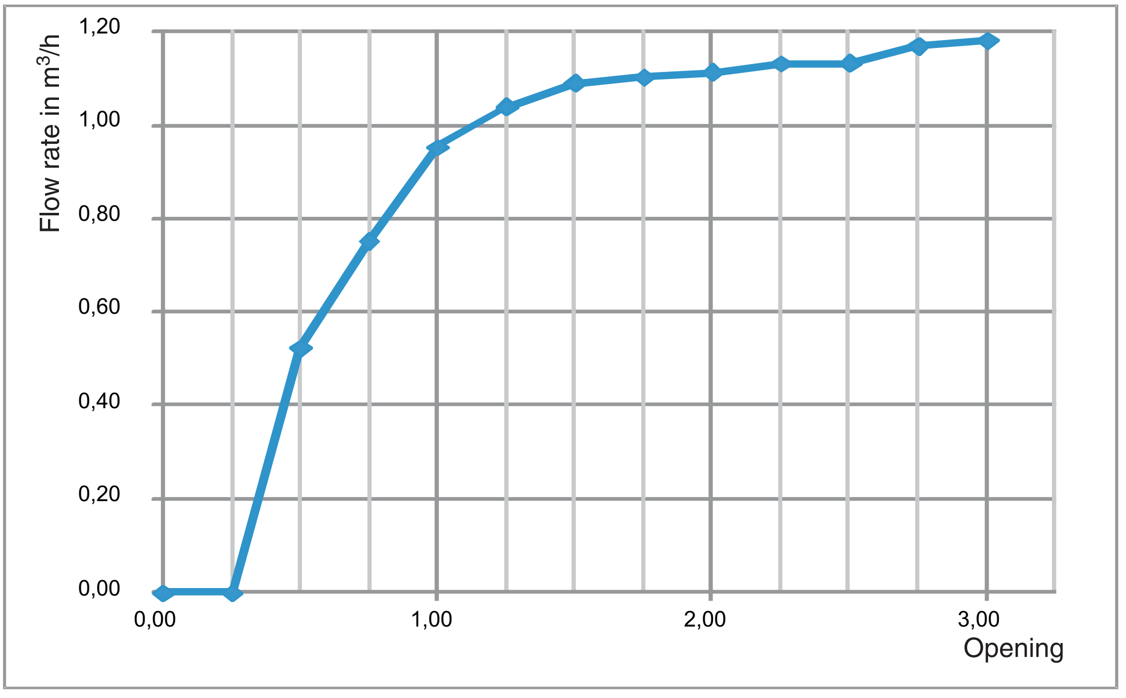


Fig. 6.11 Opening characteristics of valves

The valve opens quickly and is thus a typical shut-off device. The membrane valve is equally unsuitable for restricting a volumetric flow as the slanted seat valve. By contrast, the ball cock is much better suited as a shut-off device. However, none of the shut-off devices included with the experimental unit have a purely progressive characteristic curve or the associated good restricting properties.

6.6 Pitot tube

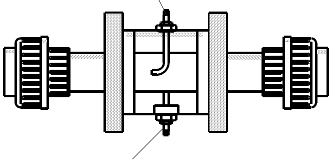


Fig. 6.12 Pitot tube

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}.

$$p_{dyn} = p_{ges} - p_{stat}$$

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

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

ρ: Specific density of water

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

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

The pressure difference can thus be used to determine the volumetric flow for a given flow cross-section.

6.6.1 Experimental method

The Pitot tube measuring object is screwed into pipe section 7. The measuring glands are connected to the two tube manometer or the differential pressure sensor. It must be ensured that the static pressure is always lower than the total pressure. The measurements are performed in accordance with the instructions in section 5.3. The volumetric flow is restricted with the slanted seat valve in the test section inlet.

This results in the following measured values:

Volumetric flow $\dot{V}$ in m^3/h	Dynamic pressure p_{dyn} in mbar	Dynamic height h_{dyn} in mm
1.36	21.5	211
1.30	19.0	186
1.09	12.6	124
0.92	9.2	90
0.76	6.6	65

The temperature of the water is at 20°C, which gives a specific density of water of

$$\rho = 998.2\ \frac{kg}{m^3}.$$

6.6.2 Comparison with calculation

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.

$$A = \frac{(d_1^2 - d_2^2) \cdot \pi}{4}$$

For steady turbulent flow in pipes of circular cross-section the average speed v 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.

$$\frac{v}{v_{max}} \approx 0.84$$

This yields a average flow speed v.

$$v \approx v_{max} \cdot 0.84.$$

This yields a calculated flow speed

$$\dot{V}_{calculated} = A \cdot v.$$

ρ in kg/m³	p_{dyn} in mbar	$\dot{V}$ measured in m³/h	$\dot{V}$ calculated in m³/h
998.2	21.5	1.36	1.38
998.2	19.0	1.30	1.30
998.2	12.6	1.09	1.06
998.2	9.2	0.92	0.90
998.2	6.6	0.76	0.77

The consistency can be described as good.

6.7 Volumetric flow measurement with nozzle/orifice

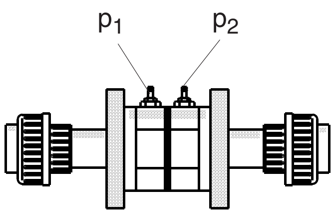


Fig. 6.13 Nozzle/orifice

The volumetric flow cannot be determined from the dynamic pressure alone. In technical fluid mechanics, orifices or nozzles are frequently used to determine the volumetric flow. Using a constant, the volumetric flow to DIN 1952 and EN ISO 5167 can be calculated as follows:

$$\dot{V} = \alpha \cdot \varepsilon \cdot A_d \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

- α: Flow coefficient
- ε: Expansion coefficient
- A_d: Orifice cross-section
- Δp: Differential pressure (p_1 - p_2)
- ρ: Specific density

The flow and expansion coefficients for diameters in the range 50 to 500 or 1,000mm are taken from DIN 1952 and EN ISO 5167.

6.7.1 Experimental method

Once either the orifice or nozzle has been fitted in the measuring object, it is installed in pipe section 7.

Caution! Ensure correct direction of flow.

When connecting the hoses to the measuring glands and to the manometers or differential pressure sensor, it must be ensured that the signs are correct. The measurements are performed in accordance with section 5.3. The volumetric flow is adjusted using the reducing valve at the inlet to the pipe section.

The following measured values are obtained:

Measuring object: Nozzle; Water temperature 20°C	
Volumetric flow $\dot{V}$ in m^3/h	Differential pressure Δp in mbar
1.3	28
1.1	20
0.9	13
0.7	9

Measuring object: Orifice plate; Water temperature 20°C	
Volumetric flow $\dot{V}$ in m^3/h	Differential pressure Δp in mbar
1.3	15
1.2	12
1.1	10
0.9	6.5

6.7.2 Comparison with calculation

To calculate the volumetric flow, the relevant aperture cross-section is first determined.

$$A_d = \pi \cdot \frac{d^2}{4}$$

To determine the flow coefficient for both experiments, the aperture ratio m is required.

$$m = \frac{d^2}{D^2}$$

D: Pipe diameter before shut-off device (28.5mm)

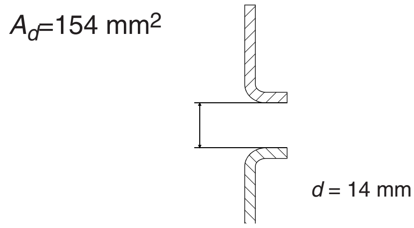


Fig. 6.15 Nozzle cross-section

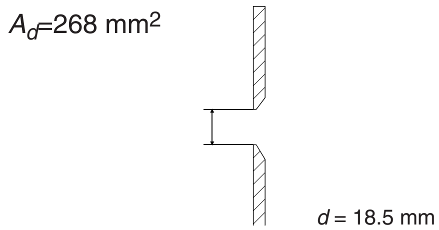


Fig. 6.14 Orifice cross-section

The following figures are calculated as the aperture ratio for the orifice and the nozzle:

$m_{Nozzle} = 0.24$ $m_{Orifice} = 0.42$

This results in flow coefficients in line with DIN 1952: $\alpha = f\ (Re, m)$The following flow coefficients can be used for the calculation:

$\alpha_{Nozzle} = 1.00$ $\alpha_{Orifice} = 0.67$

As water is an incompressible medium, the following applies for the expansion coefficients:

$$\varepsilon_{Nozzle} = \varepsilon_{Orifice} = 1$$

A comparison of the calculated and measured volumetric flows then gives the following results.

Measuring object: Nozzle					
ρ in kg/m^3	α	ε	Δp in mbar	$\dot{V}$ measured in m^3/h	$\dot{V}$ in m^3/h calculated
998.2	1	1	28	1.3	1.31
998.2	1	1	20	1.1	1.11
998.2	1	1	13	0.9	0.89
998.2	1	1	9	0.7	0.74

Measuring object: Orifice plate						
ρ in kg/m^3	α	ε	Δp in mbar	$\dot{V}$ measured in $m^3h/$	$\dot{V}$ in m^3h calculated	Variance in %
998.2	0.67	1	15	1.3	1.12	-14
998.2	0.67	1	12	1.2	1.01	-16
998.2	0.67	1	10	1.1	0.92	-16
998.2	0.67	1	6.5	0.9	0.74	-18

While volumetric flow measurement with the nozzle shows an excellent result, an error of -14% or more occurs in the calculation using the orifice measurement. The difference between the calculation and the measurement is caused by the flow coefficient. The values taken from DIN 1952 are only applicable at diameters of 50 to 1000 mm. As the flow cross-section here is smaller (d=18.5 mm), α must be corrected to approx. 0.8 to obtain a meaningful comparison with the measured values.

6.8 Venturi nozzle

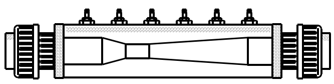


Fig. 6.16 Venturi nozzle

Using the Venturi tube the law on the conservation of energy in fluid mechanics can be demonstrated. The change of cross-section is always associated with a change of speed. Apart from a slight loss due to friction, the total pressure remains constant. Bernoulli's equation with no loss element is

$$\frac{\rho\, v_1^2}{2} + p_1 + \rho\, g\, z_1 = \frac{\rho\, v_2^2}{2} + p_2 + \rho\, g\, z_2$$

Assuming that the heights z_1 and z_2 are equal, this gives

$$p_1 + \frac{v_1^2 \cdot \rho}{2} = p_2 + \frac{v_2^2 \cdot \rho}{2}$$

After rearrangement this yields

$$p_1 - p_2 = (v_2^2 - v_1^2) \cdot \frac{\rho}{2}$$

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

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

6.8.1 Experimental method

For measurements on the Venturi nozzle, either the six tube manometer or connections P3 to P8 on the pressure measuring unit are required. The measuring glands are connected to the measuring equipment using hoses. The measurements are performed in accordance with section 5.3. The following sketch shows the flow cross-sections at the measuring points.

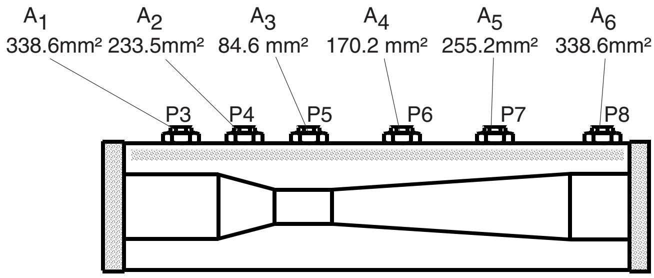


Fig. 6.17 Venturi nozzle with rectangular tube section

A higher pressure will occur at the point of the greatest cross-section.

With a volumetric flow adjusted to $\dot{V}$ von 0.5 m³/h , the following differential pressures are obtained:

Measuring point	Differential pressure in mbar	Height difference in mm
P3 - P4	+ 0	0
P4 - P5	+11	108
P5 - P6	-7	-69
P6 - P7	-2	-20
P7 - P8	-1	-10

6.8.2 Comparison with calculation

The following energy changes can then be determined between the measuring points.

Measuring point n _ n+1	Quadratic change of speed $v_{n+1}^2 - v_n^2$	Pressure difference: $p_n - p_{n+1}$ in mbar (measured)	Pressure difference: $p_n - p_{n+1}$ in mbar (calculated)
3_4	$0.59^2 - 0.41^2$	+ 0	+0.9
4_5	$1.64^2 - 0.59^2$	+11	+11.7
5_6	$0.82^2 - 1.64^2$	-7	-10.1
6_7	$0.54^2 - 0.82^2$	-2	-1.9
7_8	$0.41^2 - 0.54^2$	-1	-0.6

The relatively low variances between the calculation and the measurement are caused by friction losses.

7 Appendix

7.1 Technical data

Overall dimensions of experimental unit

Length	2220 mm
Width	820 mm
Height	1980 mm
Weight	approx. 250 kg
Electrical supply	230 V, 50 Hz
Nominal consumption (power)	0.75 kW

Optional alternatives, see rating plate

Pump

Centrifugal pump

Max. Head	24 m
Max. Capacity	7 m³/h
Water tank, capacity	75 L

Flow rate measurement

Rotameter

Measuring range	0.4 - 2.5 m³/h
Output	0 - 10 kΩ

Pressure measurement

Two tube manometer

Excess and differential pressure measurement

Filling medium	Water
Measuring range (water column)	680 mm

Six tube manometer panel

Excess and differential pressure measurement

Filling medium	Water
Measuring range (water column)	390 mm

Differential pressure transducer	
Measuring range	0 ... 200 mbar
Output	0 ... 10 V
Excess pressure sensor	
Measuring range	0 ... 600 mbar
Max. pressure	1.2 bar
Output	0 ... 10 V
Thermometer	
Range	0...60 °C

Pipe sections

- Straight pipe section, 1/2", St, galvanized, 1000 mm long
- Straight pipe section, 18 x 1, Cu, 1000 mm long
- Straight pipe section, 20 x 1.5, PVC, 1000 mm long
- Continuously constricted pipe section, 20 x 1.5 to 16 x 1.2, PVC
- Continuously expanded pipe section, 20 x 1.5 to 32 x 1.8, PVC
- Measuring section for installation of various measuring objects
- Pipe section with 90° angle and 90° bend, 20 x 1.5, PVC

Measuring objects

- Slanted seat valve	d = 20 mm
- Membrane valve	d = 20 mm
- Ball cock	d = 20 mm
- Non-return valve	d = 20 mm
- Dirt trap	d = 20 mm
- with 4 different filter inserts	
Pressure measurement tube (Pitot tube)	Ø 17 mm
Pitot tube	Ø 3 mm
Measuring orifice	Ø 18.5 mm
Measuring nozzle	Ø 14 mm
Venturi nozzle	Ø 28.4 - 14.0 mm

7.2 Bibliography

Wolfgang Kalide,
"*Einführung in die technische Strömungslehre*"
(Introduction to Technical Fluid Mechanics),
Carl Hanser Verlag,
6th revised edition, Munich, Vienna 1984

7.3 Tables and Diagrams

Kinematic viscosity of water as a function of temperature (based on Kalide: Technische Strömungslehre [Technical Fluid Mechanics])	
Temperature in °C	Kin. viscosity ν in 10^{-6} m^2/s
10	1.297
11	1.261
12	1.227
13	1.194
14	1.163
15	1.134
16	1.106
17	1.079
18	1.055
19	1.028
20	1.004
21	0.980
22	0.957
23	0.935
24	0.914
25	0.894
26	0.875
27	0.856
28	0.837
29	0.812
30	0.801

Tab. 7.1

Wall roughness

Wall roughness of experimental pipes		
Material	Surface	Wall roughness k
Copper pipe, Cu	Technically smooth	0.001 mm
PVC pipe	Technically smooth	0.001 mm
Steel pipe, St	galvanized	0.1 mm

Diagrams

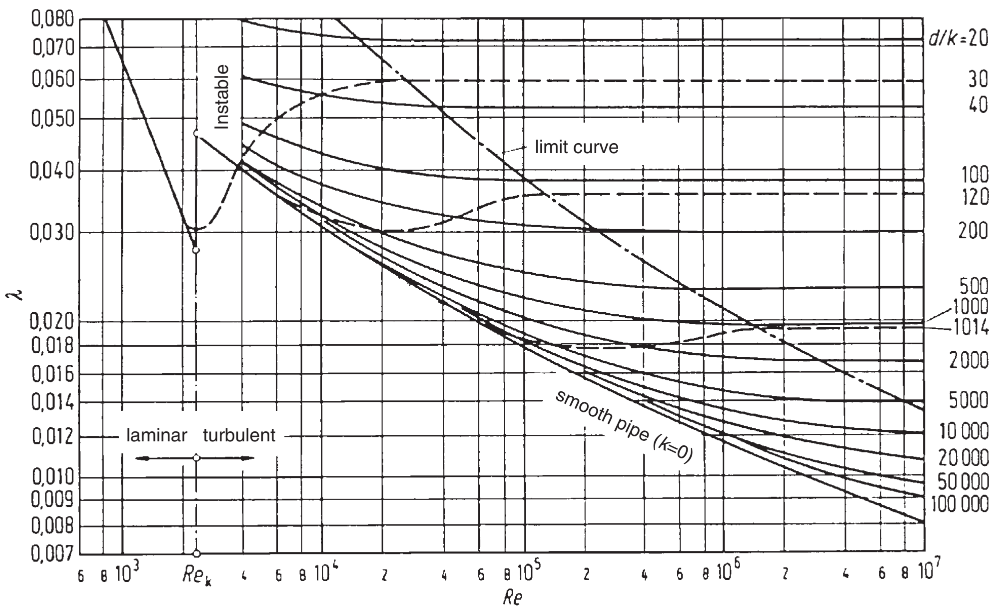


Fig. 7.1 Pipe friction coefficient corresponding to Colebrook and Nikuradse (taken from "Dubbel: Taschenbuch für den Maschinenbau") [Engineering Handbook]

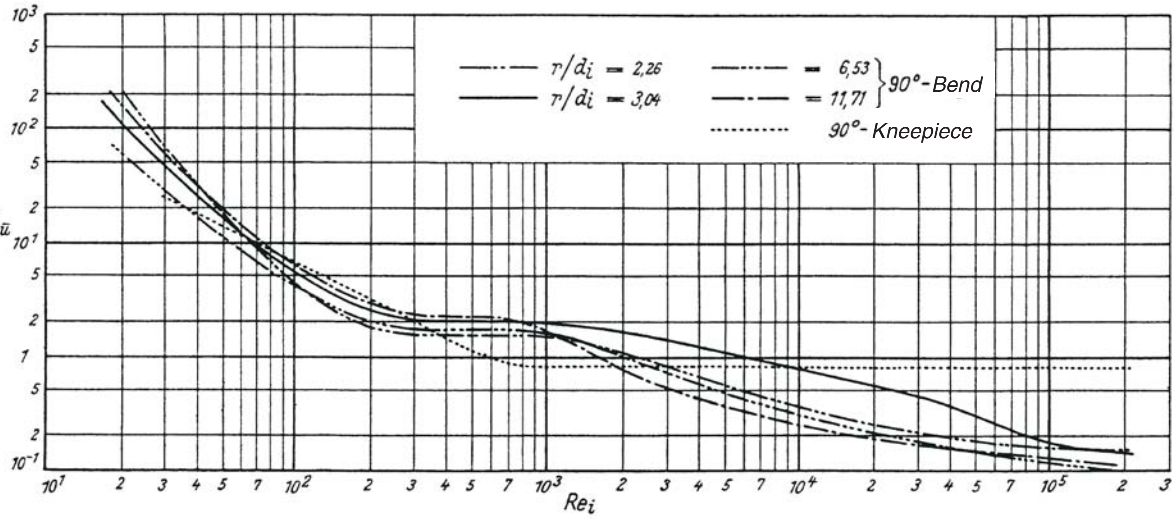


Fig. 7.2 Coefficients of resistance of smooth 90° elbows (from VDI Wärmeatlas 10. Aufl. 2006)

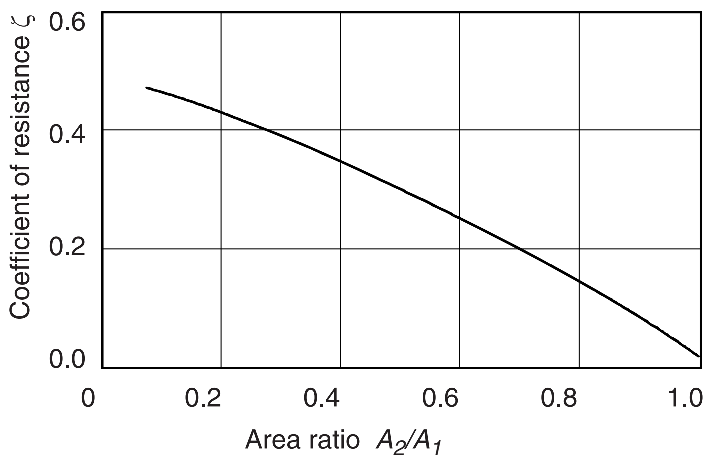


Fig. 7.3 Coefficient of resistance ζ for discontinuous contraction

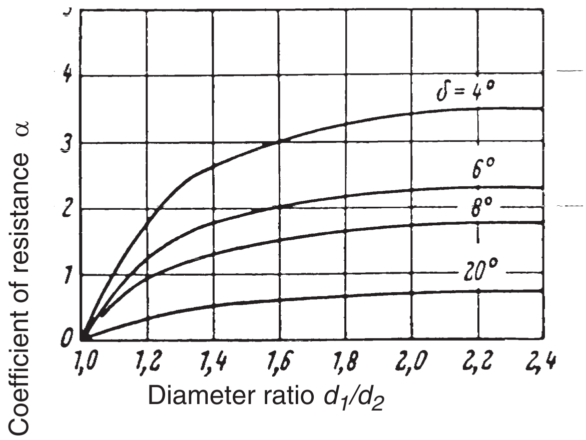


Fig. 7.4 Wall friction factor for continuous contraction(nozzle) as a function of contraction angle δ

$$\zeta = \alpha \frac{\lambda_1 + \lambda_2}{2}$$

(from Kalide: "*Einführung in die technische Strömungslehre*")

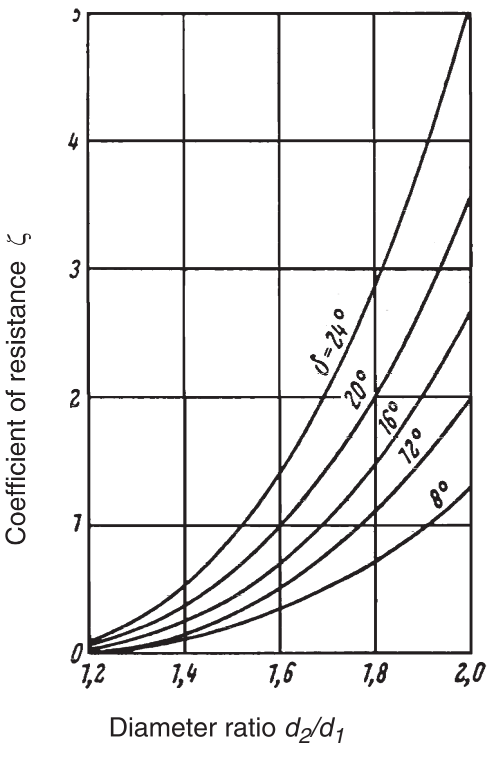


Fig. 7.5 Coefficients of resistance for continuous expansion (diffusor) as a function of contraction angle δ

7.4 Formulae

Pipe friction

Measurement performed by:		Date:	
Pipe section, type	Volumetric flow $\dot{V}$ in l/min	Head loss h_v in mm	Differential pressure p_v in mbar

Calculation of head loss							
Pipe section	Internal diameter d in mm	Volumetric flow		Flow speed in m/s	Reynolds' number Re	d/k	smooth / rough
		$\dot{V}$ in m^3/h	$\dot{V}$ in m^3/s				

Pipe section	λ calculation according to	Coefficient of pipe friction λ	Calculated head loss h_v in m	Measured head loss h_v in m	Variance

Coefficients of resistance

Measurement

Performed by: Date:

Fitting	Volumetric flow $\dot{V}$ in l/min	Head loss h_{vges} in mm	Differential pressure Δp_{vges} in mbar

Calculation of coefficients of resistance ζ for fittings

Fitting	Internal diameter d in mm	Length l in mm	Volumetric flow		Flow speed v in m/s	Reynolds' number Re	d/k
			$\dot{V}$ in m^3/h	$\dot{V}$ in m^3/s			

Fitting	λ calculation according to	Coefficient of pipe friction λ	Measured head loss h_{vges} in m	Coefficient of resistance ζ	Coefficient of resistance $\zeta_{90°}$

Flow rate measurement

Measurement Performed by: Date: Measuring object: Water temperature:	
Volumetric flow $\dot{V}$ in m^3/h	Differential pressure Δp in mbar

Evaluation						
Density ρ in kg/m^3	Flow coefficient α	Expansion coefficient ε	Δp in mbar	$\dot{V}$ in m^3/h measured	$\dot{V}$ in m^3/h calculated	Variance in %

7.5 Index

V

W

Z