Oregon State University

OREGON STATE UNIVERSITY
CBEE Department of Chemical Engineering

CHE 331
Transport Phenomena1

Dr. Goran Jovanovic

Mechanical Energy Balance Equation
Flow Through Fluidized Beds

Please turn-off cell phones

CHE 331
Fall 2022

Fluidized Bed Operations

There are two types of Fluidized Bed applications

Fluidized Bed Reactors

1. Oil Cracking
2. Coal Burning
3. Pyrolysis of FeS
4. Fuel Synthesis
5. Penicillin Production
6. . . . .
7. . . . .

Fluidized Bed Operations

1. Drying of solids
2. Heat recuperation
3. Mixing of Particles
4. Separation of Particles
5. Coating of Particles
6. Adsorption
7. Cooling of fluids
8. . . . . .

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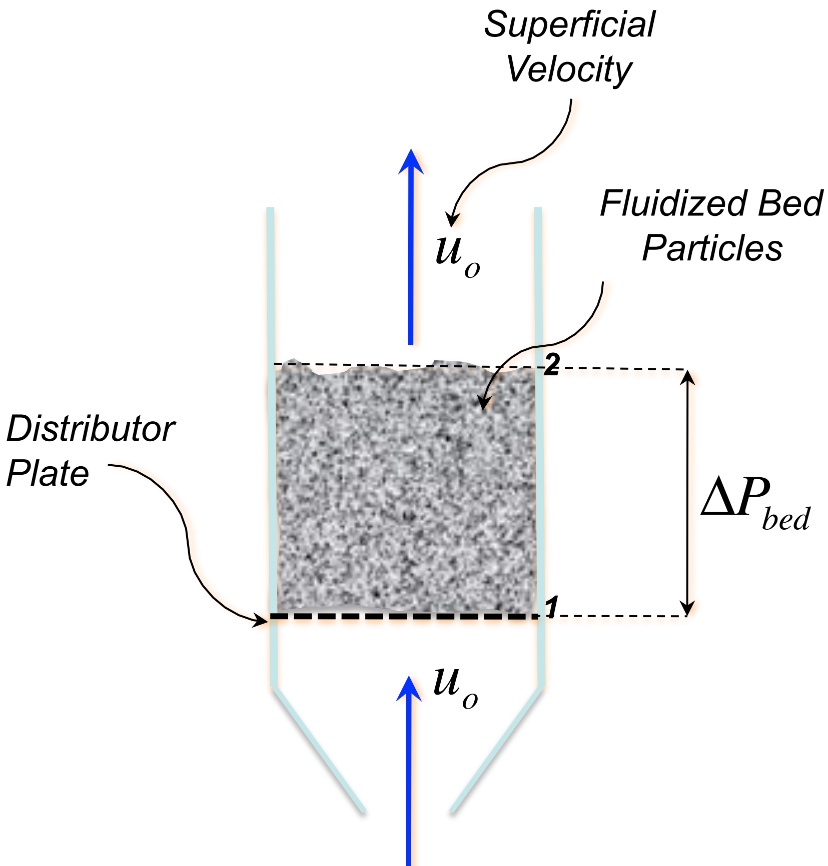
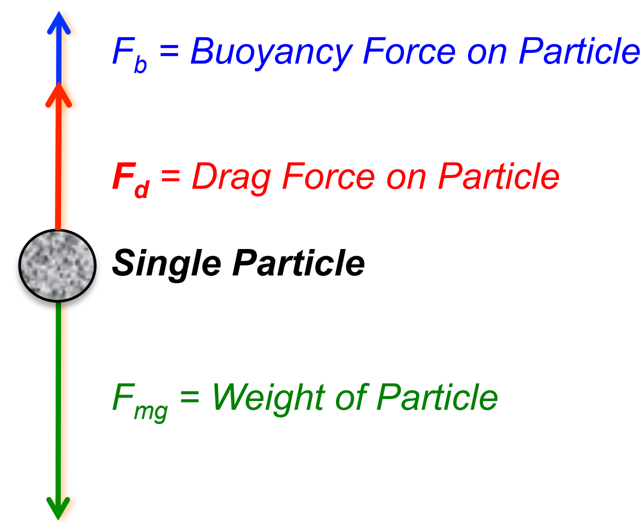
MECHANICAL ENERGY BALANCE EQUATION

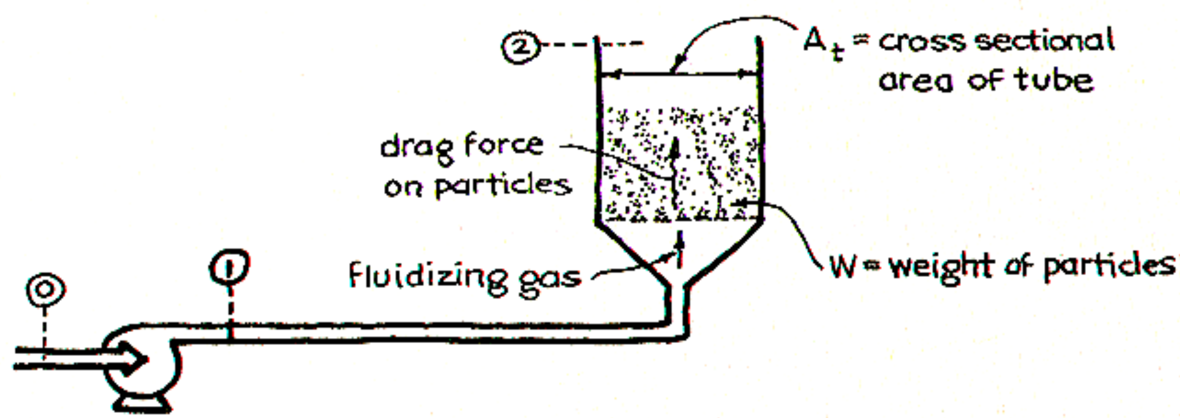
Fluidized Bed Operations





$$g\Delta Z + \frac{\Delta \bar{u}^2}{2} + \int_{P_1}^{P_2} \frac{dP}{\rho} + W_{S\,out} + \sum F = 0$$

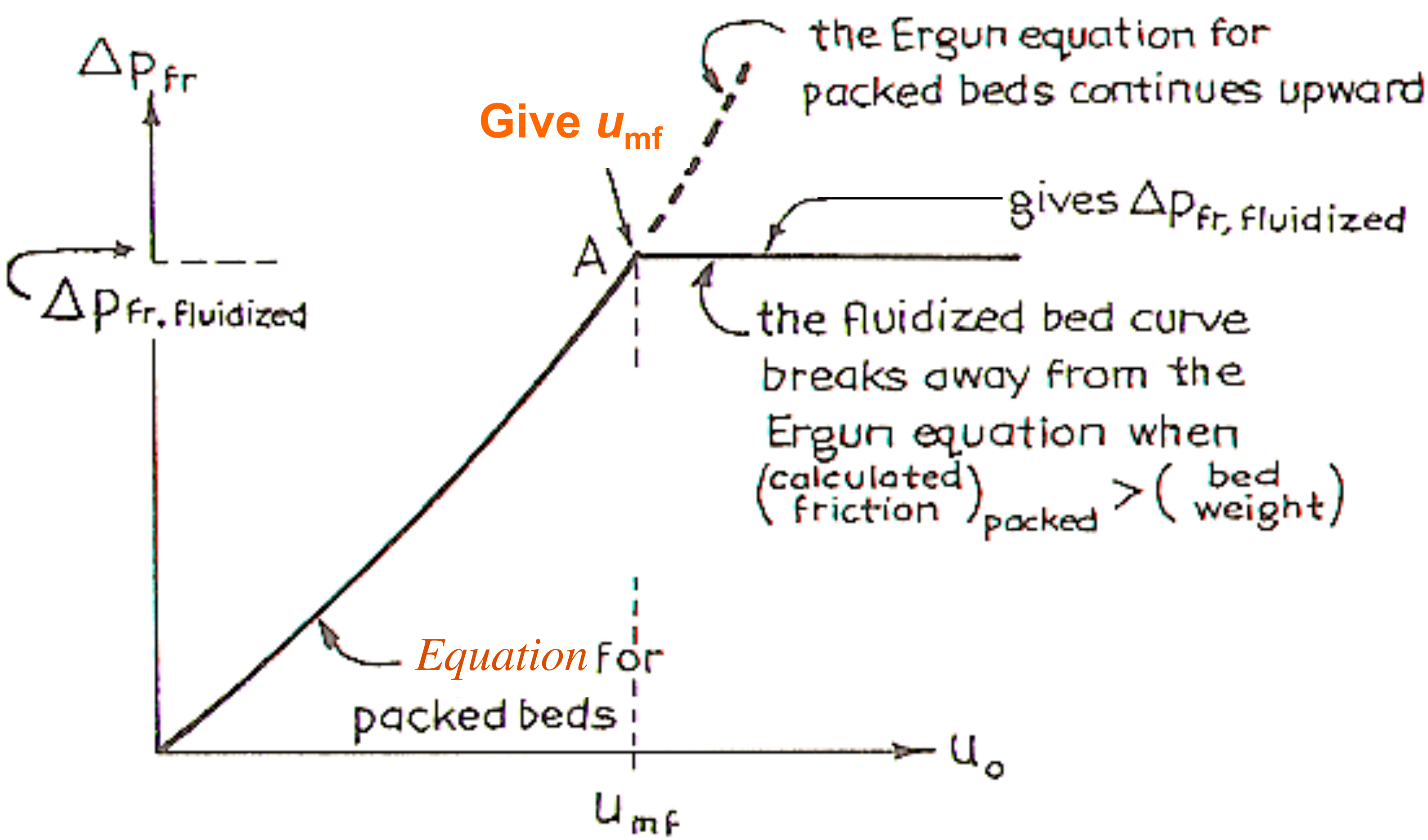
Fluidized Bed Operations



Frictional Pressure Drop	x	Cross Sectional Area of Bed	=	Volume of Bed	x	Fraction of Bed Consisting of Solids	x	Specific Buoyant Weight of Solids

$$\Delta P_{Bed} \times \left(\frac{\pi D_{Bed}^2}{4}\right) = \left(\frac{\pi D_{Bed}^2}{4}\right) \cdot L_{Bed} \times (1-\varepsilon) \times \left[\left(\rho_{par} - \rho_{flu}\right) \cdot g\right]$$

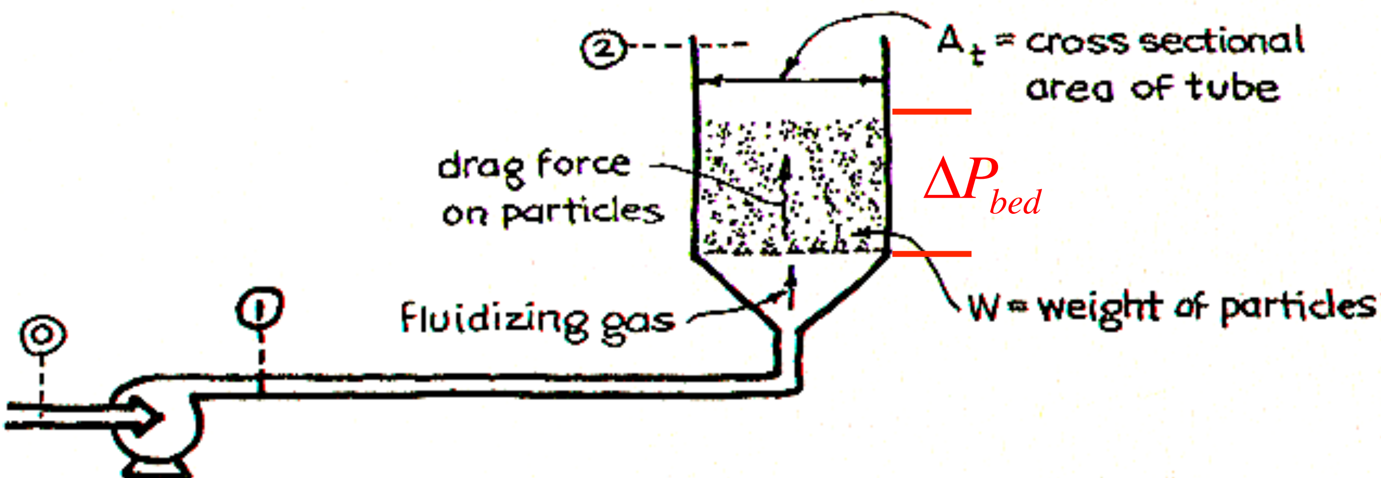
Fluidized Bed Operations



MECHANICAL ENERGY BALANCE EQUATION

Fluidized Bed Operations

Consider Ergun Equation at the moment just before the fluidization occurs; i.e. while the bed is still packed bed.



Turbulent Losses

$$\sum F = \frac{150(1-\varepsilon_{mf})^2 \mu u_{mf} L_{mf}}{\varepsilon_{mf}^3 d_{part}^2 \rho} + \frac{1.75(1-\varepsilon_{mf}) u_{mf}^2 L_{mf}}{\varepsilon_{mf}^3 d_{part}} \qquad Eq.1$$

Viscous Losses

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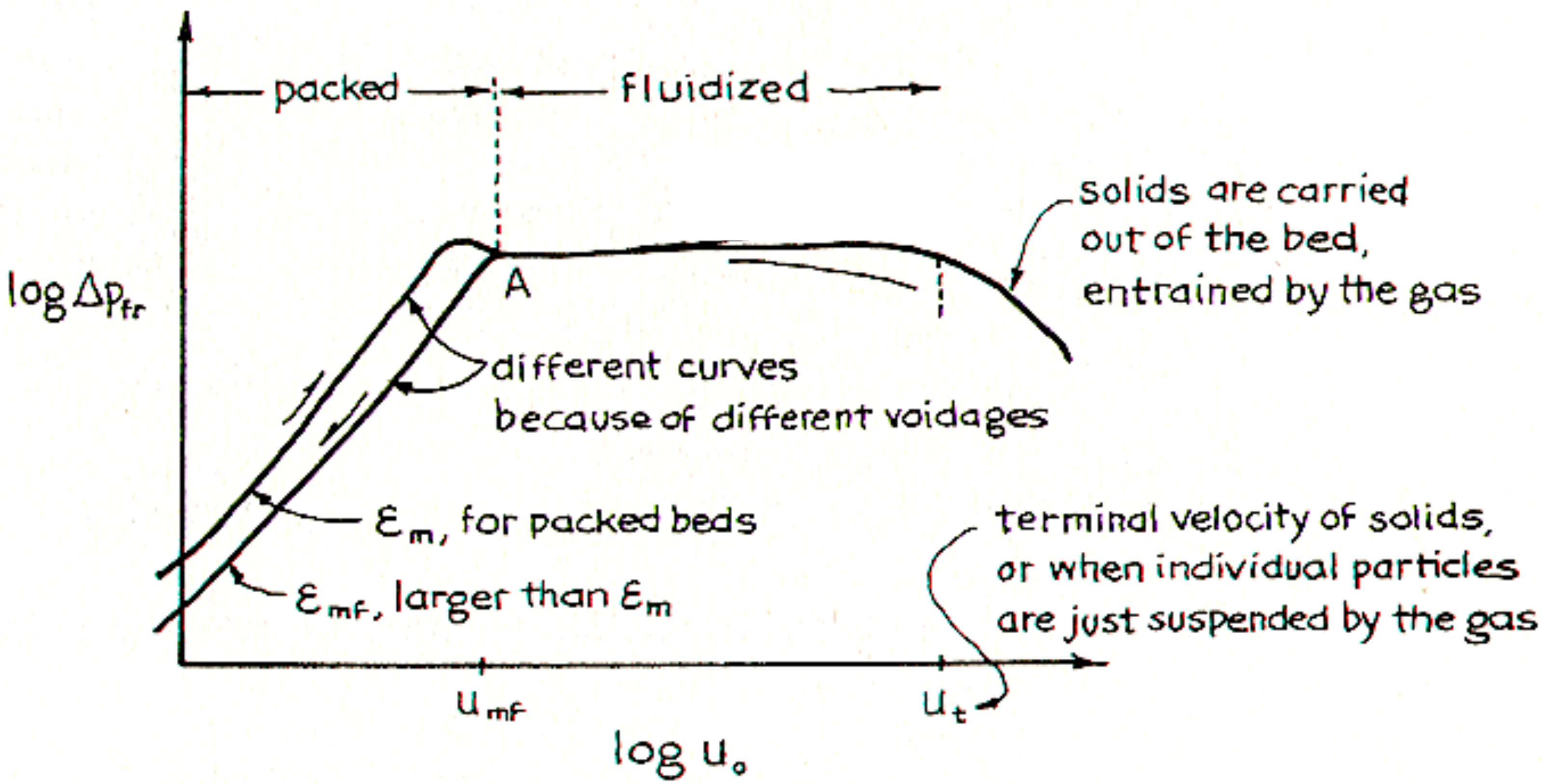
MECHANICAL ENERGY BALANCE EQUATION

Fluidized Bed Operations



MECHANICAL ENERGY BALANCE EQUATION

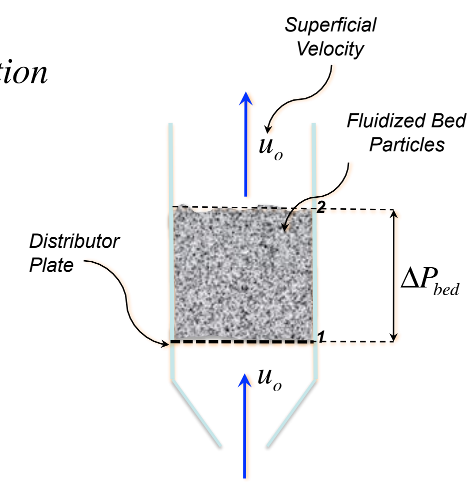
Fluidized Bed Operations

$$\left\{\begin{matrix}\text{Total Drag Force between} \\ \text{fluid on particles}\end{matrix}\right\} = \left\{\begin{matrix}\text{Weight of Solids} \\ \text{in the bed}\end{matrix}\right\}$$

$$\left\{\Delta P_{friction} A_t\right\} = \left\{A_t L_{mf}\left(1-\varepsilon_{mf}\right)(\rho_{part} - \rho_{fluid})g\right\} \qquad Eq.2$$

From the MEB equation we can estimate: $\Delta P_{friction}$

$$g\Delta Z + \frac{\cancel{\Delta \bar{u}^2}}{2} + \int_{P_1}^{P_2} \frac{dP}{\rho} + \cancel{W_{S,out}} + \sum F = 0$$



If we assume that: $\Delta P_{bed} < 0.1 P_{average}$

$$g\Delta Z + \frac{\Delta P}{\rho} + \sum F = 0 \quad \Rightarrow \quad \sum F = -g\Delta Z - \frac{\Delta P}{\rho}$$

MECHANICAL ENERGY BALANCE EQUATION

Fluidized Bed Operations

For gas-solid system: $$\sum F = -g\cancel{\Delta Z} - \frac{\Delta P}{\rho}$$

Now we can substitute Eq.1 and Eq.2 into above equation and obtain:

$$\frac{150(1-\varepsilon_{mf})^2 \mu u_{mf} L_{mf}}{\varepsilon_{mf}^3 d_{part}^2} + \frac{1.75\rho(1-\varepsilon_{mf}) u_{mf}^2 L_{mf}}{\varepsilon_{mf}^3 d_{part}} =$$

$$= \left\{ L_{mf} \left(1-\varepsilon_{mf}\right)(\rho_{part} - \rho_{fluid}) g \right\}$$

$$\frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3} \mathrm{Re}_{p,mf} + \frac{1.75}{\varepsilon_{mf}^3} \mathrm{Re}_{p,mf}^2 = \frac{d_p^3 \rho_f (\rho_p - \rho_f) g}{\mu^2}$$

MECHANICAL ENERGY BALANCE EQUATION

For predominantly viscous/laminar flow:

$$u_{mf} = \frac{d_p^2\left(\rho_p - \rho_f\right)}{150\mu}\frac{g\varepsilon_{mf}^3}{1-\varepsilon_{mf}} \quad \text{for } \mathrm{Re}_{\mathrm{p,mf}} < 20$$

For predominantly turbulent flow:

$$u_{mf}^2 = \frac{d_p\left(\rho_p - \rho_f\right)}{1.75\rho_f} g\varepsilon_{mf}^3 \quad \text{for } \mathrm{Re}_{\mathrm{p,mf}} > 1000$$

And for any Re:

$$\frac{d_p u_{mf}\rho_f}{\mu} = \sqrt{28.7^2 + \frac{0.0494 d_p^3 \rho_f\left(\rho_p - \rho_f\right)g}{\mu^2}} - 28.7$$

Fluidized Bed Operations

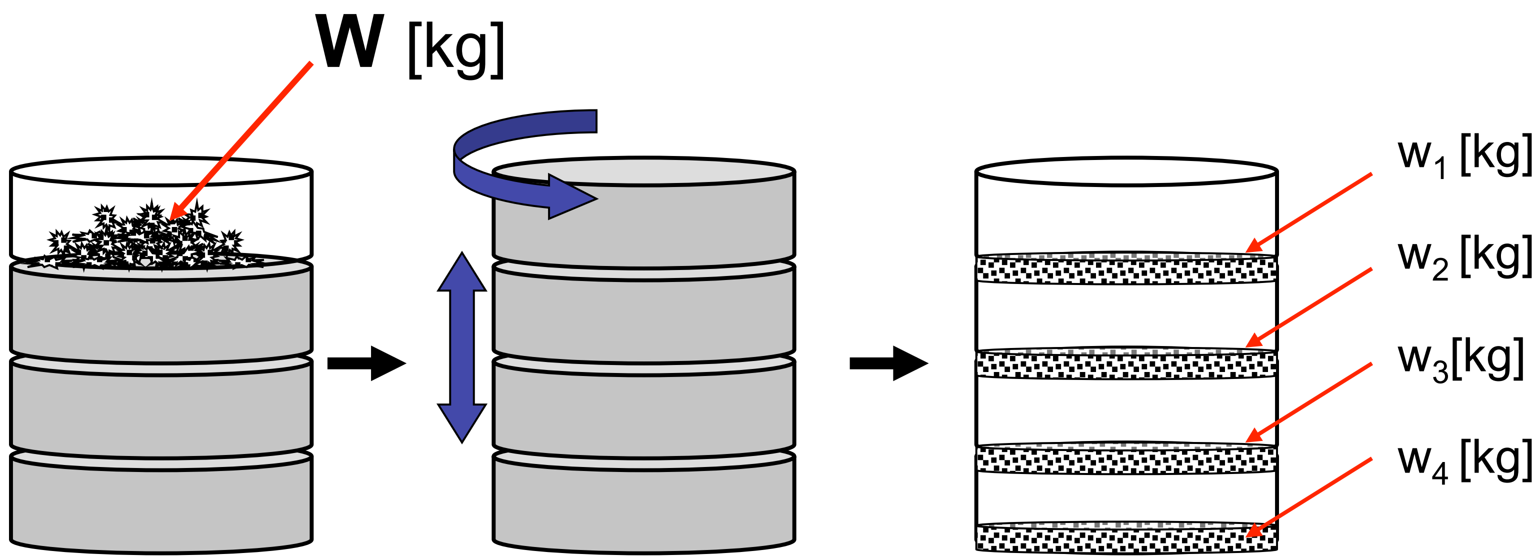
$$1 = \frac{V_{particles}}{V_{Total}} + \frac{V_{fluid}}{V_{Total}} \Rightarrow \quad 1 = \delta + \varepsilon = (1 - \varepsilon) + \varepsilon$$

Voidage

$$Voidage = \frac{V_{fluid}}{V_{Total}} = \varepsilon$$

It is also true: $Voidage = \frac{A_{fluid}}{A_{Total}} = \varepsilon$

MECHANICAL ENERGY BALANCE EQUATION – Particle Size



$$x_1 = \frac{w_1}{W};\quad x_2 = \frac{w_2}{W};\quad x_3 = \frac{w_3}{W};\quad x_4 = \frac{w_4}{W}$$

$$d_{scr \cdot i} = \frac{(\text{upper screen size} + \text{lower screen size})}{2}$$

$$d_{pi} = d_{scr \cdot i} \times \Phi$$

$$\bar{d}_p = \frac{1}{\sum\limits_{\text{all size cuts}} \left(\frac{x_i}{d_{pi}}\right)}$$

MECHANICAL ENERGY BALANCE EQUATION – Particle Size

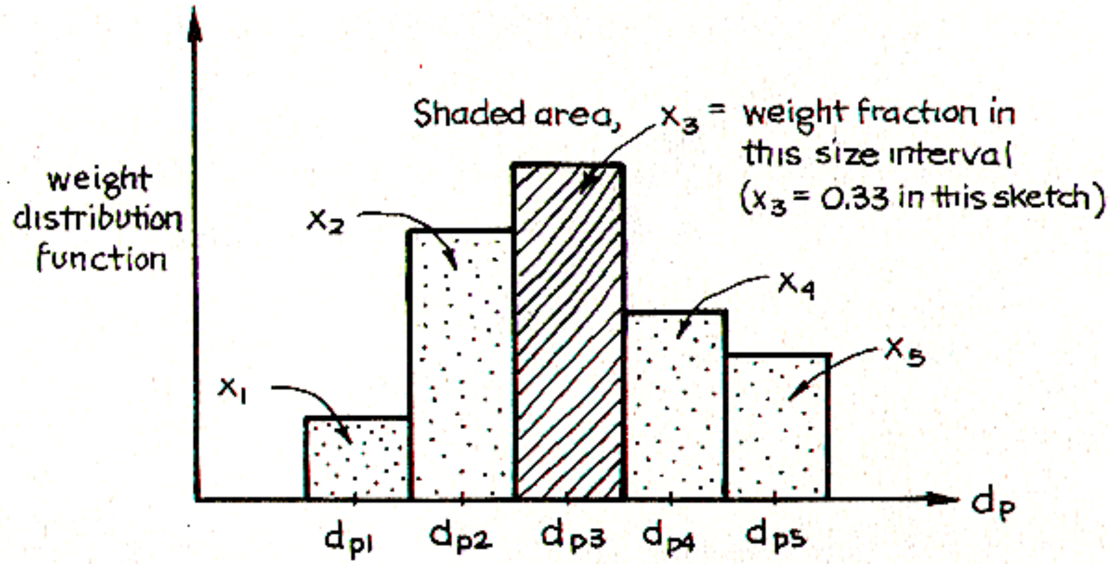


Fig. 6.2. Histogram representing the size distribution of particles in a packed bed.

$$\bar{d}_p = \left(\begin{array}{l} \text{the nominal size of particles which would have the same total} \\ \text{surface area as the size mixture in question - same total bed} \\ \text{volume and same bed voidage in both cases} \end{array} \right)$$

$$\bar{d}_p = \frac{1}{\sum\limits_{\text{all size cuts}} \left(\frac{x_i}{d_{pi}} \right)}$$

MECHANICAL ENERGY BALANCE EQUATION

Tyler Standard Screen Sizes

Mesh number (number of wires/in)	Aperture, μm (opening between adjacent wires)	Mesh number (number of wires/in)	Aperture, μm (opening between adjacent wires)
3	6680	35	417
4	4699	48	295
6	3327	65	208
8	2362	100	147
10	1651	150	104
14	1168	200	74
20	833	325	53
28	589	400	38

Unfortunately there is no general relationship between d_{scr} and d_p. The best we can say for pressure drop considerations in packed beds is

- for irregular particles with no seeming long or shorter dimension take

$$d_p \cong \phi d_{scr} = \phi d_{sph}$$

MECHANICAL ENERGY BALANCE EQUATION – Particle Size

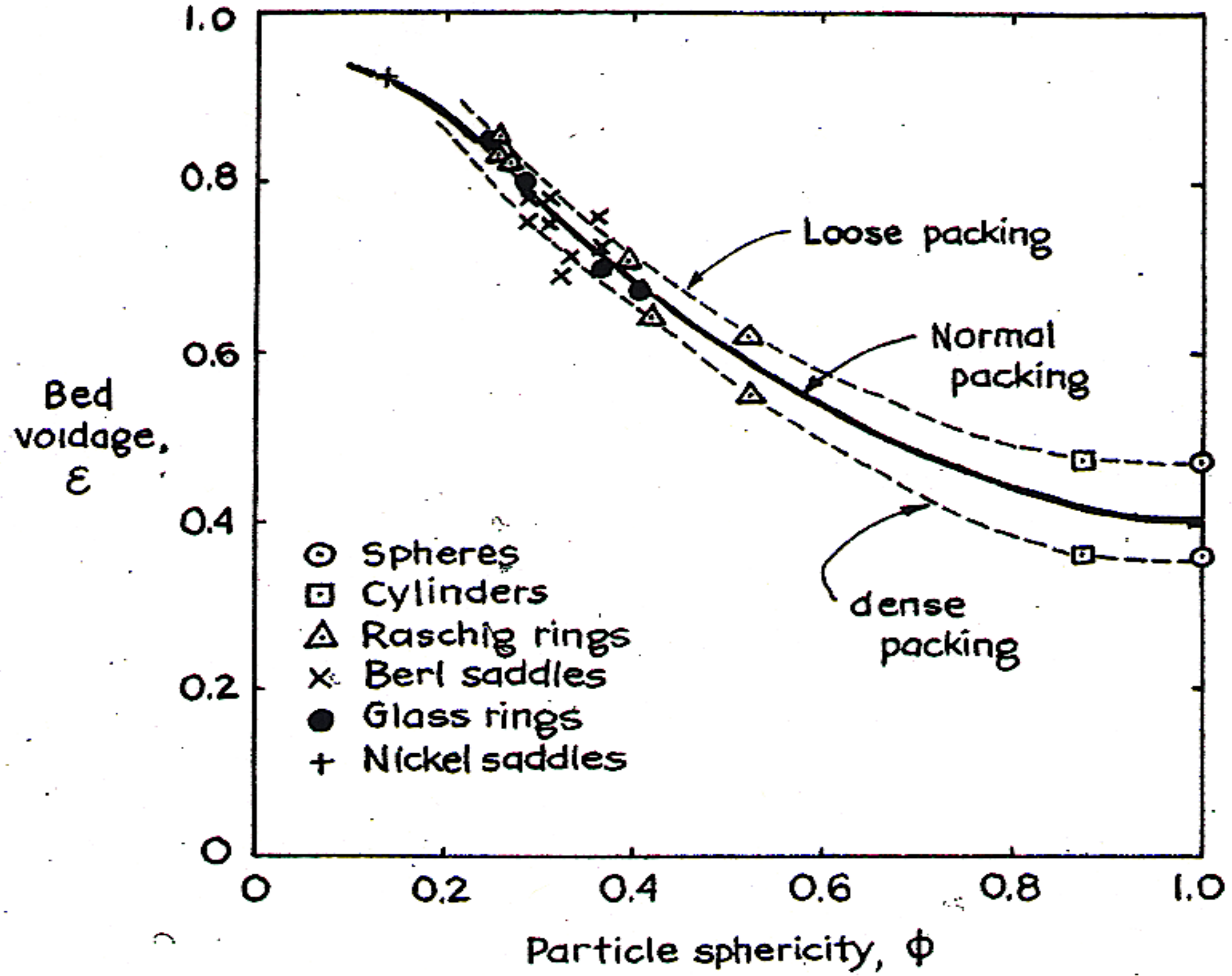
Particle shape	Sphericity ϕ
Sphere	1.00
Cube	0.81
Cylinder	
$h = d$	0.87
$h = 5d$	0.70
$h = 10d$	0.58
Disks	
$h = d/3$	0.76
$h = d/6$	0.60
$h = d/10$	0.47
Old beach sand	As high as 0.86
Young river sand	As low as 0.53
Average for various types of sand	0.75
Crushed solids	0.5–0.7
Granular particles	0.7–0.8
Wheat	0.85
Raschig rings	0.26–0.53
Berl saddles	0.30–0.37
Nickel saddles	0.14

[a] Data from Brown (1950), and from geometrical considerations.

$$\Phi = \left(\frac{\text{Surface of Sphere}}{\text{Surface of Particle}}\right)_{\substack{SAME \\ VOLUME}}$$

$$\Phi \leq 1$$

MECHANICAL ENERGY BALANCE EQUATION



The voidage increases as the sphericity decreases for randomly packed beds of uniform particles.

People. Ideas. Innovation.

Thank you for your attention!