Fluidization

- When a fluid is passed upwards through a bed of particles the pressure loss in the fluid due to frictional resistance increases with increasing fluid flow

- A point is reached when the upward drag force exerted by the fluid on the particles is equal to the apparent weight of particles in the bed

- At this point the particles are lifted by the fluid, the separation of the particles increases and the bed becomes fluidized

- The force balance across the fluidized bed dictates that the fluid pressure loss across the bed of particles is equal to the apparent weight of the particles per unit area of the bed

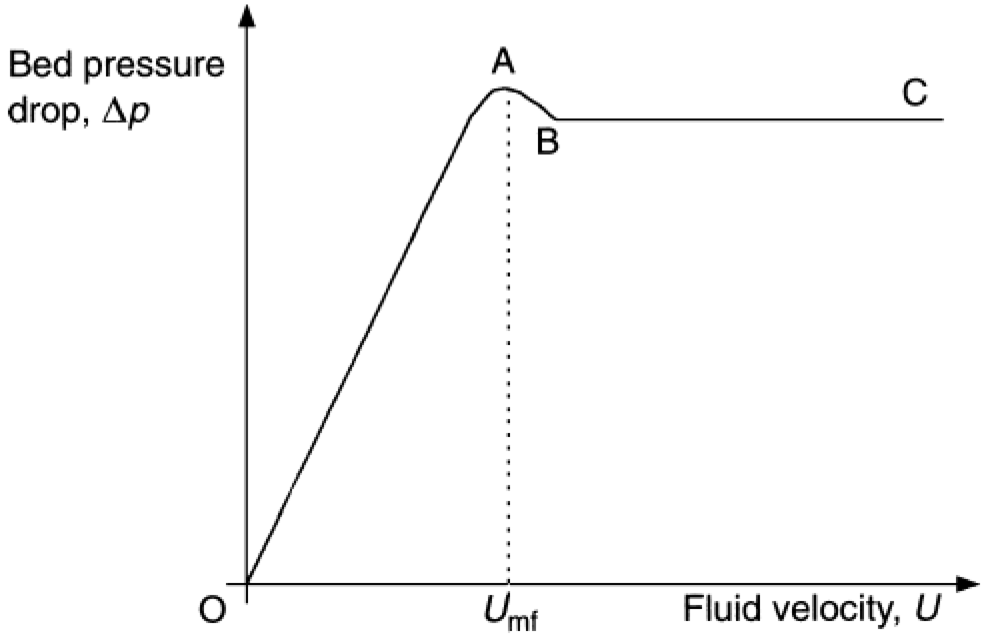
$$\text{pressure drop} = \frac{\text{weight of particles} - \text{upthrust on particle}}{\text{bed cross-sectional area}}$$

- For a bed of particles of density ρ_p, fluidized by a fluid of density ρ_f to form a bed of depth H and voidage ε in a vessel of cross-sectional area *A*

$$\Delta p = \frac{HA(1-\varepsilon)(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})g}{A}$$

or

$$\Delta p = H(1-\varepsilon)(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})g$$



A plot of fluid pressure loss across the bed versus superficial fluid velocity through the bed

https://www.youtube.com/watch?v=lFhrpSJZzck

- OA is the packed bed region
- Solid particles do not move relative to one another and their separation is constant
- Pressure loss vs fluid velocity relationship is described by the Carman-Kozeny equation and the Ergun equation
- BC is the fluidized bed region
- At point A, pressure loss rises above the value predicted
- This rise is more marked in small vessels and in powders which have been compacted to some extent before the test
- Associated with the extra force required to overcome wall friction and adhesive forces between bed and distributor

- Superficial fluid velocity at which the packed bed becomes a fluidized bed is known as the minimum fluidization velocity, $U_{mf.}$

- Sometimes referred to as the velocity at incipient fluidization

- U_{mf} increases with particle size and particle density and is affected by fluid properties

- To derive expression for U_{mf}, equate expression for pressure loss in a fluidized bed with pressure loss across a packed bed

Applying the Ergun equation-

$$\frac{(-\Delta p)}{H} = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{x_{\mathrm{sv}}^2} + 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_{\mathrm{f}} U^2}{x_{\mathrm{sv}}}$$

$$(1-\varepsilon)(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})g = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U_{\mathrm{mf}}}{x_{\mathrm{sv}}^2} + 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_{\mathrm{f}} U_{\mathrm{mf}}^2}{x_{\mathrm{sv}}}$$

Multiplying with viscosity, particle mean diameter, and fluid density-n

$$\begin{aligned}(1-\varepsilon)(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})g &= 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3}\left(\frac{\mu^2}{\rho_{\mathrm{f}} x_{\mathrm{sv}}^3}\right)\left(\frac{U_{\mathrm{mf}} x_{\mathrm{sv}} \rho_{\mathrm{f}}}{\mu}\right) \\ &\quad + 1.75\,\frac{(1-\varepsilon)}{\varepsilon^3}\left(\frac{\mu^2}{\rho_{\mathrm{f}} x_{\mathrm{sv}}^3}\right)\left(\frac{U_{\mathrm{mf}}^2 x_{\mathrm{sv}}^2 \rho_{\mathrm{f}}^2}{\mu^2}\right)\end{aligned}$$

or

$$(1-\varepsilon)(\rho_p-\rho_f)g\left(\frac{\rho_f x_{sv}^3}{\mu^2}\right)=150\frac{(1-\varepsilon)^2}{\varepsilon^3}Re_{mf}+1.75\frac{(1-\varepsilon)}{\varepsilon^3}Re_{mf}^2$$

$$Ar=150\frac{(1-\varepsilon)}{\varepsilon^3}Re_{mf}+1.75\frac{1}{\varepsilon^3}Re_{mf}^2$$

Where *Ar* is the dimensionless number known as the Archimedes number

$$Ar=\frac{\rho_f(\rho_p-\rho_f)g x_{sv}^3}{\mu^2}$$

And Re_{mf} is the Reynolds number at incipient fluidization

$$Re_{mf}=\left(\frac{U_{mf}x_{sv}\rho_f}{\mu}\right)$$

In order to obtain a value of U_{mf}, we need to know the voidage of the bed at incipient fluidization, $\varepsilon = \varepsilon_{mf}$

- A typical value of ε_{mf} is 0.4

$$Ar = 1406\, Re_{\mathrm{mf}} + 27.3\, Re_{\mathrm{mf}}^2$$

- Wen and Yu (1966) produced an empirical correlation for U_{mf}

$$Ar = 1652 Re_{\mathrm{mf}} + 24.51 Re_{\mathrm{mf}}^2$$

- This correlation is valid for spheres in the range $0.01 < Re_{mf} < 1000$ and is often expressed in the form:

$$Re_{\mathrm{mf}} = 33.7[(1 + 3.59 \times 10^{-5} Ar)^{0.5} - 1]$$

- For gas fluidization, the Wen and Yu correlation is often taken as most suitable for particles larger than 100 mm.
- The correlation of Baeyens and Geldart (1974) is best for particles less than 100 mm

$$U_{\mathrm{mf}} = \frac{(\rho_p - \rho_f)^{0.934} g^{0.934} x_{\mathrm{p}}^{1.8}}{1110 \mu^{0.87} \rho_{\mathrm{f}}^{0.066}}$$

Relevant Powder and Particle Properties

- The correct density for use in fluidization equations is the particle density
- Defined as the mass of a particle divided by its hydrodynamic volume
- Volume 'seen' by the fluid in its fluid dynamic interaction with the particle
- It Includes the volume of all open and closed pores

$$\text{particle density} = \frac{\text{mass of particle}}{\text{hydrodynamic volume of particle}}$$

- Bed density is also used in connection with fluidized beds

$$\text{absolute density} = \frac{\text{mass of particle}}{\text{volume of solids material making up the particle}}$$

- For non-porous solids, this is easily measured by a gas pycnometer or specific gravity bottle, but these devices should not be used for porous solids since they give the true or absolute density ρ_{abs} of the material of which the particle is made and this is not appropriate where interaction with fluid flow is concerned.

- For porous particles, the particle density ρ_p (also called apparent or envelope density) is not easy to measure directly. Bed density is another term used in connection with fluidized beds; bed density is defined as-

$$\text{bed density} = \frac{\text{mass of particles in a bed}}{\text{volume occupied by particles and voids between them}}$$

For example, 600 kg of powder is fluidized in a vessel of cross-sectional area 1 m^2 and achieves a bed height of 0.5 m. What is the bed density?

Mass of particles in the bed = 600 kg

Volume occupied by particles and voids = $1 \times 0.5 = 0.5\,m^3$

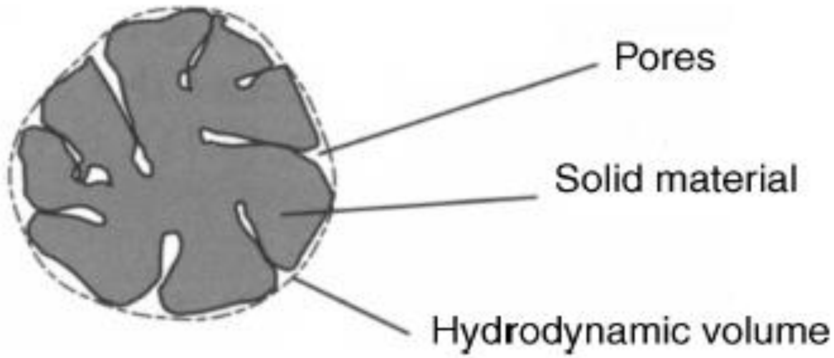
Hence, bed density = $600/0.5 = 1200\,kg/m^3$.

If the particle density of these solids is 2700 kg/m^3, what is the bed voidage?

Bed density ρ_B is related to particle density ρ_p and bed voidage ε by

$$\rho_B = (1 - \varepsilon)\rho_p$$

$$\text{voidage} = 1 - \frac{1200}{2700} = 0.555.$$



Hydrodynamic volume of a particle

- Another density often used is the bulk density, defined in a similar way to fluid bed density-

$$\text{bulk density} = \frac{\text{mass of particles}}{\text{volume occupied by particles and voids between them}}$$

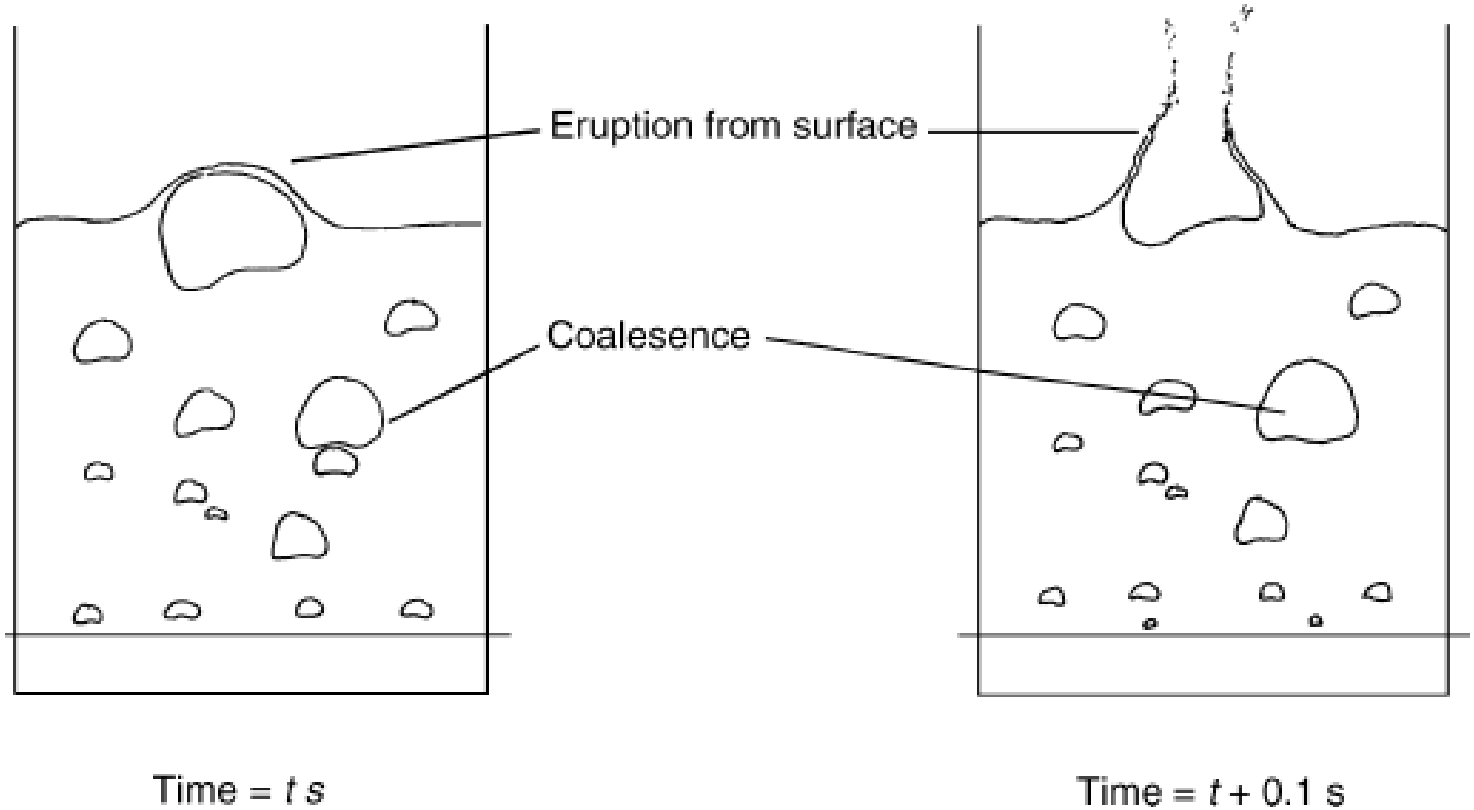
- The most appropriate particle size to use in equations relating to fluid-particle interactions is a hydrodynamic diameter i.e. an equivalent sphere diameter derived from a measurement technique involving hydrodynamic interaction between the particle and fluid.

$$\text{mean } x_{\mathrm{p}} = \frac{1}{\sum m_i / x_i}$$

Where x_i is the arithmetic mean of adjacent sieves between which a mass fraction m_i is collected.

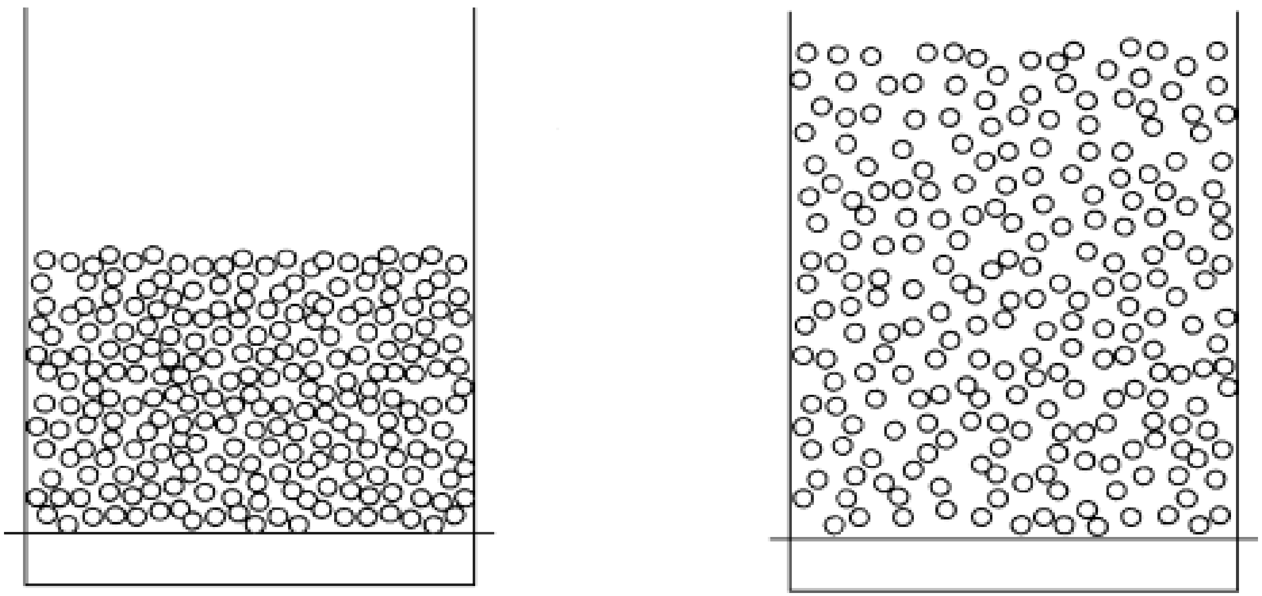
Bubbling and Non-bubbling Fluidization

- Beyond the minimum fluidization velocity bubbles or particle-free voids may appear in the fluidized bed
- At superficial velocities above the minimum fluidization velocity, fluidization may in general be either bubbling or non-bubbling
- Some combinations of fluid and particles give rise to only bubbling fluidization and some combinations give only non-bubbling fluidization



Bubbles in gas fluidized bad

- Most liquid fluidized systems, except those involving very dense particles, do not give rise to bubbling.
- The Figure shows the bed of glass spheres fluidized by water exhibiting non-bubbling fluidized bed behavior.



Expansion of a liquid fluidized bed: (a) just above U_{mf} (b) liquid velocity several times U_{mf}

- Gas fluidized systems give either only bubbling fluidization or non-bubbling fluidization beginning at U_{mf}, followed by bubbling fluidization as fluidizing velocity increases
- Non-bubbling fluidization is also known as particulate or homogeneous fluidization
- Bubbling fluidization is often referred to as aggregative or heterogeneous fluidization

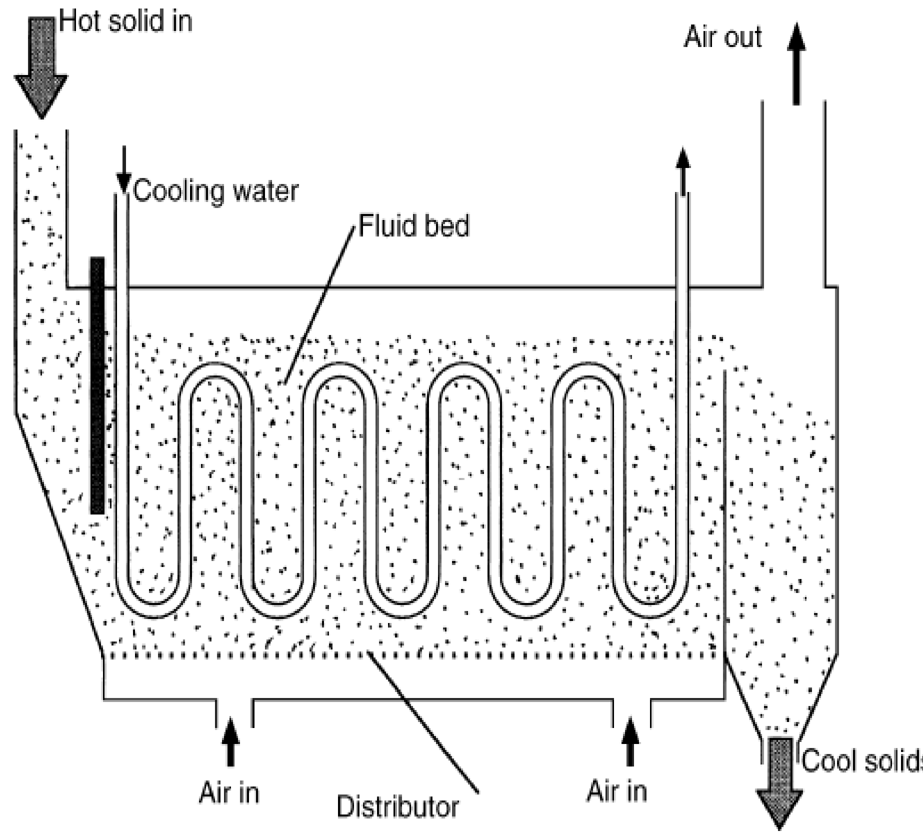
Applications of Fluidized Beds

Physical processes

- Physical processes include drying, mixing, granulation, coating, heating and cooling.
- These processes take advantage of the excellent mixing capabilities of the fluidized bed.
- Good solids mixing gives rise to good heat transfer, temperature uniformity and ease of process control
- One of the most important applications is to the drying of solids.
- Fluidized beds are currently used commercially for drying such materials as crushed minerals, sand, polymers, pharmaceuticals, fertilizers and crystalline products.

- Fluidized beds are often used to cool particulate solids following a reaction

- Cooling may be by fluidizing air alone or by use of cooling water passing through tubes immersed in the bed



Schematic diagram of a fluidized bed solid cooler

Schematic diagram of a fluidized bed solid cooler

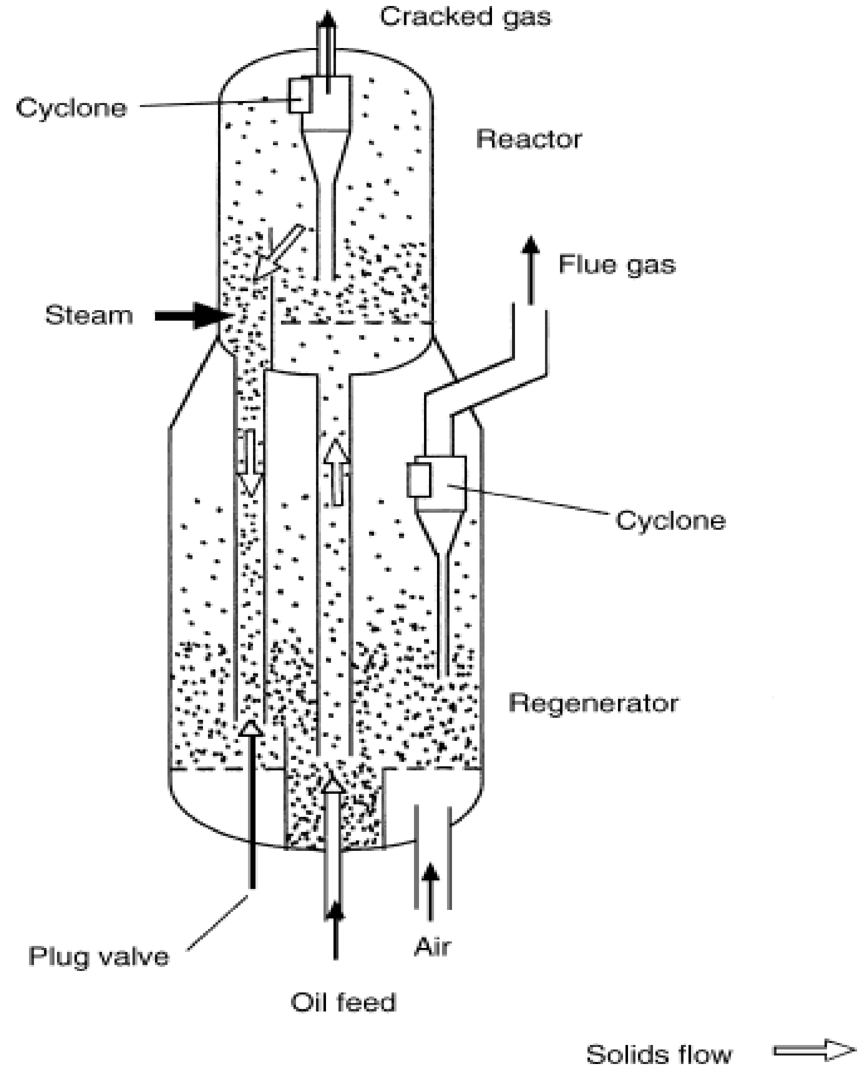
Chemical Processes

- Gas fluidized bed is also a good medium to carry out a chemical reaction involving a gas and a solid.

Advantages of the fluidized bed for chemical reaction include:

- Gas-solid contacting is generally good
- Excellent solids circulation within the bed promotes good heat transfer between bed particles and fluidizing gas and between the bed and heat transfer surfaces immersed in the bed
- Gives rise to near isothermal conditions even when reactions are strongly exothermic or endothermic
- Good heat transfer gives rise to ease of control of the reaction
- Fluidity of the bed makes for ease of removal of solids from reactor

Fluid catalytic cracking (FCC) unit, a celebrated example of fluidized bed technology for breaking down large molecules in crude oil to small molecules suitable for gasoline, etc.



Types of gas-solid chemical reactions employing fluidization

Type	Example	Reasons for using a fluidized bed
Homogeneous gas-phase reactions	Ethylene hydrogenation	Rapid heating of entering gas. Uniform controllable temperature
Heterogeneous non-catalytic reactions	Sulfide ore roasting, combustion	Ease of solids handling. Temperature uniformity. Good heat transfer
Heterogeneous catalytic reactions	Hydrocarbon cracking, phthalic anhydride, acrylonitrile	Ease of solids handling. Temperature uniformity. Good heat transfer

References

Martin Rhodes, "Introduction to Particle Technology", 2nd Edition, John Wiley & Sons, 2008.

Mechanical Operations. Authors: A.K. *Swain*, H. Patra and G.K. Roy. Publisher: Tata McGraw Hill Education Pvt. Ltd., New Delhi