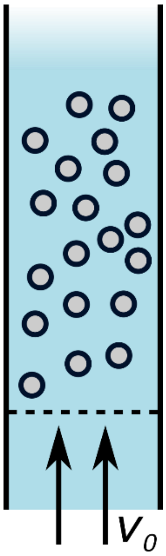
Fluidization

Theoretical background

During fluidization, granulates are held afloat using a fluid (gas or liquid) flowing upwards. The phenomenon can be best compared to boiling liquids. The application of a fluidized bed provides a very intensive contact between the solid phase (the particles) and the fluid. It is a special case of flow in a packed column and can be found in several sectors of the chemical industry. As examples, fluidized bed drying, fluidized bed pyrites-sintering, or several heterogeneous chemical reactions using fluidized catalyst particles can be mentioned.



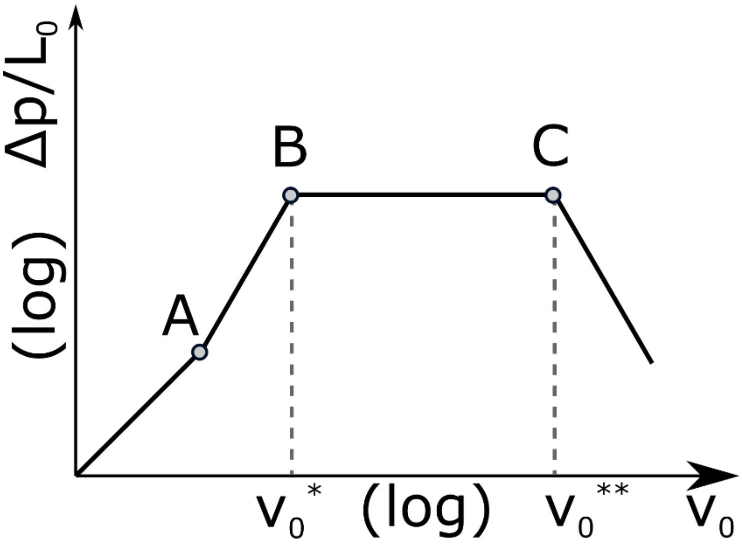
1. Figure – A schematic depiction of the fluidization process

Fluidized beds have many advantages compared to fixed beds. If the packing is fluidized, it starts behaving like a liquid: the surface of a solid particulate material fluidized using a gas resembles a boiling liquid. Objects having a lower density than the bed float on the top of it while objects having a higher density sink. The liquid-like behavior of the fluidized bed makes it possible to handle a solid material like a liquid. This way, it becomes possible to continuously feed and draw a solid material.

Another great advantage of applying a fluidized bed is the perfect mixing in the bed making it possible to provide an even temperature distribution in highly endo- or exothermic reactions. Because of the excellent mixing, the contact between the solid particles and the fluid is much more intensive, and because of that we can calculate with better heat and mass transfer coefficients [1].

The most common applications of fluidization are systems using gas-solid fluidization like fluid catalytic cracking in the oil industry (FCC), fluidized bed dryers often used in the food industry and the fluidized burners developed to combust coal. Mentionable processes using fluidization with liquids are the fluidized bed bioreactors used in wastewater treatment and fluidized bed electrolysis.

If the particles are spheres and we plot the pressure drop of the column (difference of pressure between the bottom and the top of the column) as a function of the linear velocity calculated for the empty column in logarithmic scales a graph like Fig 2. is obtained. [1]:



2. Figure

Increasing the flow velocity the pressure drop increases proportionally, then, the exponent of velocity gradually increases to 2, meaning that the pressure drop is proportional to the square of the flow velocity. In figure 2, the flow between the points A and B (on a fixed packed bed) is turbulent, thus, the slope of the linear plotted on the logarithmic scale is 2. When the point B is reached by increasing the velocity, the pressure drop will equal the grid pressure, the resultant force on the particles will be zero, meaning that particles will start to float, fluidization begins.

If the linear velocity referred to the empty column (v_0) is smaller than v_0* we talk about packed column applications and calculations. In these cases pressure drop of the column is smaller than the pressure drop at fluidization. The particles are fluidized if v_0 is between v_0* and v_0**. In this region the pressure drop is constant and equals to the grid pressure.

Grid pressure is the Archimedean weight of the particulate bed on a unitary surface area of the grid. ([2], page 102.):

$$\Delta p_{grid} = L \cdot (1-\varepsilon) \cdot (\rho_p - \rho_f)$$

L	height of the fluidized bed [m]
ε	voidage [-]
ρ_p	density of the packing [kg/m^3]
ρ_f	density of the fluid [kg/m^3]

According to the definition of the voidage, the fraction of the bed volume that is occupied by the voids (the fluid spaces between the particles), the height of the packing in the column would be L_0 if there were no empty spaces among the particles. This is called *reduced packing height*.

$$L_0 = L \cdot (1-\varepsilon)$$

This value is constant throughout the process, so pressure drop can referred to reduced packing height.

$$\frac{\Delta p_{grid}}{L_0} = (\rho_p - \rho_f) \cdot g$$

Pressure drop caused by the flow can be calculated using the formula derived for the hydrodynamic resistance in packed bed columns.

$$\frac{\Delta p}{L_0} = 4 f_m \cdot \frac{1}{d_p} \cdot \frac{v_0^2 \cdot \rho_f}{2}$$

v_0	flow velocity in an empty column [m/s]
f_m	friction coefficient [-]
d_p	diameter of the fluidized particles [m]

The value of the f_m friction coefficient depends on the Reynolds-number that can be determined using the $f_m Re_m^2 - Re_m$ diagram (Figure 3) if the flow velocity and the voidage are known.

$$Re_m = \frac{d_p \cdot \rho_f \cdot v_0}{\eta_f}$$

η_f	dynamic viscosity of the fluid [Pas]

At point B in figure 2, particles start to separate from each other (and begin moving) and float one-by-one in the fluid. This marks the beginning of fluidization and the flow velocity corresponding to it is the initial fluidization velocity (v_0^*). On further increasing the velocity (the interval between B and C) the fluidized bed expands, L and ε increase, but the pressure drop remains constant.

In a fluidized bed, the forces acting upon the particles are in equilibrium, which means that the the Archimedean weight of the particles equals the drag of the fluid.

$$\frac{D^2 \cdot \pi}{4} \cdot L_0 \cdot (\rho_p - \rho_f) \cdot g = \frac{D^2 \cdot \pi}{4} \cdot L_0 \cdot 4 \cdot f_m \cdot \frac{1}{d_p} \cdot \frac{v_0^2 \cdot \rho_f}{2}$$

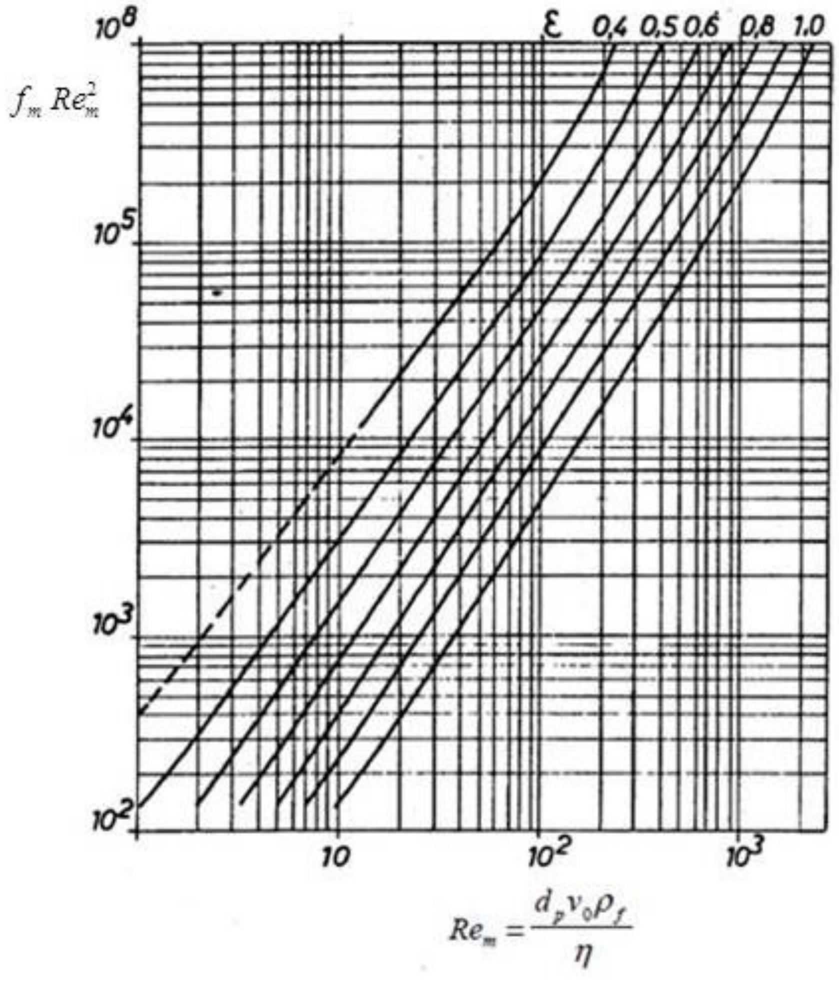
D	inner diameter of the column [m]

Rearranging the Reynolds-number to get v_0 (the flow velocity in an empty column) and substituting it into the last equation, and after rearranging it, the formula of $f_m \cdot Re_m^2$ can be obtained in an equilibrium of forces. This value does not depend on the Reynolds-number, it is only determined by the size of the particles and the characteristics of the fluids.

$$f_m \cdot Re_m^2 = \frac{d_p^3 \cdot (\rho_p - \rho_f) \cdot \rho_f \cdot g}{2 \cdot \eta^2}$$

When the expansion of the fluidized bed reaches a point when the particle are so far from each other that each particle floats in an infinite space (point C in Figure 2.) the velocity of dragging out (v_0^{**}) is reached. On increasing the flow velocity beyond this value, all of the particles will exit the column with the fluid. In an ideal case, if no wall effect is present, and the flow velocity can be considered constant along the total cross section of the column, the flow velocity at the point C equals the sedimentation (deposition) velocity of the particle.

The flow velocity needed to initiate fluidization and the velocity of dragging out can be determined using the $f_m \cdot Re_m^2 - Re_m$ diagram (Figure 3). The parameter of the system of curves is the voidage. Using the diagram, knowing the properties and the packing, the Reynolds-number at the beginning of fluidization and the Reynolds-number of deposition can be determined, from which the corresponding velocities can be calculated. In case of spherical particles, the projection on the horizontal axis of the point corresponding the $f_m \cdot Re_m^2$ value calculated with the last equation and a voidage value of 0.4 is the Reynolds-number at the beginning of fluidization, while using the voidage value 1 will lead to the Reynolds-number at the beginning of dragging out particles.



3. Figure

If we intend to calculate the pressure drop in a fluidized bed, and in an equilibrium of forces (in the interval $Re_m^* < Re_m < Re_m^{**}$) using

$$\frac{\Delta p}{L_0} = 4 f_m \cdot \frac{1}{d_p} \cdot \frac{v_0^2 \cdot \rho_f}{2}$$

the f_m value needed can be determined from the formula of $f_m \cdot Re_m^2$ to a specific Reynolds-number. Provided that, in an equilibrium of forces, the pressure drop equals the grid pressure, and the latter has a much simpler calculation method, it is beneficial to use that equation.

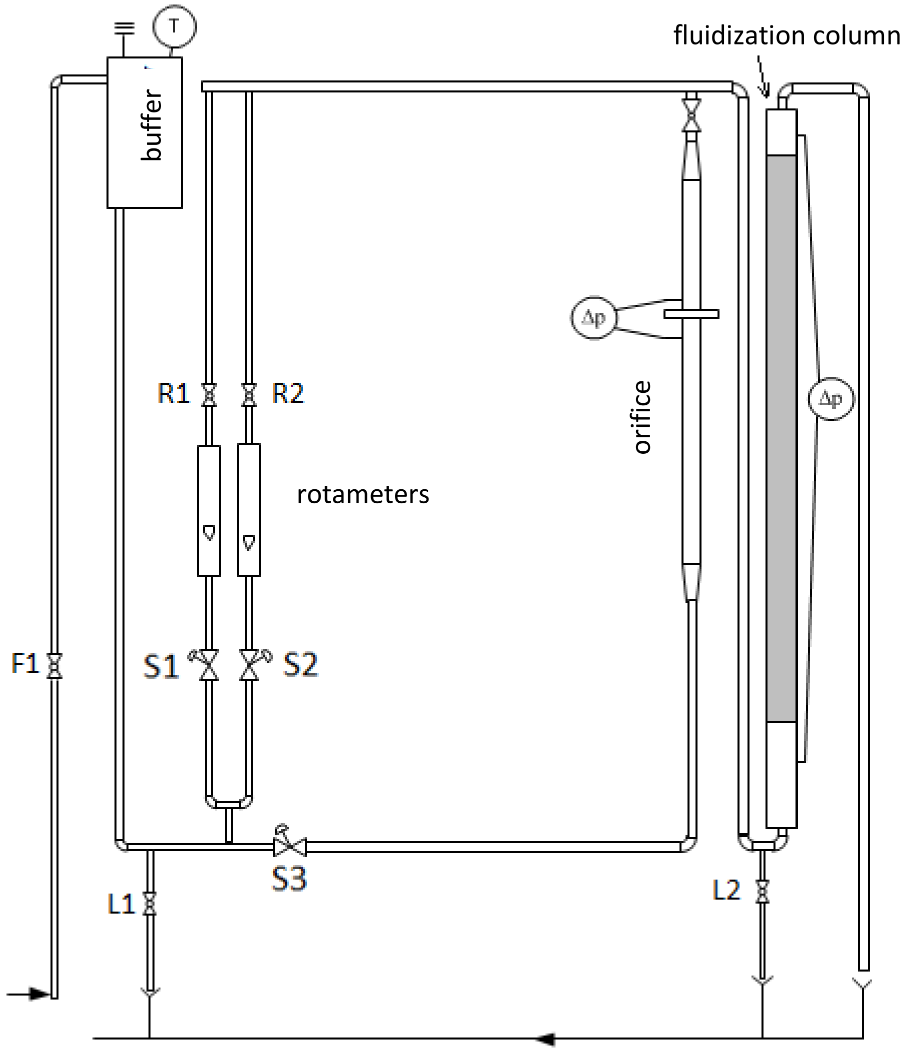
It has to be mentioned that the pressure drop of a fixed bed can be calculated using the Ergun-formula [2] too, if the voidage does not exceed 0.5.

$$\Delta p = v_0^2 \cdot \rho_f \cdot \left(\frac{L_0}{d_p}\right) \cdot \frac{1}{\varepsilon^3} \cdot \left[\frac{150 \cdot (1-\varepsilon)}{Re_m} + 1.75\right]$$

Description of the measurement process

The schematic of the measurement equipment is shown in Figure 4. The phenomenon of fluidization is studied in a plexiglas tube with in inner diameter of 54 mm. The packing consists of glass spheres with the diameter of 3 mm, the density of which is 2500 kg/m^3. The total mass of the packing in the equipment is 1 kg. The limits of the rotameters are 0-250 dm^3/h and 100-1000 dm^3/h. The larger diameter of the orifice is 5.1 cm while its smaller diameter is 2 cm. The volumetric flowrate can be calculated from the pressure drop measured on the orifice. This calculation does not have to be carried out during the measurement because in case of the orifice, the volumetric flowrate can be determined using a calibration curve. The measurement of the pressure drop on the column and on the orifice is carried out using two-fluid differential-manometers, the reference liquid in which is chloroform. Its density can be calculated using linear interpolation from the following table.

Temperature [°C]	Density of reference liquid [kg/m^3]
15	1498
20	1489
25	1480
30	1471



4. Figure

1. Ensure that taps L1 and L2 and valves S1, S2 and S3 are closed while the taps after the orifice are completely open.
2. Open the tap F1 all the way.
3. Open the valve S1 slowly and record the flowrate, the packing height and the pressure drop at 5 different flowrates.
4. Close the valve S1 and gradually open the valve S2. Continue increasing the flowrate and record another 5 data points.
5. When the flowrate approaches 900 lit/h, close the valve S2 and gradually open the valve S3. Record the pressure drop on the orifice, the pressure drop on the column and the packing height in case of a minimum of 5 different settings.
6. Make sure that the whole flowrate passes through only one rotameter or orifice at a time. During the measurement, the temperature of water needs to be measured once. When switching between the rotameters and the orifice, choose settings with no overlap in the measured data (this can be proved with the height of the bed).
7. At the end, the tap F1 and the valve S3 have to be closed.

Evaluation of the measurement

1. Knowing the mass and the bulk density of the packing, calculate the void-free packing height. Calculate the initial voidage (ε) from the measured initial packing height.
2. Determine the bulk density of the water (ρ_f) based on the measured temperature. Using this, and the level difference read from the manometer, determine the pressure drop of the column in each measurement point.
   Temperature dependent properties of water

Temperature $[°\boldsymbol{C}]$	**Bulk density** $\left[\frac{\boldsymbol{kg}}{\boldsymbol{m^3}}\right]$	**Viscosity** $[\boldsymbol{Pa \cdot s}]$
8	999,85	0,0013663
10	999,70	0,0013077
12	999,50	0,0012337
14	999,25	0,0011699
16	998,95	0,0011093
18	998,60	0,0010339
20	998,21	0,0010027
22	997,77	0,0009553
24	997,30	0,0009113
26	996,79	0,0008708
28	996,24	0,0008330
30	995,65	0,0007977

3. Using the values read from the rotameter and the pressure drops measured with the orifice, calculate the volumetric flowrate for each measurement point. Use the calibration diagram for the oracle when needed.
4. Using the values obtained in point 3., calculate the linear velocity of the fluid referring to the empty column for each measurement point.
5. Based on the measured packing heights and L_0, calculate the voidage for every datapoint.
6. Create a $log - log$ diagram of the pressure drop on a unitary voidage-free packing height $\frac{\Delta p}{L_0}$ on the basis of the linear speed of the fluid referring to the empty column. Also depict the voidage (ε) on the basis of the same speed. Mark the starting point of the fluidization and read the velocity at this point.
7. Calculate the velocity needed for fluidization then also read it from the $f_m Re_m^2 - Re_m^2$ diagram. Compare the values with the ones read at the task 7.
8. Calculate the pressure drop before the fluidization for each measurement conditions when packed column operation was performed using the suitable equations. Compare the obtained values with the measured results.
9. Calculate the grid-pressure (Δp_{grid}) and compare it with the measured pressure drop values before and at fluidization. Comment.
10. Determine the final velocity of fluidization (v_0^{**}) using the $f_m Re_m^2 - Re_m^2$ diagram.
11. Summarize your results in a table.

Nr.	Equip-ment	Rota-meter [*lit/h*]	Orifice		W $\left[\frac{lit}{h}\right]$	v_0 $\left[\frac{m}{s}\right]$	L $[m]$	Pressure drop on package					ε	
								Measured			Calculated		Based on measured L^{**}	Calculated
			Δh $[mm]$	Δp $[Pa]$				Δh $[mm]$	Δp $[Pa]$	$\frac{\Delta p}{L_0}$ $\left[\frac{Pa}{m}\right]$	Δp $[Pa]$	$\frac{\Delta p}{L_0}$ $\left[\frac{Pa}{m}\right]$		
1	Small rotameter													
2														
3														
4														
5														
6														
7	Large Rotameter													
8														
9														
10														
11														
12														
13														
14	Orifice													
15														
16														
17														

Initial fluidization speed (v_0^*) $\left[\frac{m}{s}\right]$		Carrying out speed (v_0^{**}) $\left[\frac{m}{s}\right]$	
From measured values		**Calculated**	
Calculated		**From the diagram**	
From the diagram			

Comparison of pressure drops		
Measured grid pressure		Pa
Calculated grid pressure		Pa
Relative error		%

[1] Wen-Ching Yang: Handbook of Fluidization and Fluid-Particle Systems, Routledge, 2003
[2] Fonyó Zs., Fábry Gy.: Vegyipari művelettani alapismeretek, Nemzeti Tankönyvkiadó, 2004
[3] Tanszéki munkaközösség: Vegyipari félüzemi praktikum, (átdolgozott kiadás), Egyetemi jegyzet, 65029, Műegyetemi Kiadó, 2000

Measurement data

Laboratory temperature: °C

The temperature of water: °C

The height of a non-operative packing: cm

Nr.	Measurement tool	Rota. [lit/h]	Orifice manometer		Column manometer		L [cm]
			h_1 [mm]	h_2 [mm]	h_1 [mm]	h_2 [mm]	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							