Experiment Instructions

CE 220       Fluidised Bed Formation
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.
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1 Introduction

In fluidised beds, granular solid matter is held in suspension by a fluid flowing through it. As a result the solid matter takes on the character of a liquid. This relates both to its fluid-mechanical and its thermodynamic properties.

Fluidised beds are in wide use in industry, e.g.:
- Tempering baths with even temperature distribution
- Powder coating
- Drying plant
- Furnaces

Using the CE 220 Fluidised Bed Formation unit, investigations can be performed on solid and fluidised masses of fine granular solid matter. In particular, the conditions that lead to a fluidised bed can be investigated. The unit can be used in higher education in the fluid mechanics and process technology areas. The range of experiments covers the following topics:
- Observation of the fluidisation process
- Influence of the particle size on the fluidisation process
- Fluidisation process in different media (air and water)
- Fluid permeability of the solid mass and also the fluidised bed
- Height of the fluidised bed
- Pressure required for varying flow rates for separation of mixtures of varying particle sizes (sedimentation)
The unit is designed as a table unit. All controls and measuring equipment are clearly laid out on a panel.

The supplies (compressed air and flow of water) are integrated into the unit, so that no external connections are required.
2 Safety

2.1 Intended Use

The unit is to be used only for teaching purposes.

2.2 Structure of the Safety Instructions

The signal words DANGER, WARNING or CAUTION indicate the probability and potential severity of injury.

An additional symbol indicates the nature of the hazard or a required action.

<table>
<thead>
<tr>
<th>Signal word</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>⚠ DANGER</td>
<td>Indicates a situation which, if not avoided, will result in death or serious injury.</td>
</tr>
<tr>
<td>⚠ WARNING</td>
<td>Indicates a situation which, if not avoided, may result in death or serious injury.</td>
</tr>
<tr>
<td>⚠ CAUTION</td>
<td>Indicates a situation which, if not avoided, may result in minor or moderately serious injury.</td>
</tr>
<tr>
<td>NOTICE</td>
<td>Indicates a situation which may result in damage to equipment, or provides instructions on operation of the equipment.</td>
</tr>
</tbody>
</table>
2.3 Safety Instructions

⚠️ WARNING
Exposed electrical connections at open rear.
Risk of electric shock.
- Disconnect from the mains supply before opening.
- Work should only be performed by qualified electricians.
- Protect the unit against moisture.

NOTICE
Particles from the fluid bed must not enter the water tank, as the diaphragm of the pump will be damaged if it draws in solid matter.

NOTICE
Do not over exceed the measuring range of the single tube manometer, as otherwise measuring liquid will enter the test vessel.
NOTICE
Do not operate the pump or compressor against a closed valve for too long, as otherwise the drive motor will be overloaded.

NOTICE
Do not fill the test vessel with materials that attack or damage plastics. The test vessel will be rendered unusable if such materials are used.

NOTICE
Only operate the unit in dry rooms indoors in which there are no flammable or caustic gasses, vapours or dusts.
3  Unit Description
3.1  Unit Layout

1  Table support with panel
2  Bypass valve for air with sound absorber
3  Rotameter for air with needle
4  Single tube manometer for differential air pressure
5  Switch for diaphragm compressor
6  Test vessel for air
7  Air filter
8  Scale
9  Water overflow
10  Fixing for the upper Sintered plate
11  Test vessel for water
12  Bleed / vent valve
13  Two tube manometer for water pressure
14  Switch for diaphragm pump
15  Rotameter for water with needle valve
16  Bypass valve for water
17  Water supply
18,20  Sintered plate (not visible)
19,21  Distribution chamber
22  Air supply
23  Supply tank for water with drain tap and safety valve
24  Diaphragm pump
25  Compressed air reservoir with safety valve
26  Diaphragm compressor

Further components are behind the cover and not visible:

Fig. 3.1  Layout CE 220
The test stand is designed as a table unit. All components, controls and displays are clearly arranged on a panel.

All the electrical circuitry is protected behind the panel.

### 3.2 Function of the System

The function of the system is explained using the block diagram. The unit contains two separate test systems.

#### 3.2.1 Test Vessel for Compressed Air

The fluidised bed is formed in a transparent cylinder (6). For this purpose compressed air is blown through the mass of solid matter from below. To
distribute the air evenly, the base of the cylinder is made of a porous sintered metal plate (19).

**NOTICE**

With very fine particle sizes (<0.05mm, dusts), a fluidised bed is very difficult to demonstrate, as the material tends to clump. This also applies to damp materials.

The necessary air pressure underneath the sintered plate in the distribution chamber (19) is generated by a double diaphragm compressor (26). To smooth the flow of air, an air reservoir (25) is fitted in the compressed air line.

**NOTICE**

A safety valve (25) limits the pressure in the reservoir to 3bar.

The air blown into the cylinder leaves the cylinder at the top end via a dry paper air filter (7). In this way particles drawn off from the mass are securely retained and no loss of material occurs.

The air flow is adjusted using two valves. The needle valve (3) on the rotameter is used to set low volumetric flow rates. Larger volumetric flow rates are set using the bypass valve (2), this has an sound absorber (10) connected in series. The flow rate is measured using a directly indicating variable area rotameter (3).

To measure the differential pressure across the height of the mass, two couplings are fitted at the
top and bottom of the cylinder. The respective pressure can be measured at the couplings using hoses. The differential pressure is displayed using a single tube manometer (4).

3.2.2 Test Vessel for Water

The fluidised bed is generated in a transparent cylinder (11). For this purpose water is pumped into the mass of solid matter from below. To obtain an even flow of water, the base of the cylinder is made of a porous sintered metal plate (20).
The water pressure required below the sintered plate in the distribution chamber (21) is generated using a diaphragm pump (24) that pumps the water around a circuit. A supply tank (23) open to the atmosphere contains a sufficient quantity of water.

The flow of water is adjusted using two valves. The needle valve (15) on the rotameter is used to set low flow rates. Larger flow rates are set using the bypass valve (16). The flow rate is measured using a directly indicating variable area rotameter (15).

**NOTICE**
A safety valve (23) limits the pressure in the reservoir to 1,5bar.

After flowing through the cylinder, the water returns to the supply tank via an overflow (9). To measure the differential pressure across the height of the mass, two couplings are fitted at the top and bottom of the cylinder. The respective pressure can be measured at the couplings using hoses.

The differential pressure is displayed using a two tube manometer, the display range of which can be varied by changing the initial air pressure. The initial air pressure can be set using a valve.
3.3 Commissioning

1. Switch off the pump (Fig. 3.1, Page 6, 14).
2. Switch off the compressor (Fig. 3.1, Page 6, 5).
3. Fully open the bypass valve for water (Fig. 3.1, Page 6, 16).
4. Fully open the bypass valve for air (Fig. 3.1, Page 6, 2).
5. Close the needle valve on the rotameter for water (Fig. 3.1, Page 6, 15).
6. Close the needle valve on the rotameter for air (Fig. 3.1, Page 6, 3).
7. Connect the unit to the power supply, making sure the details on the rating plate correspond to those of the power supply.
3.3.1 Single tube manometer

The procedure for filling the single tube manometer is as follows:

1. Slightly loosen the knurled screws that secure the scale so that the scale can be moved (there are two knurled screws).
2. Move the scale to a central position so that you can move it up and down for subsequent corrections.
3. Detach the hose at the pressure fitting from the pressure connection on the test vessel for air.
4. Carefully unscrew the pressure fitting.
5. Pour the special liquid supplied (type AWS 10, \( \rho = 0.87 \text{ g/cm}^3 \)) into the free opening until the "0" mark on the scale is reached.
6. If necessary, correct the zero mark by moving the scale, until the line for the "0" mark is aligned with the liquid level.
7. Secure the scale by tightening the knurled screws.
8. Carefully screw the pressure fitting back in.
9. Replace the previously detached hose on the pressure fitting on the test vessel for air.
10. The single tube manometer is now ready for use.

**NOTICE**

The pressure fitting (+) is connected to the lower pressure connection on the test vessel for air, and the fitting (-) on the left-hand side of the single tube manometer is connected to the upper pressure connection on the test vessel for air.
3.3.2 U-tube manometer

The U-tube manometer is prepared for measurements as follows:

1. Close the upper bleed valve and open the two lower bleed valves.
2. Fully open the bypass valve (Fig. 3.1, Page 6, 16).
3. Switch on the pump (Fig. 3.1, Page 6, 14).
4. Fill the test vessel for water completely with water.
5. Allow the water to continue flowing through the test vessel at a low flow rate. Depending on the material depth in the test cylinder, the water levels in the two manometer capillary tubes may be different for the next step - adjust the average water level with the centre of the scale.
6. Slightly open the upper bleed valve so that the water flows through the hoses into the manometer capillary tubes.
7. Close the upper bleed valve as soon as the averaged water level reaches the centre of the scale.
8. Switch off the pump; the water level in the manometer capillary tubes should now be at the level of the centre of the scale.
9. The U-tube manometer is now ready for use.

**NOTICE**
The right connection is connected to the lower pressure connection on the test vessel for water, and the left connection is connected to the upper pressure connection.
3.3.3 Test vessel for air

The procedure for filling the test vessel for air is as follows:

1. Loosen the four knurled screws.
2. Lift the air filter off the cylinder flange. Exercise caution when lifting, as there are spacer sleeves under the air filter through which the knurled screws are fed.
3. Set aside the air filter with the knurled screws and spacer sleeves.
4. Pour the mass into the cylinder.
   In our experiment, glass beads with a particle diameter $d_p = 0.180...0.300\text{mm}$ are used at a mass height of $h = 50\text{mm}$.
5. Place the spacer sleeves onto the threaded holes on the cylinder flange.
6. Carefully place the air filter onto the spacer sleeves.
7. Replace the knurled screws in their original position, making sure that they are fed through the spacer sleeves.
8. Tighten the knurled screws.
9. The test vessel for air is now ready for use.

Fig. 3.6 Test vessel for air
3.3.4 Test vessel for water

The test vessel for water must be filled in very small doses to achieve the desired material depth. The particles sink very slowly in the water, which means that the depth of the material can only be seen some time after filling.

The procedure for filling the test vessel for water is as follows:

1. Fully open the bypass valve (Fig. 3.1, Page 6, 16).
2. Switch on the pump (Fig. 3.1, Page 6, 14).
3. Half fill the test vessel for water with water.
4. Switch off the pump.
5. Detach the drain hose from the water overflow.
6. Detach the measurement hose from the water overflow.
7. Loosen the two knurled nuts.
8. Lift the water overflow off the cylinder flange. Exercise caution when lifting as there is a sealing ring under the water overflow, which is located in a groove on the water overflow.
9. Set aside the water overflow with the knurled nuts and sealing ring.
10. Remove the sintered plate from the cylinder flange and set it aside.
11. Pour the mass into the cylinder.

In our experiment, glass beads with a particle diameter $d_p = 0.420...0.590\text{mm}$ are used at a mass height of $h = 100\text{mm}$.
12. Place the sintered plate in the recess provided in the cylinder flange.

13. Place the sealing ring in the groove on the water overflow.

14. Carefully place the water flow on the cylinder flange, making sure that the sealing ring remains in the groove.

15. Place the knurled nuts onto the threaded rods.

16. Tighten the knurled nuts.

17. Reconnect the drain hose to the coupling on the water overflow.

18. Reconnect the measurement hose to the coupling on the water overflow.

19. The test vessel for water is now ready for use.
4 Principles

The basic principles set out in the following make no claim to completeness. For further theoretical explanations, refer to the specialist literature.

A fluidised bed is a layer of fine granular solid matter (mass) that is loosened by a fluid flowing through it to such an extent that the particles of solid matter are free to move within certain limits. The layer of solid material takes on similar properties to a fluid.

To characterise a fluidised bed, the pressure loss of the fluid flowing through the bed can be used. When a fluid flows through the mass, initially the pressure underneath the mass increases as the flow speed increases until the pressure forces match the weight of the mass, and the mass becomes suspended. With further increasing flow rate, the layer is set in motion and reaches a fluidised state. The pressure loss now remains almost constant, even with further increasing flow rate. From a certain flow rate, the particles at the top no longer fall back into the fluidised bed; they are drawn off by the fluid flow and removed.

Fluidised beds are widely used in process technology. Gaseous and solid or liquid components of a chemical reaction are well mixed and brought into close contact with each other. This also applies to fluidised bed furnace applications that incinerate problem materials with low levels of pollution.
4.1 Pressure Losses in Fluidised Beds

From the equilibrium of drag, weight and lift, the pressure loss $\Delta p$ of a fluid flowing through the turbulent mass of particles is given by

$$\Delta p = g \cdot \left(1 - \frac{\rho_f}{\rho_p}\right) \cdot h \cdot \rho_{ps}$$  \hspace{1cm} (4.1)

- $\rho_f$ Density of the fluid,
- $\rho_p$ Density of the particle,
- $\rho_{ps}$ Density of the particle mass,
- $h$ Height of the mass.

4.2 Pressure Curve in the Fluidised Bed

The equilibrium of drag, weight and lift not only applies at the base, but at any height in the mass. As can be seen in the previous section, the pressure loss is linearly dependent on the height of the mass. Thus the pressure curve drops linearly to zero from the base to the surface. With $y$ as the immersion depth in the mass, the following applies

$$p(y) = \frac{\Delta p}{h} \cdot y$$  \hspace{1cm} (4.2)
4.3 Loosening Speed

This is the fluid speed at which the mass of solid matter passes the transition to a fluidised bed. The speed of the fluid in the space between the particles can be calculated from Reynolds’ number, the diameter of the particles and the kinematic viscosity of the fluid.

\[ w_{lo} = \frac{Re_{lo}}{d_p} \cdot \nu_f \]  

(4.3)

- \( w_{lo} \): Speed of the fluid between the spherical particles,
- \( Re_{lo} \): Reynolds’ number of the fluid
- \( d_p \): Diameter of the particle
- \( \nu_f \): Kinematic viscosity

As the calculation of the fluid speed applies to spherical particles, the speed for particles of irregular shape must be corrected using a form factor.

\[ w = w_{lo} \cdot \varphi \]  

(4.4)

- \( \varphi \): Form factor
- \( w \): Corrected speed of the fluid

The voids fraction defines the size of the fraction of hollow space in the mass. It is calculated from the density of the particle material and the mean density of the mass.
The equilibrium of pressure loss and particle drag yields a relationship between the dimensionless numbers $Re$ and $Ar$

$$Re_{lo} = 42.86 \cdot (1 - \varepsilon) \cdot \left(1 + 3.11 \cdot 10^{-4} \cdot Ar \cdot \frac{\varepsilon^3}{(1 - \varepsilon)^2} - 1\right)$$

$Ar$ Archimedes’ Number

The **Archimedes’ Number** $Ar$ is calculated from the density, particle diameter and viscosity of the fluid

$$Ar = \frac{g \cdot d_p^3}{\nu^2} \cdot \frac{\rho_p - \rho_f}{\rho_f}$$
5 Experiments

The selection of experiments makes no claims of completeness but is intended to be used as a stimulus for your own experiments. The results shown are intended as a guide only. Depending on the construction of the individual components, experimental skills and environmental conditions, deviations may occur in the experiments. Nevertheless, the laws can be clearly demonstrated.

5.1 Preparing the Experiment

- Place the unit on a flat bench top.
- Connect to power supply.
- Fill the storage tank with water (approx. 4ltr).
- Secure all hoses at the designated points.
- Open the bypass valves for air and water.
- Close the needle valves on the rotameters.
- Start the compressor with the relevant switch and check the function (delivery noise).
- Start the pump with the relevant switch and check the function (test vessel fills with water).
5.1.1 Filling the Test Vessels

Before experiments, the test vessels must be filled with the required mass. To practice using the unit, we recommend initially using one of the two specimen materials supplied. These are glass beads (ballotinis) with two different particle sizes and bulk densities.

\[
\begin{align*}
\rho_p &= 0.180 - 0.300 \text{mm}, \quad \rho_{ps} = 1500 \frac{\text{kg}}{\text{m}^3} \\
\rho_p &= 0.420 - 0.590 \text{mm}, \quad \rho_{ps} = 1500 \frac{\text{kg}}{\text{m}^3}
\end{align*}
\]

The particle density for both is:
\[
\rho_p = 2400...2600 \frac{\text{kg}}{\text{m}^3}
\]

The air filter must be removed from the test vessel for air to fill it with the bulk material.

The water vessel must be filled in very small doses to achieve the desired material depth. The particles sink very slowly in the water, which means that the depth of the material can only be seen some time after filling.

**NOTICE**

Before filling the water vessel, make a rough calculation of how deep the fluidised bed will be. No particles may get into the overflow as otherwise this can destroy the pump diaphragm.
5.1.2 Emptying the Air Test Vessel

- Detach all hoses on the test vessel.
- Unscrew the knurled screws (2) at the clamp (3).
- Remove the cylinder with the air filter and holder (1).
- Remove the knurled screws (4) on the air filter. Caution when removing. Maintain the seal.
- Empty the cylinder. To loosen adherent material, tap on the cylinder while simultaneously turning it.
- Blow clear the pores in the sintered plate using compressed air through the distribution chamber connection. Adherent material can be detached from inside with a jet of compressed air.

NOTICE
Dust formation. Blow out in the open air if required.

NOTICE
Never rinse out the air cylinder with water. This washes the fine particles into the pores in the sintered plate and clog them up.
5.1.3 Cleaning the Air Filter

If the air filter is clogged up by particles carried along, it must be cleaned as follows.

- Remove the air filter as described in Chapter 5.1.2.
- Beat the air filter on a solid surface. Material beaten out can be returned to the solid mass.
- Blow out the air filter from outside with a compressed air jet.

**NOTICE**

*Dust formation.* Blow out in the open air if required.

5.1.4 Emptying the Water Test Vessel

The test vessel is removed in a similar way to that described in Chapter 5.1.2 for the air test vessel.

- Detach all hoses on the test vessel.
- Unscrew the two knurled screws to remove the water overflow.
- Detach the water overflow.
- Detach the two nuts on the retaining plate and remove the retaining plate upwards.
- Unscrew the two knurled screws at the clamp for holding the test vessel.
- Empty the cylinder. To loosen adherent material, tap on the cylinder while simultaneously turning it.
• Blow the pores in the sintered plate clear with compressed air through the distribution chamber connection. Adherent material can be removed from inside with a compressed air jet.

• Particles that are not removed from the wall by compressed air can be removed by half filling the cylinder with water and then lightly shaking it. The particles can be separated from the liquid with a fine filter (coffee filter).

5.1.5 Plotting a Calibration Curve for Recording the Pressure Losses without Filling the Test Vessel

To record the individual pressure losses for the water test vessel, a calibration curve must be plotted for each device without filling. Make sure that no air bubbles form on the sintered metal as they falsify the measured results.

Procedure:

• Connect the pressure measuring connections to the manometer. On a two tube manometer, the display value can be set to the centre of the manometer with the venting and bleed valve.

• Fully open the bypass valve below the rotameter.

• Fully close the needle valve on the rotameter.

• Turn on the pump.

• Increase the flow in small increments by opening the needle valve.

• Continuously note the flow rate and differential pressure in the table (see Appendix).
- Continue the measurements up to the maximum flow.
- Plot the measured values in a diagram.

<table>
<thead>
<tr>
<th>$\frac{Q}{\text{min}}$ (L)</th>
<th>0</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$ (m$^3$/s) 10$^{-3}$</td>
<td>0</td>
<td>2.19</td>
<td>3.29</td>
<td>4.38</td>
<td>5.48</td>
<td>6.57</td>
<td>7.67</td>
<td>8.77</td>
<td>9.86</td>
<td>10.96</td>
<td>12.06</td>
</tr>
<tr>
<td>Left scale</td>
<td>189</td>
<td>181</td>
<td>177</td>
<td>174</td>
<td>170</td>
<td>167</td>
<td>164</td>
<td>160</td>
<td>156</td>
<td>153</td>
<td>148</td>
</tr>
<tr>
<td>Right scale</td>
<td>190</td>
<td>198</td>
<td>202</td>
<td>206</td>
<td>210</td>
<td>214</td>
<td>217</td>
<td>222</td>
<td>226</td>
<td>230</td>
<td>235</td>
</tr>
<tr>
<td>$\Delta p$ (mmWG)</td>
<td>1</td>
<td>17</td>
<td>25</td>
<td>32</td>
<td>40</td>
<td>47</td>
<td>53</td>
<td>62</td>
<td>70</td>
<td>77</td>
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</table>

<table>
<thead>
<tr>
<th>$\frac{Q}{\text{min}}$ (L)</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
<th>1.6</th>
<th>1.7</th>
<th>1.8</th>
<th>1.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$ (m$^3$/s) 10$^{-3}$</td>
<td>13.15</td>
<td>14.25</td>
<td>15.35</td>
<td>16.44</td>
<td>17.54</td>
<td>18.63</td>
<td>19.73</td>
<td>20.83</td>
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<tr>
<td>Left scale</td>
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<td>131</td>
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<tr>
<td>Right scale</td>
<td>239</td>
<td>244</td>
<td>248</td>
<td>254</td>
<td>258</td>
<td>263</td>
<td>267</td>
<td>270</td>
</tr>
<tr>
<td>$\Delta p$ (mmWG)</td>
<td>94</td>
<td>104</td>
<td>112</td>
<td>123</td>
<td>131</td>
<td>140</td>
<td>148</td>
<td>154</td>
</tr>
</tbody>
</table>

Tab. 5.1 Pressure loss against flow - liquid medium
The measurements with the water test vessel must be corrected with the calibration curve you have plotted yourself. This means that the pressure loss value through the sintered metal plates at the corresponding flow rate must be subtracted from the pressure difference values from the experiments. The measurements in this manual are corrected.

Fig. 5.4 Example calibration curve for pressure losses
The pressure losses were plotted with the water test vessel without filling.
5.2 Measuring the Pressure Loss with Air Flow

5.2.1 Experiment Aim

Measuring the pressure loss with air flow with a mass with a mean particle diameter of $d_p = 0.240\text{mm}$.

The mass depth is $h = 50\text{mm}$.

5.2.2 Performing the Experiment

The pressure connections are connected to the single tube manometer.

- Fully open the bypass valve below the rotameter.
- Fully close the needle valve on the rotameter.
- Turn on the compressor.
- Increase the flow in small increments by opening the needle valve and observe the mass.
- Continuously note the flow rate and differential pressure.
- As soon as the first signs of particle movements appear, the loosening speed has been reached. Note the associated flow.

Repeat the measurements until a flow of $30\frac{L}{\text{min}}$ is reached. Above a certain value, the flow rate can only be increased by closing the bypass valve.
5.2.3 Evaluation of the Experiment

Example results are summarised in the following table.

The second row specifies the speed associated with the flow. It is calculated using the cross-section of the cylinder with $A_z = 15.21\,\text{cm}^2$ and the flow $Q$ in $\frac{\text{L}}{\text{min}}$ as:

$$w = \frac{Q}{6 \cdot A_z} \text{ in } \frac{\text{m}}{\text{s}}$$  \hspace{1cm} (5.1)

<table>
<thead>
<tr>
<th>$Q$ in $\frac{\text{L}}{\text{min}}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>5,5 First movement</th>
<th>6</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$ in $\frac{\text{m}}{\text{s}} \cdot 10^3$</td>
<td>10.95</td>
<td>21.91</td>
<td>32.87</td>
<td>43.83</td>
<td>54.79</td>
<td>60.27</td>
<td>66.75</td>
<td>109.57</td>
<td>219.15</td>
<td>328.73</td>
</tr>
<tr>
<td>$\Delta p$ in mmWC rising</td>
<td>14</td>
<td>32</td>
<td>46</td>
<td>60</td>
<td>68</td>
<td>72</td>
<td>68</td>
<td>72</td>
<td>72</td>
<td>73</td>
</tr>
</tbody>
</table>

Tab. 5.2 Pressure loss against flow

The measured results can be represented in a diagram.

![Pressure loss against flow speed](image)

Fig. 5.5 Pressure loss against flow speed
It is characteristic that, as the flow increases, there is initially an excess pressure. This indicates the *loosening speed* $w_{lo}$. As the flow decreases, this effect cannot be identified.
5.3 Measuring the Pressure Loss with Water Flow

5.3.1 Experiment Aim

Measuring the pressure loss with water flow with a mass with a mean particle diameter of $d_p = 0.505\text{mm}$.

The mass depth is $h = 100\text{mm}$.

5.3.2 Performing the Experiment

The pressure connections are connected to the two tube manometer. The display value can be set to the centre of the manometer with the venting and bleed valve.

- Fully open the bypass valve below the rotameter.
- Fully close the needle valve on the rotameter.
- Turn on the pump.
- Increase the flow in small increments by opening the needle valve and observe the mass.
- Continuously note the flow rate and differential pressure.
- As soon as the first signs of particle movements appear, the loosening speed has been reached. Note the associated flow.

Repeat the measurements until a flow of $1.5 \dfrac{L}{\text{min}}$ is reached. Above a certain value, the flow rate can only be increased by closing the bypass valve.
5.3.3 Evaluation of the Experiment

Example results are summarised in the following table.

The second row specifies the speed associated with the flow. It is calculated using the cross-section of the cylinder with $A_z = 15.21 \text{cm}^2$ and the flow $Q \text{ in } \frac{\text{L}}{\text{min}}$ as:

$$w = \frac{Q}{6 \cdot A_z} \text{ in } \frac{\text{m}}{\text{s}}$$

<table>
<thead>
<tr>
<th>$Q \text{ in } \frac{\text{L}}{\text{min}}$</th>
<th>0,1</th>
<th>0,15</th>
<th>0,2</th>
<th>0,25 First movement</th>
<th>0,3</th>
<th>0,4</th>
<th>0,6</th>
<th>0,8</th>
<th>1,0</th>
<th>1,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w \text{ m/s} \cdot 10^3$</td>
<td>1,096</td>
<td>1,645</td>
<td>2,192</td>
<td>2,739</td>
<td>3,287</td>
<td>4,383</td>
<td>6,575</td>
<td>8,766</td>
<td>10,957</td>
<td>16,437</td>
</tr>
<tr>
<td>$\Delta p \text{ in mmWC rising}$</td>
<td>55</td>
<td>66</td>
<td>79</td>
<td>88</td>
<td>86</td>
<td>87</td>
<td>87</td>
<td>87</td>
<td>87</td>
<td>87</td>
</tr>
</tbody>
</table>

Tab. 5.3 Pressure loss against flow

The measured results can be represented in a diagram.

![Graph](Fig. 5.6 Pressure loss against flow speed)
5.4 Comparing Different Masses

5.4.1 Experiment Aim

The comparison of different masses in the air test vessel is initially carried out using a mass with a mean particle diameter of \( d_p = 0.240 \text{mm} \).

The mass depth is \( h = 50 \text{mm} \).

The experiment is then repeated with a mean particle diameter of \( d_p = 0.505 \text{mm} \).

5.4.2 Performing the Experiment

The pressure connections are connected to the single tube manometer.

- Fully open the bypass valve below the rotameter.
- Fully close the needle valve on the rotameter.
- Turn on the compressor.
- Increase the flow in small increments by opening the needle valve and observe the mass.
- Continuously note the flow rate and differential pressure.

The compressed air flow rate is increased until the differential pressure is constant. The maximum pressure loss is noted.
5.4.3 Evaluation of the Experiment

It can be seen that, despite different particle sizes, the maximum differential pressure is the same for both masses.

The measured maximum pressure loss for both beds is $\Delta p = 72\text{mmWC}$. This measured value is now compared with the theoretical value.

According to Formula (4.1):

$$\Delta p = g \cdot \left(1 - \frac{\rho_f}{\rho_p}\right) \cdot h \cdot \rho_{ps}$$

(5.2)

Bulk density $\rho_{ps} =$ 1500 kg/m$^3$

Particle density $\rho_p =$ 2500 kg/m$^3$

Fluid density $\rho_f =$ 1.25 kg/m$^3$

Material depth $h =$ 0.05 m

$$\Delta p = 9.81 \frac{m}{s^2} \cdot \left(1 - \frac{1.25 \frac{kg}{m^3}}{2500 \frac{kg}{m^3}}\right) \cdot 0.05 \cdot 1500 \frac{kg}{m^3}$$

(5.3)

$$\Delta p = 0.735 \frac{kPa}{= 73,5\text{mmWC}}$$

(5.4)

The measured values and calculated values are a good match.

This experiment indicates that the maximum pressure loss in a fluidised bed depends on the bulk density, particle density, fluid density and the material depth. Unlike when determining the loosening speed, the particle size is unimportant.
5.5 Determination of the Loosening speed

5.5.1 Experiment Aim

Determination of the loosening speed from the results of the experiments in Chapter 5.2 and Chapter 5.3.

5.5.2 Performing the Experiment

The flow speeds at which the first movement within the mass is visible in the experiments described above (Chapter 5.2 and Chapter 5.3) are noted.

5.5.3 Evaluation of the Experiment

The following values were measured:

Air: \( d_p = 0.240 \text{mm}, \ w = 0.0603 \ \frac{\text{m}}{\text{s}} \)

Water: \( d_p = 0.505 \text{mm}, \ w = 0.0274 \ \frac{\text{m}}{\text{s}} \)

The measured values are now compared with the theoretical values.

First of all, the Archimedes number is calculated using Formula (4.7), page 20. The viscosity of the air is

\[ \nu = 16 \cdot 10^{-6} \ \frac{\text{m}^2}{\text{s}} \]

For \( d_p = 0.240 \text{mm} \)
According to Formula (4.5), page 20 the voidage is:

$$
\varepsilon = 1 - \frac{1500\, \text{kg}}{2500\, \text{m}^3} = 0.4 \quad (5.6)
$$

Formula (4.6), page 20 gives the Reynolds number:

$$
Re_{lo} = 42.86 \cdot (1 - 0.4) \cdot \left[ \sqrt{\frac{1 + 3.11 \cdot 10^{-4} \cdot 1059 \cdot \frac{0.4^3}{1 - 0.4^2}}{1 - 0.4^2}} - 1 \right] = 0.742 \quad (5.7)
$$

and thus the speed according to Formula (4.3), page 19:

$$
w_{lo} = \frac{0.773}{0.00024\, \text{m}} \cdot 16 \cdot 10^{-6} \, \text{m}^2 / \text{s} = 0.049 \, \text{m} / \text{s} \quad (5.8)
$$

This value is a good match with the measured value of $w = 0.060 \, \text{m} / \text{s}$.

For water, the same calculation

$$\nu = 1 \cdot 10^{-6} \, \text{m}^2 / \text{s} \quad (5.9)$$
and

\[ \rho = 1000 \frac{kg}{m^3} \]  \hspace{1cm} (5.10)

and

\[ d_p = 0.505 \text{mm} \]

gives the following values:

\[ A = 1895 \]
\[ \varepsilon = 0.4 \]
\[ Re_{lo} = 0.002601 \frac{m}{s} \]

This value is also a good match with the measured value of \( w = 0.002739 \frac{m}{s} \).

If the particles do not have the form of spheres, the theoretically calculated loosening speed must be multiplied by a shape factor \( \phi \) to obtain the actual speed. This shape factor converts any cross-section into an spherical alternative cross-section. The factor can be found in tables.
5.6 Relationship between Flow Rate and Depth of the Fluidised Bed

5.6.1 Experiment Aim

To determine the relationship between flow rate and the depth of the fluidised bed. A mass with a mean particle diameter of $d_p = 0.505\text{mm}$ is used. The material depth is $h = 100\text{mm}$.

This experiment is only possible in the water vessel as it is only here that the depth of the fluidised bed is clearly identifiable.

5.6.2 Performing the Experiment

The pressure connections are connected to the two tube manometer. The display value can be set to the centre of the manometer with the venting and bleed valve.

- Fully open the bypass valve below the rotameter.
- Fully close the needle valve on the rotameter.
- Turn on the pump.
- Increase the flow in small increments by opening the needle valve and observe the mass.
- Continuously note the flow rate and bed depth.

Repeat the measurements until a flow of $1.5 \frac{L}{\text{min}}$ is reached. Above a certain value, the flow rate can only be increased by closing the bypass valve.
5.6.3 Evaluation of the Experiment

Example results are summarised in the following table.

<table>
<thead>
<tr>
<th>Flow rate $Q$ in $\frac{L}{min}$</th>
<th>0.1</th>
<th>0.2</th>
<th>0.25</th>
<th>0.3</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed depth $h$ in mm</td>
<td>100</td>
<td>100</td>
<td>105</td>
<td>111</td>
<td>119</td>
<td>130</td>
<td>145</td>
<td>157</td>
<td>172</td>
<td>196</td>
</tr>
</tbody>
</table>

Plotting the measured values in a diagram gives the following figure:

It can be seen that, once the loosening speed is reached, the depth of the fluidised bed increases proportionately to the flow rate.
This experiment is only possible with fluidised beds in liquids, as this is the only place that a homogeneous fluidised bed is formed. Masses in gas flows form non-homogeneous fluidised beds with lots of bubbles, making it impossible to read the depth.
6 Appendix

6.1 Technical Data

Dimensions
Length x width x height 750mm x 610mm x 1010 mm
Weight approx. 74 kg

Connections
Power supply 230V / 50 Hz
Nominal consumption (rating) 0,2 kW
Alternatives optional, see type plate

Test vessel (air and water)
Material PMMA
Length 550 mm
Diameter 44 mm
Capacity approx. 1,2 L
Scale 0...500 mm
Division 1 mm

Diaphragm compressor
Volumetric flow rate, maximum 39 \( \frac{L}{min} \)
Pressure, maximum 2,0 bar

Compressed air reservoir
Capacity 2 L
Proof pressure 10 bar
Safety valve adjustable 0...4 bar

Rotameter (air)
Measuring range 4...32 \( \frac{L}{min} \)
Single tube manometer (air)
Messbereich 0...200 mmWS

Diaphragm pump
Volumetric flow rate
at 1,0 bar
1,8 \( \frac{L}{min} \)

Supply tank (water)
Capacity ca. 4L
Safety valve adjustable 0...4 bar

Rotameter (water)
Measuring range 0,2... 2,2 \( \frac{L}{min} \)

Two tube manometer (water)
Measuring range 0...500 mmWS

Sample material
Type Glass beads (Ballotini)
Particle diameter 0,180...0,300 mm
and 0,420...0,590 mm
Density 2,4...2,6 \( \frac{kg}{m^3} \)
Density of mass approx. 1,5 \( \frac{kg}{m^3} \)
6.2 List of Symbols and Units

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Mathematical / physical unit</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_r$</td>
<td>Archimedes' number</td>
<td></td>
</tr>
<tr>
<td>$A_z$</td>
<td>Cross-section of the mass</td>
<td>cm², m²</td>
</tr>
<tr>
<td>$d$</td>
<td>Diameter</td>
<td>mm, m</td>
</tr>
<tr>
<td>$d_p$</td>
<td>Particle diameter</td>
<td>mm, m</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
<td>m/s²</td>
</tr>
<tr>
<td>$h$</td>
<td>Height of the mass</td>
<td>mm, m</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>bar, N/m², Pa</td>
</tr>
<tr>
<td>$Q$</td>
<td>Volumetric flow rate</td>
<td>L/min</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds' number</td>
<td></td>
</tr>
<tr>
<td>$w$</td>
<td>Speed</td>
<td>m/s</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Voids fraction</td>
<td></td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Form factor</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>Viscosity</td>
<td>m²/s</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>
### 6.3 Work Sheets

#### 6.3.1 Pressure Loss against Flow

<table>
<thead>
<tr>
<th>( \dot{Q} ) in ( \frac{L}{min} )</th>
<th>0</th>
<th>0,2</th>
<th>0,3</th>
<th>0,4</th>
<th>0,5</th>
<th>0,6</th>
<th>0,7</th>
<th>0,8</th>
<th>0,9</th>
<th>1,0</th>
<th>1,1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w ) in ( \frac{m}{s} \times 10^3 )</td>
<td>0</td>
<td>2,19</td>
<td>3,29</td>
<td>4,38</td>
<td>5,48</td>
<td>6,57</td>
<td>7,67</td>
<td>8,77</td>
<td>9,86</td>
<td>10,96</td>
<td>12,06</td>
</tr>
<tr>
<td>Left scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \Delta p ) in mmWG decreasing</th>
<th>1,2</th>
<th>1,3</th>
<th>1,4</th>
<th>1,5</th>
<th>1,6</th>
<th>1,7</th>
<th>1,8</th>
<th>1,9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{Q} ) in ( \frac{L}{min} )</td>
<td>13,15</td>
<td>14,25</td>
<td>15,35</td>
<td>16,44</td>
<td>17,54</td>
<td>18,63</td>
<td>19,73</td>
<td>20,83</td>
</tr>
<tr>
<td>( w ) in ( \frac{m}{s} \times 10^3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left scale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Right scale                        |     |     |     |     |     |     |     |     |

| \( \Delta p \) in mmWG decreasing |     |     |     |     |     |     |     |     |

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### 6.3.2 Calibration Curve for Pressure Losses

![Graph showing the relationship between flow rate (Q) in L/min and pressure difference (Δp) through sintered metal plates in mmWS.](image)
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<th>Contents</th>
</tr>
</thead>
</table>
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