# 8 Fluidization

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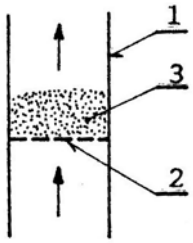
## I Basic relations and definitions

Fluidization is a process where the liquid flows in opposite direction the gravitation and creates a suspension together with solid particles. Suspension can fill the apparatus to the arbitrary depth and solid particles intensively move in whole volume of the suspension.

The suspension layer is called ***fluidized (moving) bed***. Its existence is delimited by accurately defined area of the superficial velocity of the liquid

$$\upsilon \in \langle \upsilon_0, \upsilon_e \rangle$$

where $\upsilon_0$ is the critical velocity (threshold) and $\upsilon_e$ is the terminal velocity.




1 fluidization column
2 grid
3 fluidized bed

*Fig.8-1* Scheme of the fluidization column

Terms used in previous text can be illustrated in schematic figure of the fluidization column, see Fig. 8-1. In fluidization column **1** the fluidized bed of solid particles **3** is lying on the grid **2**. The liquid flows through the fluidized bed of solid particles in opposite direction to the gravitation. Behaviour of the fluidized bed depends on ***superficial velocity of the liquid*** $\upsilon$ defined as

$$\upsilon = \dot{V} / S \tag{8-1}$$

where $\dot{V}$ is the volume flow of the liquid and $S$ is the cross-sectional area of the fluidization column. At the beginning of the work we fill the apparatus by defined amount of solid particles $m_p$ (with the density $\rho_p$) which forms the static bed of solid material with bed depth $h_0$ and with porosity $\varepsilon$. ***Porosity*** $\boldsymbol{\varepsilon}$ is defined as ratio of free volume of the static bed to overall volume of the fluidized bed:

$$\varepsilon = \frac{\left(V_B - m_p / \rho_p\right)}{V_B} = 1 - \frac{m_p}{\left(h_B S \rho_p\right)} \tag{8-2}$$

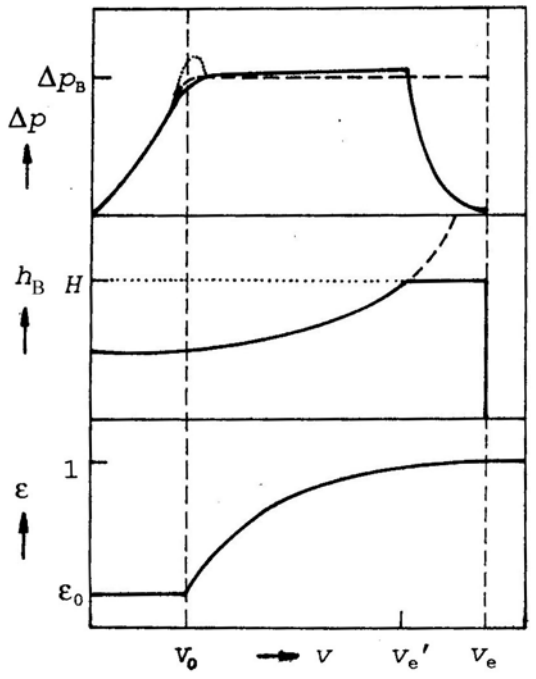
where $h_B$ is bed depth and $V_B$ is volume of the bed.

Now we lay on flow of the liquid to column and we increase flow rate. Particles in the static bed are effected on gravity, lifting power, resistance force of flowing liquid and grid reaction. Due to the bed does not move (is static) the resultant of effecting forces to particles is equal to zero. By increasing flow rate of the liquid the resistance force also increases. In order to the resultant force is zero, another force must decrease. From definition the gravity and lifting power do not depend on flow rate, i.e. grid reaction must decrease. At the moment when grid force is equal to zero the static bed starts to move and merges into fluidized state,

i.e. the fluidization threshold appears. Theoretical value of ***the pressure drop through the bed*** $\Delta p_B$ for critical velocity (threshold) of the fluidization $\upsilon_0$ is defined as

$$\Delta p_{\mathrm{B}} = \frac{m_{\mathrm{p}}(\rho_{\mathrm{p}} - \rho)\mathrm{g}}{\mathrm{S}\rho_{\mathrm{p}}} \tag{8-3}$$

where $\rho$ is density of the liquid and $g$ is acceleration of gravity. By another increasing of flow rate size of gaps (pores) between particles increases so that the resistance force is equal to the value at fluidization threshold, i.e. Eq. (8-3) must be still valid. At this moment expansion, bed depth and porosity of the fluidized bed increase to the state when bed depth is equal to depth of the fluidization column ($h_B = H$). Corresponding superficial velocity is signed $\upsilon_e'$. In this velocity violation particles start to leave the apparatus and after reaching ***the terminal velocity*** $\upsilon_e$ all particles are leaving the column. Terminal velocity is approximately equal to settling velocity of the isolated particle ($\upsilon_e \approx \upsilon_u$), i.e. pores between particles are large and particles do not interplay.




_____ process in real apparatus

--------- theoretical behaviour

*Fig.8-2* Dependence of the pressure drop, the bed depth and the porosity of the fluidized bed on the superficial velocity

These dependencies are shown in Fig. 8-2. The full lines represent behaviour in real apparatus (the bed depth is limited). The dashed line represents theoretical behaviour where influence of the apparatus is neglected. Dependence of the pressure drop in fluidized bed $\Delta p$ can not have sharp turning point. Rise of the bed depth can appear only during increasing of flow rate and not during decreasing. It is caused by surface activity of particles (for example gluey material) or by settling down of the fluidized bed. Non-shape of turning point in dependence of the pressure drop should also be caused by non-homogeneities of the particles (polydispersity or different density).

In area of expansion of fluidized bed the pressure drop slightly increases due to pressure drop on walls of the apparatus

$$\Delta p = \Delta p_B + \lambda \frac{h'}{d} \frac{\upsilon^2}{2} \rho \tag{8-4}$$

where $\lambda$ is friction coefficient, $h'$ is distance between connections of the differential manometer and $d$ is column diameter.

Fluidization threshold of spherical particles can be calculated from empirical Equation in form:

$$Re_0 = 42{,}86\left(1-\varepsilon_0\right)\left[\left(1+\frac{7}{150^2}\frac{\varepsilon_0{}^3}{\left(1-\varepsilon_0\right)^2}Ar\right)^{1/2}-1\right] \tag{8-5}$$

where $\varepsilon_0$ is the porosity of the bed calculated from Eq. (8-2), $Re_0$ is Reynolds number for fluidization threshold

$$Re_0 = \upsilon_0 d_p \rho / \eta \tag{8-6}$$

and $Ar$ is Archimedes number defined as

$$Ar = g\, d_p^3\, \rho\left(\rho_p - \rho\right) / \eta^2 \tag{8-7}$$

In Eqs. (8-6) and (8-7) $d_p$ is particle diameter, $\rho$ is density of the liquid, $\eta$ is dynamical viscosity and $\upsilon_0$ is the critical velocity of fluidization threshold.

Expansion of the fluidized bed of uniform spherical particles can be approximately described by empirical correlations. Eq. (8-8) represents one of many examples:

$$Re = \frac{Ar\ \varepsilon^{4{,}75}}{18+0{,}6\left(Ar\ \varepsilon^{4{,}75}\right)^{1/2}} \tag{8-8}$$

Here $Re$ is Reynolds number for expansion of the fluidized bed defined as

$$Re = \upsilon d_p \rho / \eta \tag{8-9}$$

## II Objectives

1. Determining of the density of solid particles.
2. Experimental determining of the critical velocity
    - obtained from direct visual observation
    - determined from graphical dependence of the pressure drop on the superficial velocity
    - calculated from Eqs. (8-5) to (8-7).
3. Graphical representation of experimentally measured dependence of $\varepsilon = \varepsilon(Re)$ and its comparison with results obtained from Eq. (8-8).
4. Graphical representation of experimentally measured dependence of the pressure drop in fluidization column on the superficial velocity of the liquid.
5. Determining of the critical velocity and the terminal velocity.

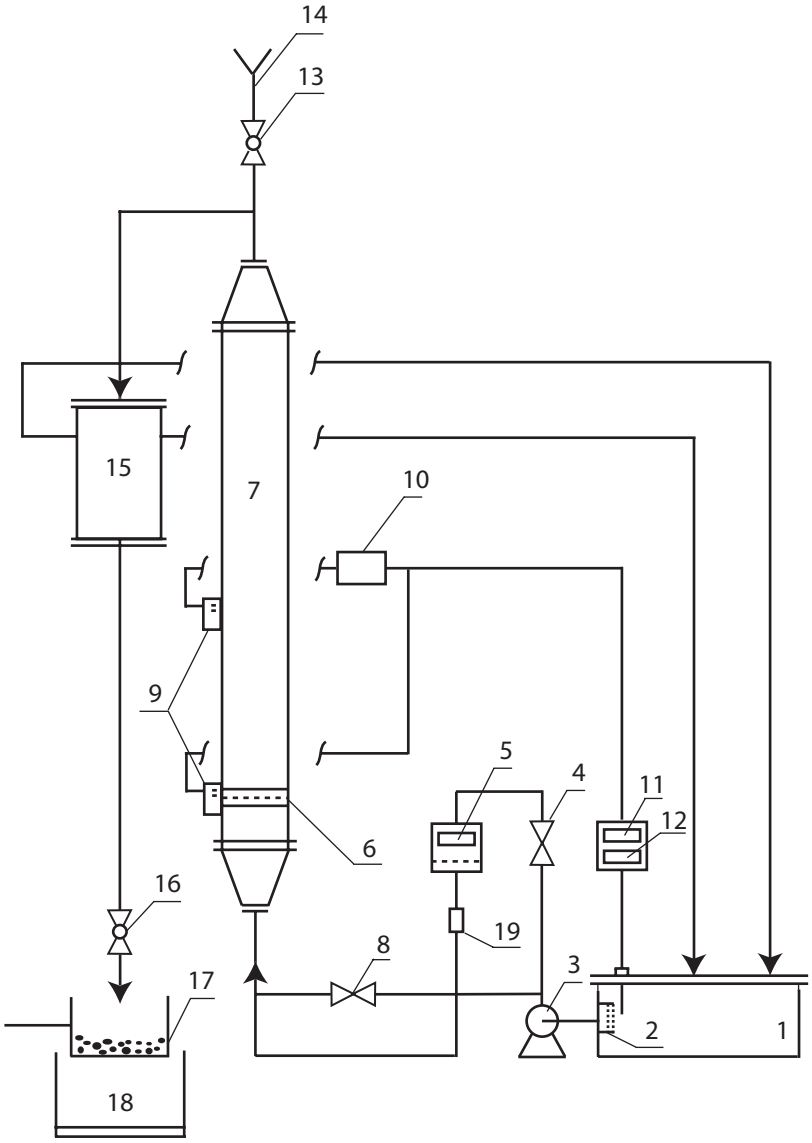



*Fig. 8-3* Scheme of the fluidized column

1 reservoir
2 barrier - sieve
3 centrifugal pump
4 governing valve
5 flow indicator
6 grid
7 fluidization column (with internal diameter 80 mm)
8 valve
9 points of differential pressure measurement
10 sensor of the differential pressure
11 differential pressure indicator
12 indicator of temperature inside reservoir
13 stop-cock
14 funnel
15 particle separator
16 stop-cock
17 particle sieve
18 container
19 electromagnetic flowmeter sensor

## III Plant description

Schematic figure of the fluidization column is shown in Fig. 8-3. Water used for fluidization is in reservoir **1**, from there water is transported by centrifugal pump **3** through flow-

meter indicator **5** and electromagnetic flowmeter sensor **19** to the fluidization column **7** and then returns through the particle separator **15** back to the reservoir **1**. Valve **8** is used for direct connection of the pump with the fluidization column. The volumetric flow of the water is regulated by governing valve **4**. Funnel **14** together with stop-cock **13** is used for pouring of particles to the column. Particle separator **15** traps particles running out from the column. After finishing the measurement (i.e. after exhaustion of the column and switching off the pump) empty particles to the particle sieve **17** and catch the water to the container **18**. The fluidization column is tube with internal diameter 80 mm. Grid **6** is made from perforated metal plate. The pressure drop is measured by sensors of the differential pressure **10** at points of differential pressure measurement **9** and is displayed on differential pressure indicator 11. The temperature of the water inside reservoir is displayed on indicator **12**.

## IV Work description

### IV.1 Plant preparation

Check if the reservoir **1** is fully filled by the water, close valve **8** and stop-cocks **13** and **16**. Check if the governing valve **4** is closed and then switch on the pump by the switch held on the wall. By slow opening of the governing valve **4** deaerate feed pipe-line to the fluidization column and fill the apparatus by the water. After filling close governing valve **4** and switch off the pump. Open stop-cock **13** and fill the column by known amount of solid particles (amount is written in your laboratory protocol) using funnel **14** and close stop-cock **13**. Switch on the pump and by slow increasing the flow using valve **4** approximately find the fluidization threshold, i.e. find the flow rate when the static bed is starting to move (particles start to move and the static bed starts to "boil"). The visual measurement of flow rate of the fluidization threshold will be used for next measurements (see following section).

### IV.2 Measurement

1. Pycnometric ***determining of the density of particles*** in two parallel measurements. During scaling follow the next instructions:

a) Scale the absolutely dry empty pycnometer – dry it using ethanol.
b) Scale pycnometer with particles – it is not necessary to fill pycnometer absolutely, 1/3 to 1/2 of the volume of pycnometer will be enough, particles must be absolutely dry as well.
c) Scale pycnometer with particles and distilled water – first fill pycnometer with particles by the water closely under the particles, deaerate air bubbles between the particles by mixing, then absolutely fill pycnometer (capillary tube of pycnometer stopper must be fully filled as well).
d) Scale pycnometer with distilled water in known temperature (measure temperature of the water before scaling).

Write all these values to the laboratory protocol.

***It is necessary to calculate the density of solid particle using Eq. 8-10 before you leave the laboratory and consult results with supervisor.***

2. Before and after the measurement in the fluidization column read the water temperature

inside the fluidization column on panel **12** and write it to the protocol.

3. In the first part of the measurement observe changes in pressure drop through the static bed of solid particles. Slowly increase flow rate from zero to value which corresponds to critical velocity of the fluidization. In this interval measure at least 8 measurements. For uniform distribution of experimentally measured points use the value of the critical velocity obtained from direct visual observation of the fluidization threshold (when the packed bed starts to move). Write volumetric flow, pressure drop $\Delta p$ and bed depth $h_B$ to the protocol.

4. In the second part of the measurement measure expansion of the fluidized (moving) bed – write to the protocol the same values as in point 3. Slowly increase flow rate of the water from the critical velocity of the fluidization to the terminal velocity. In this interval measure at least 15 measurements. Determine value of the terminal velocity. Slowly increase the volumetric flow of the water to the moment when first particles start to leave the column. Write this value to the protocol. By another increasing of the volumetric flow find value when all particles leave the column. Use this value for determining of the terminal velocity. Particles removed from the column cumulate in the tube beyond the stop-cock **16**. If it is necessary remove particles from the column using valve **8** (governing valve **4** must be closed).

**IV.3 End of the measurement**

After finishing the measurement switch of the pump, close governing valve **4** and open stop-cock **13**. Then open stop-cock **16**, remove particles to the particle siege **17** and catch the water to the container **18** (siege and container can be found in laboratory). After removing of particles close stop-cocks **13** and **16**. Return particles to the instructor.

## V Safety instructions

1. During measurement watch carefully if water is not running into the pump electromotor.
2. At the moment when particles start to leave the column, increase the flow rate of the water very slowly.

## VI Experimental data processing

1. Calculate density of particles by pycnometric measurement using definition

$$\rho_p = (m_b - m_a)\,\rho / (m_d + m_b - m_c - m_a) \qquad (8\text{-}10)$$

where $m_a$ is the mass of the empty pycnometer, $m_b$ is the mass of the pycnometer with particles, $m_c$ is the mass of the pycnometer with particles and water, $m_d$ is the mass of the pycnometer with water and $\rho$ represents density of the water in pycnometer.

2. Using Eq. (8-1) calculate the superficial velocity.
3. Using Eqs. (8-7) and (8-9) calculate values of Archimedes and Reynolds numbers. Porosities of the static and the fluidized beds can be obtained from Eq. (8-2).
4. Plot graphically dependence of the pressure drop $\Delta p$ on the superficial velocity of the water $\upsilon$. Smooth experimental values of this dependence by curve (see Fig. 8-4). Determine the critical velocity of the fluidization $\upsilon_0$ in turning point experimentally and compare obtained value with value calculated from Eqs. (8-5) and (8-6). Compare it also with value obtained

from visual observation of transition from static bed to fluidized bed.

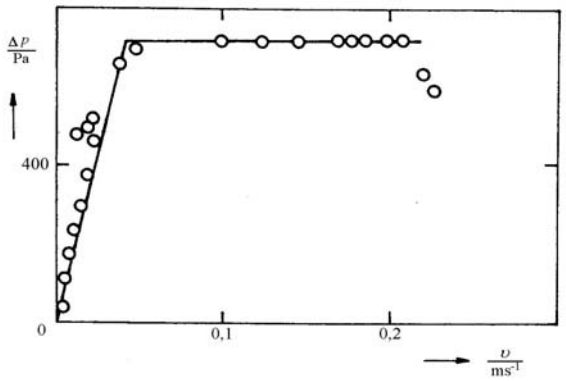



*Fig.8-4* Dependence of the pressure drop on the superficial velocity

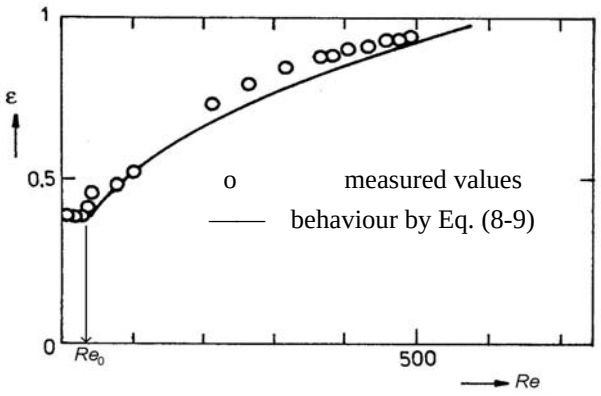



*Fig.8-5* Dependence of the porosity on Reynolds number

5. For chosen values of the porosity calculate Reynolds numbers (using Eq. (8-8)) and plot this dependence in one graph – experimentally measured values plot as points and theoretically obtained values smooth in curve (see. Fig. 8-5).

## VII List of symbols

| | | |
|---|---|---|
| *d* | diameter of the fluidization column | m |
| *H* | depth of the fluidization column | m |
| *h* | depth | m |

Subscripts

| | |
|---|---|
| B | fluidized bed |
| e | terminal |
| 0 | critical |
| u | sedimentation |

## VIII Questions

1. Why does the static bed in flow rate velocities $\upsilon$ bigger than $\upsilon_0$ start to move?
2. What is the critical velocity of the fluidization and how can be measured in laboratory?
3. What is the practical importance of the knowledge of the porosity of the fluidized (moving) bed?
4. How do non-uniformities of the fluidized bed originate? How can we minimize them?