3. Fluid Dynamics Blood Circuit

3.1 Medical reference and goal of the experiment

The behaviour of fluid currents is described by the theory of fluid dynamics. It is the foundation for the description of the blood circulation in the human body.

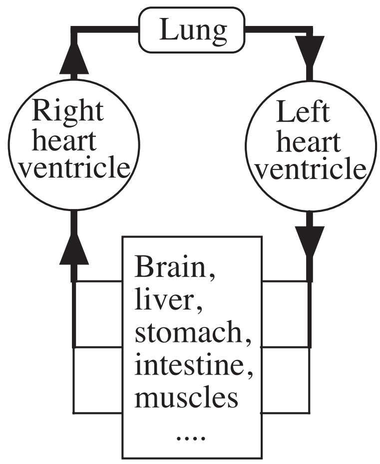


Figure 3.1.1: *Schematic representation of the human blood circuit.*

In the blood circuit (Fig. 3.1.1), blood serves as a drifting medium for the transport of O_2, CO_2 and other substances. The whole human circulation system consists of the smaller pulmonary(lungs), as well as the bigger systemic circulation, they are cascaded one after the other from the moment of birth on. In the pulmonary-circuit, oxygen-deficient blood is being pumped from the right ventricle (heart chamber) through the lungs, where CO_2 is being released and the blood gets enriched with O_2, before it reaches the right atrial. Valve flaps ensure that a directed current is being created and maintained. The vascular system includes arteries, arterioles, capillaries, venules and veins in serial connection. The oxygen supply for the individual organs is provided by a highly branched

parallel arrangement of blood vessels. The elastic venous system and the right atrium form a blood reservoir, from which the blood flows back to the heart.
For this experiment a circular flow model, representing the human blood circuit, has been developed. The heart is being replaced by a single piston pump. The fluid (paraffin oil is being used), flows through a simplistic vascular system, which consists of pipes of various lengths and diameters.
With the help of the model one can study the fundamental function of a circulatory system and the relevance of its individual components. For a periodically working pump in particular, you will study the influence of a so-called air vessel on the pressure and current conditions. In the human circulation system this function is mainly undertaken by the stretchable aorta.
The fundamentals of fluid dynamics, which you acquire through the example of the blood circuit, are also valid in a wide range for the alveolar ventilation, the transportation of breathing gas between the alveoli and the environment. The moving medium in that case is the breathing gas, which flows through the respiratory tract due to pressure differences.
Note: For this experiment it is highly recommended to bring coloured pencils with you.

3.2 Experimental part

3.2.1 Functional principle of the circuit model and air vessel

3.2.1.1 Running without air vessel

First, you should acquaint yourself with the components of the circuit model and their meaning for the functionality of the model.
The components are (Numbers cf. Fig. 3.2.1):

- a pump (9) with 2 valve flaps (8), on which, for periodic operation, a crank handle (11) has to be mounted,
- an air vessel (6), whose functionality is not being used until the next measurement and therefore remains closed for the moment, (turn in the screw on top clockwise)
- various current pipes (1 to 4), which can be locked individually via valves (10),
- a storage vessel (7), into which the fluid from the pipe system flowing, before it is being sucked out by the pump afterwards,
- a manometer (5), which indicates the pressure difference Δp in the fluid, i.e. the difference of pressure between the starting and end points of pipes

The functionality of the individual components can be understood best when the device is in slow periodic operation. **The following tasks will be performed together with the assistant on a demonstration model.**

- The manometer has to be connected to the power supply. The scale indicates the pressure difference Δp in hPa (Full-scale deflection: 100 hPa).

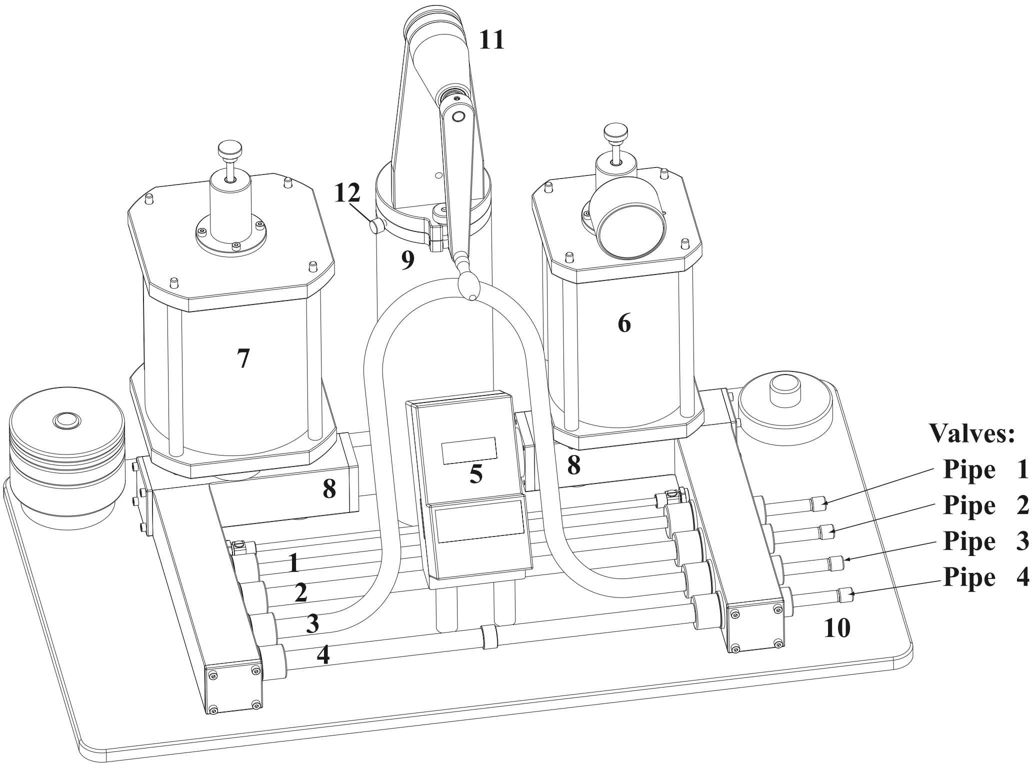


Figure 3.2.1: *Draft of the circuit model with mounted crank handle – the numbered items are being annotated in the text*

- **Open the valves of all fluid pipes!**
- Turn on the manometer.
- Untighten the locking screw (12) of the pump piston, which is located at the cover of the piston casing (pump).
- Take the white teflon sleeve of the piston rod and mount the crank assembly.
- Now, operate the crank **slowly and uniformly and without excessive exertion of force with approximately one cycle per second**.

◇ Watch closely the pressure indication, the function of the valve flaps, the fluid level in the storage vessel and the direction of the current. Record your observations **qualitatively** (in words) in the following chart. The emission phase of the pump is, the phase, where the pump pumps fluid into the pipe system. The suction phase is the phase, where the fluid is being sucked out of the storage vessel by the pump.

	Suction phase	Emission phase
Pressure difference		
Position of the left valve flap		
Position of the right valve flap		
Fluid level in the storage vessel		
Direction of current in pipes		

◇ What are the requirements, for a flow to occur inside the pipe system? What is the storage vessel necessary for?

◇ Which components ensure the rectification of the current and which are their anatomical correspondents?

Pressure fluctuations in the pipe system without air vessel

◇ Double-check, that all valves are still open and the air vessel (6) is closed (screw on top completely screwed in clockwise - **without exertion of force!**). Now turn the crank with approx. *one turn per second*. Thereby the difference Δp of pressures in front of the pipes and behind them changes periodically. Read out the minimum (Δp_{min}) and maximum (Δp_{max}) value, of the pressure difference during a pumping cycle (units!):

without air vessel:	$\Delta p_{min} \approx$	$\Delta p_{max} \approx$

3.2.1.2 Running with air vessel

◇ Open the air vessel (6), by loosening the screw on top of the air vessel clockwise. Just like before, turn the crank. What qualitative changes do you observe, compared to the setup without the air vessel? While doing so, also observe the behaviour of the fluid inside the air vessel.

◇ From the pressure indication on the air vessel you can read off the pressure of the air over the fluid inside the air vessel. What happens to the air during the suction and emission phase?

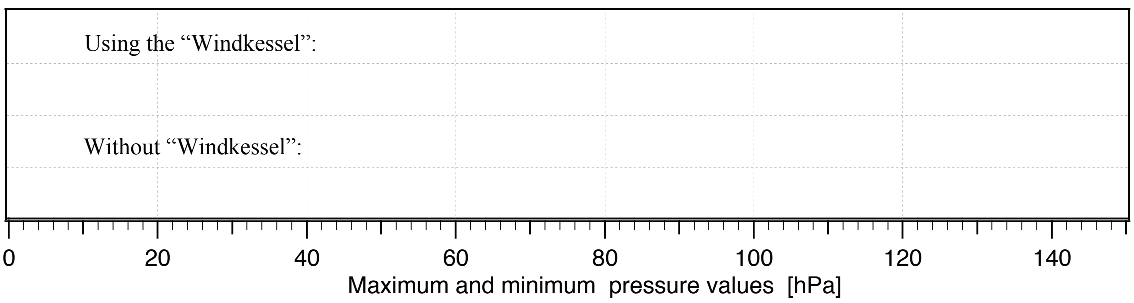
Pressure fluctuations in the pipe system with air vessel

◇ Again, measure the minimum and maximum pressure difference, that occurs during one pumping cycle. (Here it is important, to crank roughly with the frequency as you did for the measurements without the air vessel.)

with air vessel:	$\Delta p_{min} \approx$	$\Delta p_{max} \approx$

Comparison of measurements with and without air vessel

◇ Register the measured pressure differences as crossbars with different colours for the measurements without and with air vessel in the following scale:
(Windkessel means air vessel)



◇ How does the air vessel influences the occurring pressure differences and the behaviour of the currents and why is this of importance for the blood circuit? (How is this functionality implemented in the human body?)

- Release the piston by setting it to the highest position possible, removing the pivot between crank handle and piston and reinstalling the teflon sleeve. This prevents oil from rising above the piston.
- Lock up the air vessel by closing the valve by hand, turning it clockwise.

3.2.2 Flow behaviour of fluids

In this section, further investigation on the correlation of pressure difference and flow behaviour is being undertaken. For the description of the flow behaviour you have to determine the volumetric flow rate I. It specifies the ratio of a volume element ΔV of the fluid that passes a cross section of the pipe and the period of time Δt it takes to do so.[1]:

$$I = \frac{\Delta V}{\Delta t}.$$

- To examine the correlation of pressure difference and volumetric flow rate systematically, running the device in a periodical manner is inappropriate due to the permanent pressure fluctuations. Therefore, you will only work with the piston and weight plates.
- Furthermore, for the time being, the fluid should flow through one pipe at a time only. Therefore, close the pipes 1, 3 and 4 with the valves and open **pipe 2**.

For the determination of the pressure difference $\Delta\ p$, once again the manometer is used:
You now have the possibility to apply a constant pressure on the piston by laying on some weight plates and therefore letting it drop a predefined distance.
Caution: It is forbidden to push down the piston by hand violently or to pull up the piston violently otherwise the apparatus becomes leaky. For the same reasons, weight plates are only allowed to lay on the piston during the measurement and have to be taken away during measurement pauses.

[1] In this experiment we will often use the unit mm instead of the SI-unit m, e.g. the unit of a volume element is mm^3 respectively. Take this into account for further calculations!

◇ For test purposes, put the 0.5 kg–weight plate on the piston and let it sink a few centimetres. What can you observer (notice the manometer)?

This effect can be attributed to the column of liquid in the pump cylinder, which exerts an additional hydrostatic pressure. When the piston descends, the height of the column of the fluid drops and therefore the hydrostatic pressure decreases. To be able to compare the measurements with each other, you will always use the same mean value for the hydrostatic pressure, by always reading off the pressure difference at the 100mm-mark and choosing the way of the piston to be **symmetric around the read off mark** for the time measurement. The specific weight plates and the sinking distances, i.e. their starting- and endpoints, for the different measurements are given.
So for the following measurements you will...

- load the piston with a predefined weight,
- let it sink a predefined distance Δx between starting-point x_1 and endpoint x_2,
- read off the pressure difference Δp from the manometer, when the piston passes the read-off mark at 100 mm,
- measure the time Δt, the piston needs to drop for the **whole sinking distance** from x_1 to x_2 (Caution: Do not stop the time measurement already when the piston passes the 100 mm read off mark!).

The time measurement can be enhanced, if you let the piston a little higher than x_1 go and start the time measurement when passing the starting-point. (For the simultaneous measurement of Δt and Δp team work is vital!)
For the determination of the volumetric flow rate I you proceed as follows:

- When the piston (cross sectional area A) sinks a distance Δx in the time period Δt, it displaces a volume of fluid $\Delta V = A \cdot \Delta x$ from the pump cylinder. So during that time period the same volume (with closed air vessel) has to run through the opened pipe. With the sinking distance of the piston and the corresponding time period we can calculate the volumetric flow rate I :

$$I = \frac{\Delta V}{\Delta t} = \frac{A \cdot \Delta x}{\Delta t}$$

  The cross sectional area of the piston is: $A = 5025\ \text{mm}^2$.

3.2.2.1 Relation of pressure difference and volumetric flow rate

◇ With the measurement for **pipe 2** you can determine how the volumetric flow rate is related to the pressure difference over this pipe. Perform the measurements, as described above, for the given weights and calculate the volumetric flow rate respectively.

Measurement on pipe 2			
m [kg]	2.0	1.5	1.0
x_1 [mm]	60	70	80
x_2 [mm]	140	130	120
Δx [mm]	80	60	40
Δp [hPa]			
Δt [s]			
I [10^4 mm^3 s^{-1}]			

- Now **unload** the piston, pull it a little bit upwards and lock it with a clamp.

◇ Fill in the values for Δp and I into the table on page 14 and plot the volumetric flow rate against the pressure difference in the diagram on page 15.

◇ What kind of relation do you expect between those two quantities, based the information you can extract from the diagram?

◇ Now, determine the slope of the straight line **with the help of a slope triangle**.
The slope indicates the conductance G of the resistance pipe, through which the fluid streams.
From G, calculate the flow resistance R as the inverse of G (pay attention to the units!):

Pipe 2

$G_2 =$

$R_2 =$

3.2.2.2 Dependence of the flow resistance from the length of the pipe

With this measurement you will examine the relation between the length of the pipe and its flow resistance.

◇ To do this you perform the same measurement on **pipe 3**, which is approximately double the length of pipe 2 (while having the same diameter). For this measurement, you have to close the valves for the pipes 1, 2 and 4.

Measurement on pipe 3			
m [kg]	2.0	1.5	1.0
x_1 [mm]	68	76	84
x_2 [mm]	132	124	116
Δx [mm]	64	48	32
Δp [hPa]			
Δt [s]			
I [10^4 mm^3 s^{-1}]			

- Unload and lock the piston again.

◇ Again, fill in the values for Δp and I into the table on page 14 and plot the volumetric flow rate against the pressure difference in another colour in the diagram on page 15. Determine the conductance and the flow resistance of pipe 3.

Pipe 3

$G_3 =$

$R_3 =$

◇ Compare your results to those from pipe 2, which has the same diameter but is only about half as long as pipe 3. What kind of relation (proportional, exponential, ...) do you expect between the flow resistance and the length of the pipe?

◇ One could as well look at pipe 3 as two serially-connected pipe 2's. What kind of law do you expect due to the flow resistance of pipe 2 and pipe 3 for serially connected flow resistances?

3.2.2.3 Dependence of the flow resistance from the diameter of the pipe

The goal of the following measurement is to determine how the flow resistance of a pipe depends on the diameter of the pipe. For this you perform the same measurement as before with **pipe 1**, which has roughly half the diameter of pipe 2 (but same length). For this measurement you have to close the valves of the pipes 2, 3 and 4.

Measurements with pipe 1			
m [kg]	3.0	2.0	1.5
x_1 [mm]	86	90	92
x_2 [mm]	114	110	108
Δx [mm]	28	20	16
Δp [hPa]			
Δt [s]			
I [10^4 mm^3 s^{-1}]			

- Unload and lock the piston.

◇ Again, plot the the volumetric flow ratio against de pressure difference on page 15 (with an other colour, so we can easily compare the different slopes) and fill in your data in the table on page 14. Determine the conductance and the flow resistance for pipe 1.

Pipe 1

$G_1 =$

$R_1 =$

◇ Compare your results with those of pipe 2, the one with a radius about twice as big while having the same length like pipe 1. By which factor do the flow resistances differ from each other? Does this result indicates a proportionality[2] between the current conduction value (or the flow resistance) and the diameter or cross sectional area? Justify your answer with your measurement results.

◇ What conclusions can you draw for a pathological vasoconstriction of a patient, based on this results?

3.2.2.4 The Hagen-Poiseuille Equation

The flow resistances you measured for the pipes 1 to 3, can be calculated for known dimensions and laminar flows (no turbulence) with the help of the Hagen-Poisseuille Equation (Part 3.3, *Physikalische Grundlagen*):

$$R = \frac{8\eta l}{\pi r^4}$$

[2] If two quantities are proportional to each other, they always change by the same factor. In our case, the diameter changes by the factor of 2. What factor then follows for the cross sectional area? You can extract the changes of the flow resistance and the conduction from your measurement results

Here, r and l denote the radius and the length of the pipe respectively and η is the viscosity of the flowing fluid. The viscosity is a quantity, that describes the inner resistance of the fluid and therefore depends on the fluid (and the temperature).

◇ Calculate de flow resistances of the resistance pipes 1, 2 and 3 of the circuit model and compare your results with the measurement values. Assume a viscosity of $\eta = 0.1\ \mathrm{Pa \cdot s}$ (paraffin oil) and the following pipe parameters (caution: units!):

Pipe	**Flow resistance**	
	calculated	measured
1 $r_1 = 3.15$ mm $l_1 = 400$ mm		
2 $r_2 = 6.05$ mm $l_2 = 400$ mm		
3 $r_3 = 6.05$ mm $l_3 = 800$ mm		

3.2.2.5 Parallel connection of resistance pipes

In a systemic circulation, the vascular system is highly branched and numerous vessels are connected parallel. Using our circuit model, a simplistic case of such a parallel circuit can be studied by opening two pipes at the same time: **pipe 2 and pipe 3**. Therefore, close the vessels for pipe 1 and 4 and perform the measurement for this grouping.

Measurement for the parallel connection of pipe 2 and pipe 3			
m [kg]	2.0	1.5	1.0
x_1 [mm]	64	73	82
x_2 [mm]	136	127	118
Δx [mm]	72	54	36
Δp [hPa]			
Δt [s]			
I [10^4 mm^3 s^{-1}]			

- Unload and lock the piston.

◇ Again, plot the volumetric flow rate against the pressure difference with another colour in the diagram on page 15 and fill the measured values into the table on page 14. Determine the conduction value and the flow resistance of the parallel connection of the two pipes.

Parallel connection of pipe 2 and pipe 3

$G_{2\|3} =$

$R_{2\|3} =$

◇ Compare your results with those of pipe 2 and 3. What kind of relation do you expect between the conduction of the single pipes and the conduction of the parallel-connected pipes? Base your assumptions on the measurement results, you obtained.

3.2.2.6 Influence of turbulences on the flow behaviour of fluids

Midway through **pipe 4**, the so-called turbulence pipe, there is an inserted foil with a small hole in the center. The laminar flow of the paraffin oil suddenly breaks down after the hole and turbulences can occur. In the following, the influence of such turbulences to the flow behaviour is being examined. Therefore, close the pipes 1, 2 and 3, such that the paraffin oil flows through **pipe 4** only and perform the following measurements.

Measurements with pipe 4 (turbulence pipe)

m [kg]	1.0	2.0	2.5	3.0	3.5	4.0
x_1 [mm]	92	85	82	79	76	73
x_2 [mm]	108	115	118	121	124	127
Δx [mm]	16	30	36	42	48	54
Δp [hPa]						
Δt [s]						
I [10^4 mm^3 s^{-1}]						

- **IMPORTANT! After the measurements:** Unload the piston.
- ***Pull out the piston just far enough, such that you can put the white teflon sleeve over the piston rod. The piston should be locked in this position by the sleeve. Additionally, tighten the locking screw on the cover of the piston casing.***

◇ One more time, plot the volumetric flow rate against the pressure difference in another colour in the diagram on page 15 and fill your measured values into the table on page 14. In doing so, pay special attention to the **curve shape** (in comparison to the preceding measurements)! What is the pressure range, that leads to the strongest turbulences and what is their influence on the curve shape, i.e. the relation between the volumetric flow strength and the pressure differences?

◇ Based on these measurements, can you make a statement concerning the flow resistance?

Critical velocity and Reynolds number

In conventional pipes without obstacles (aperture or necking) turbulences due to the inner friction of the fluid can occur as well. For that to happen the current velocity has to exceed a certain value, the so-called critical velocity v_{crit}, which depends on the pipe dimensions, the pipes shape and the viscosity of the fluid. The following relation can be found (cf. Part 3.3, *Physikalische Grundlagen*):

$$v_{\mathrm{crit}} = \frac{Re\,\eta}{2\,r\,\rho}$$

Here, $2r$ denotes the diameter of the pipe, η, again, is the viscosity and ρ is the fluid density. Re is an empirically determined constant of proportionality, the so-called Reynolds number. Its value is roughly 2300 for simple pipes. The current velocity relates to the volumetric flow rate by the equation $v = I/(\pi r^2)$.

◇ With the help of these two equations, calculate the maximum current velocity v_{max} that occurred in pipe 3 during your measurements, as well as the critical velocity for Re =2300, $r_3 = 6.05$ mm, $\eta = 0.1$ Pa·s and $\rho = 850$ kg m^{-3} (units! 1 N = 1 kg·m/s^2). Was the current laminar or turbulent in pipe 3 during the measurement?

$$v_{\mathrm{max}} = \frac{I_{\mathrm{max}}}{\pi r_3^2} =$$

$$v_{\mathrm{crit}} = \frac{Re\,\eta}{2\,r_3\,\rho} =$$

3.2.3 Evaluation of the measurement curves

Fill all measured values into the following table and plot the results in the diagram on the following page. Next, calculate the slope with the help of an appropriate slope triangle as:

$$\text{slope} = \text{conduction } G = \frac{\Delta I}{\Delta(\Delta p)}.$$

Measurement on pipe 2

Δp [hPa]			
I [10^4 mm^3 s^{-1}]			

Measurement on pipe 3

Δp [hPa]			
I [10^4 mm^3 s^{-1}]			

Measurement on pipe 1

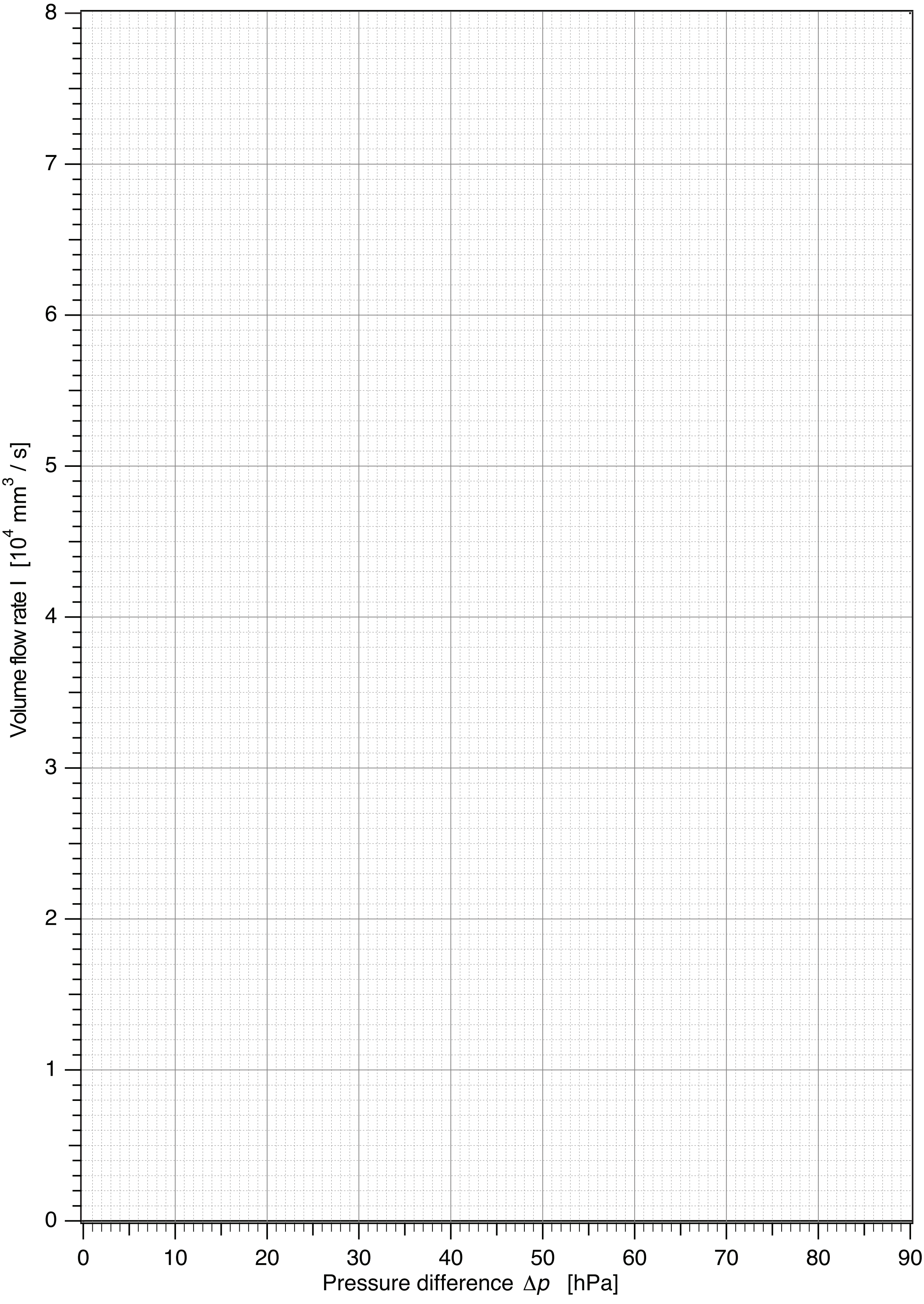
Δp [hPa]			
I [10^4 mm^3 s^{-1}]			

Measurement on the parallel connection of pipes 2 and 3

Δp [hPa]			
I [10^4 mm^3 s^{-1}]			

Measurement on pipe 4 (turbulence pipe)

Δp [hPa]						
I [10^4 mm^3 s^{-1}]						


Volume flow rate I [10^4 mm^3 / s]
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
Pressure difference Δp [hPa]

3.3 Physics behind this experiment

This section only exists in the German version of the lab manuals.