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DIFFICULTIES
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BY

# Design and Operation of Moving Bed Processors

Greg Mehos, Ph.D., P.E.

Greg Mehos & Associates LLC

gmehos@uri.edu

greg@mehos.net

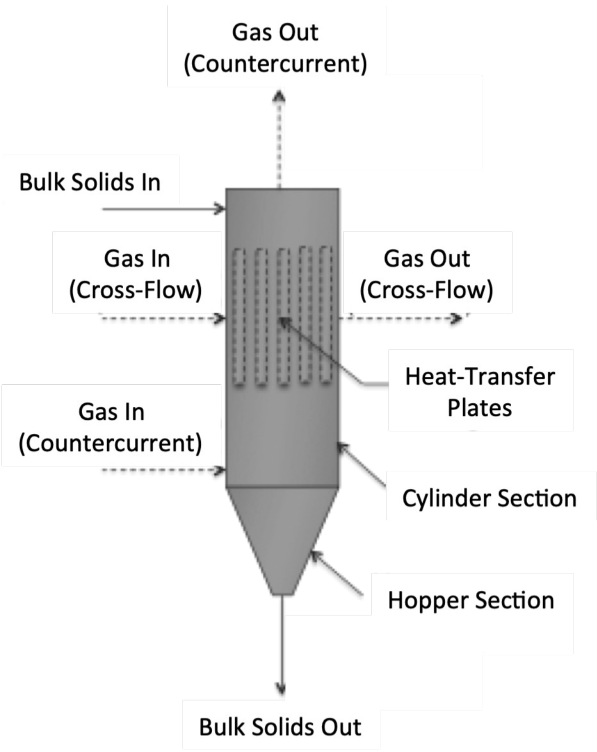
www.mehos.net

https://www.linkedin.com/in/gmehos/

978-799-7311

# Happiness Equals Reality Minus Expectations

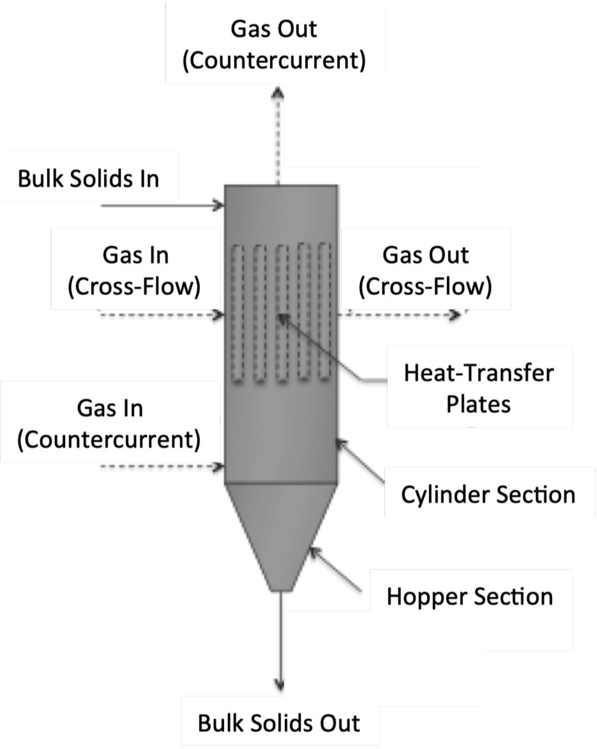
# Moving bed processors




*"GRUMP"*

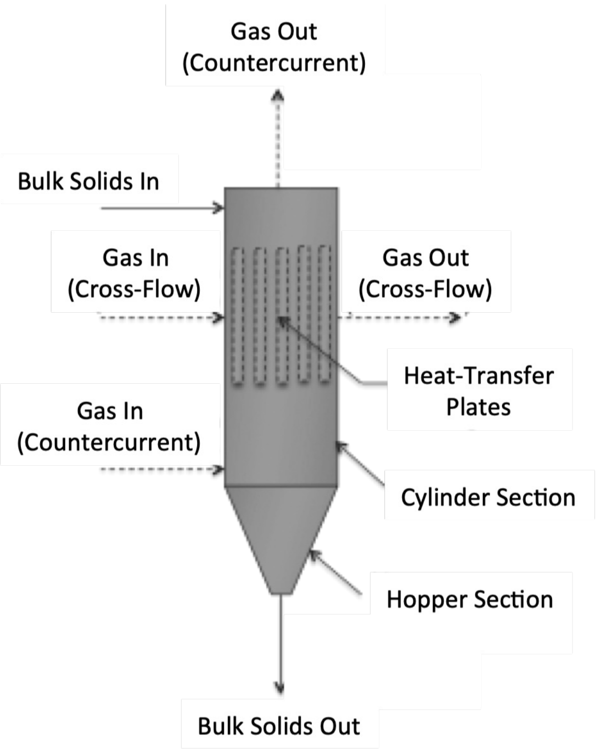
# Advantages

- Lower capital, operating, and maintenance costs
  - No moving parts
  - Higher throughputs
- Offers surge or storage capacity
- Long residence times



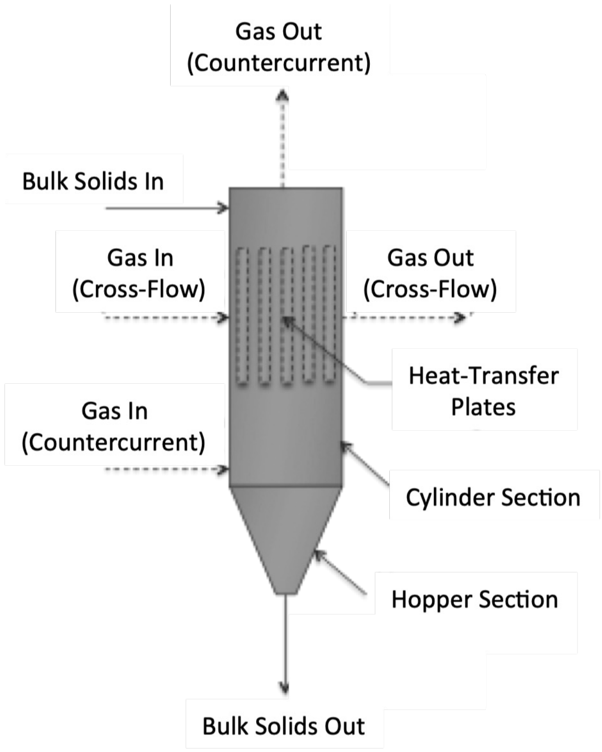
# Disadvantages

- No mixing
- Not amenable to batch processes
- Fine powders may need large diameters or multiple vessels



# Requirements

- Plug flow of solids
- Proper outlet size
- Uniform gas flow
- Stable solids bed
- Necessary volume/ residence time



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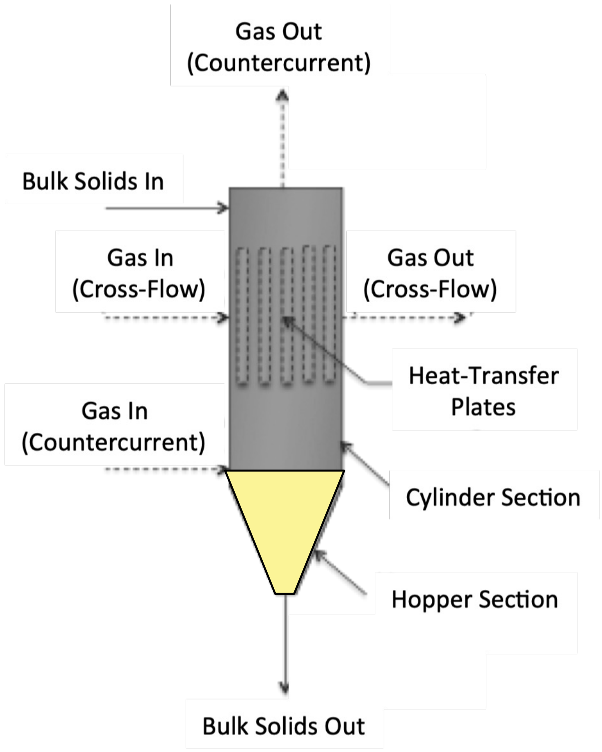
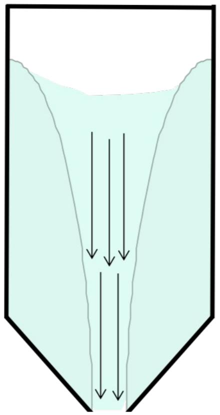
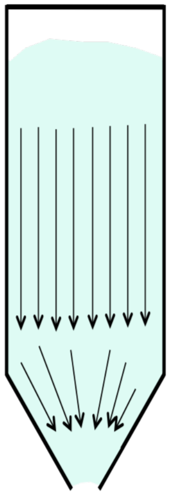


# Flow patterns

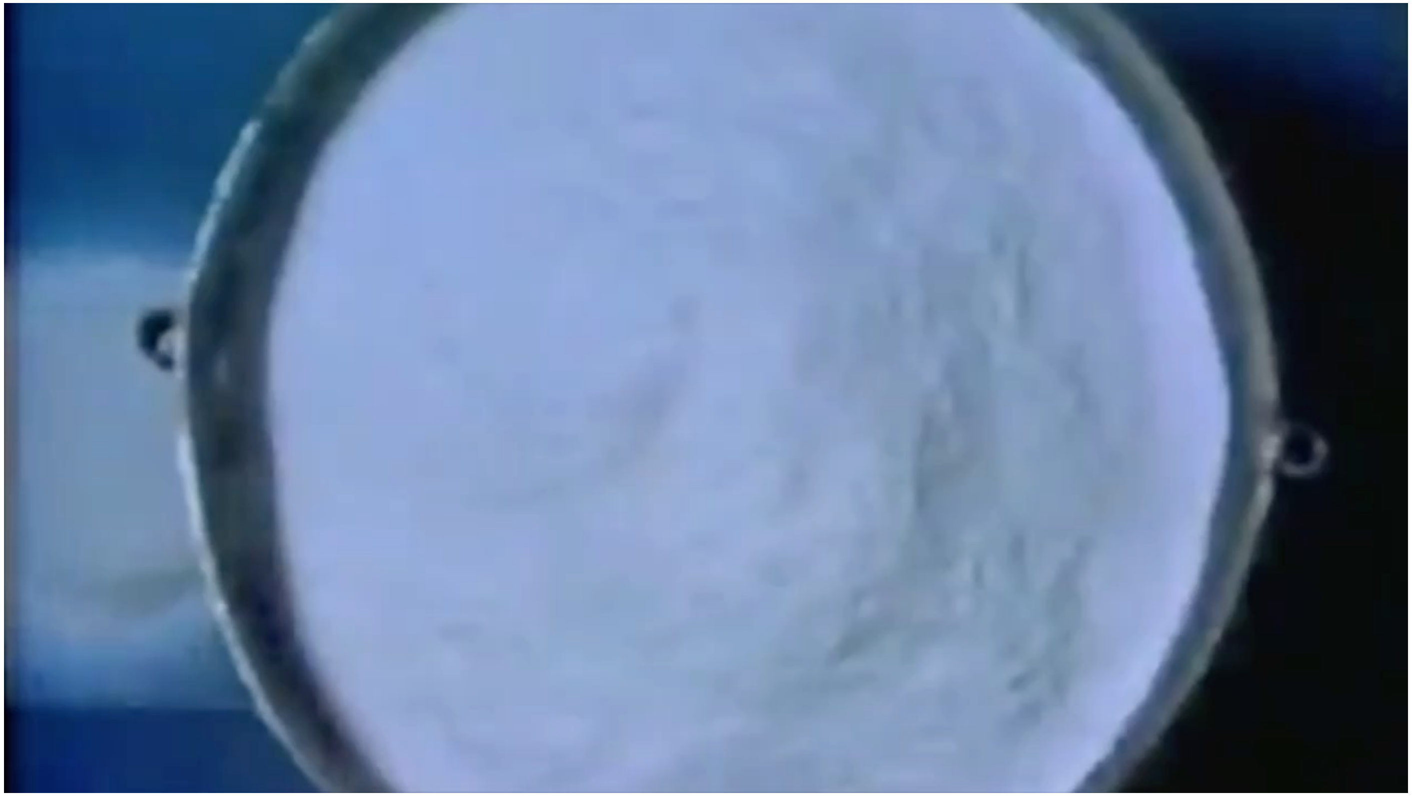
- Funnel flow



- Mass flow



# Funnel flow



# Funnel flow

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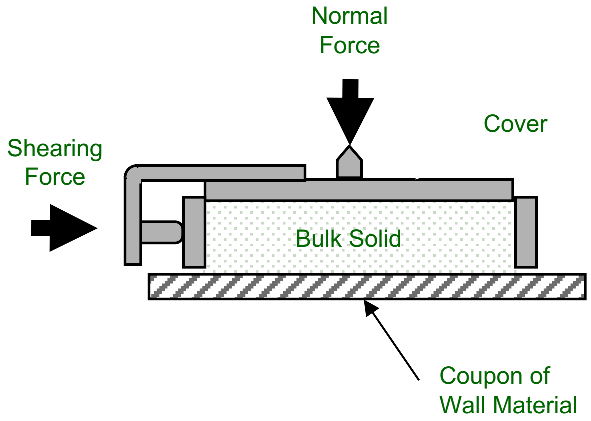
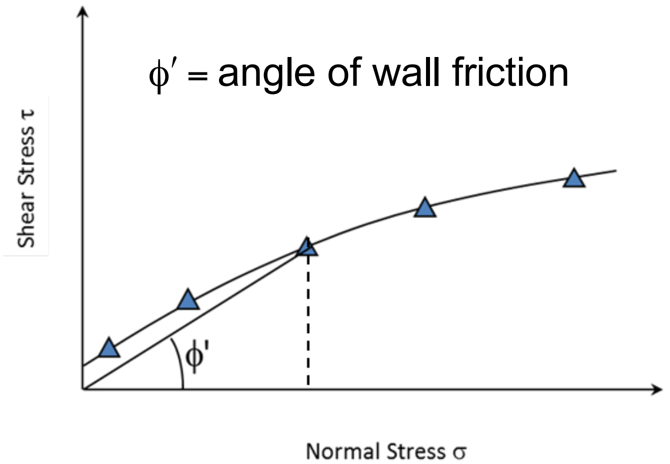
# Mass flow

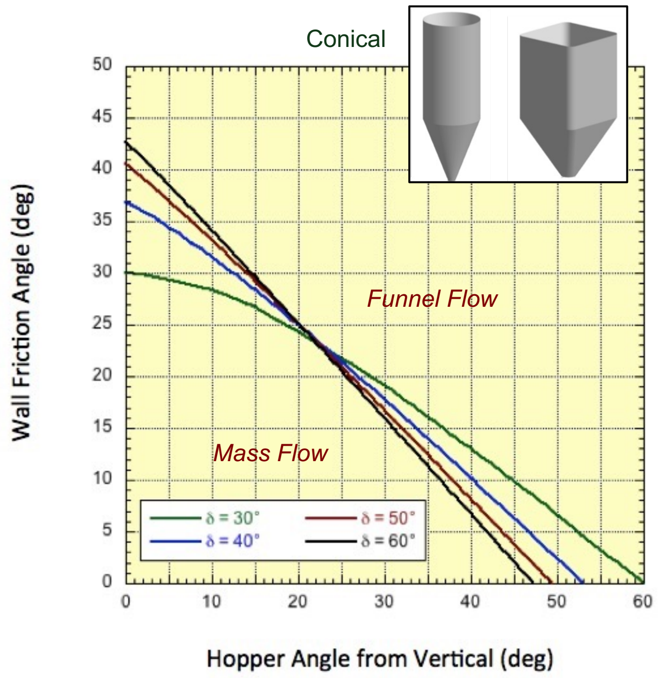
# Wall friction




$$\tan\phi' = \frac{\text{Shear Stress}}{\text{Normal Stress}} = \mu$$

# Mass flow hopper angle



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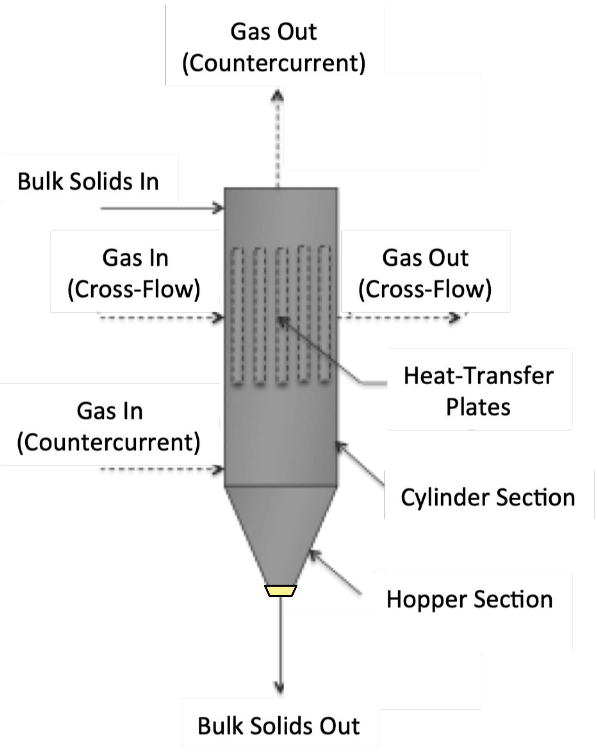
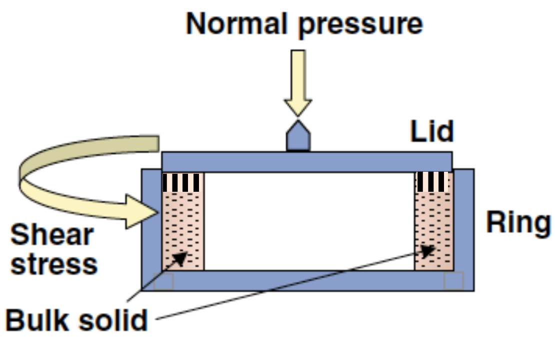
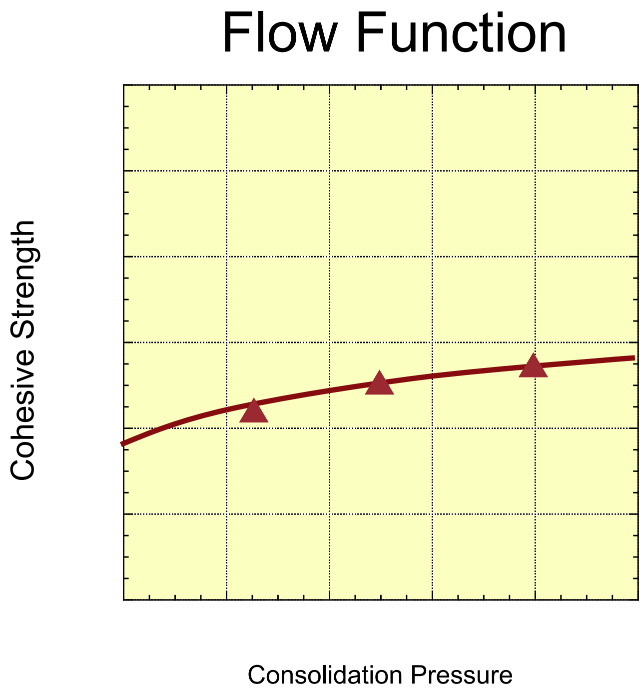
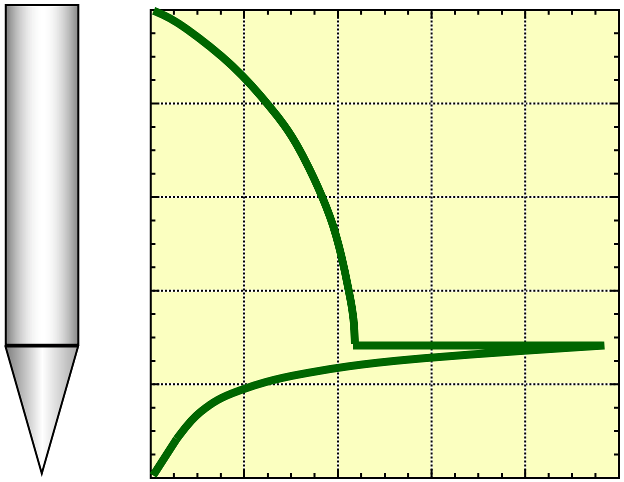


# Cohesive strength



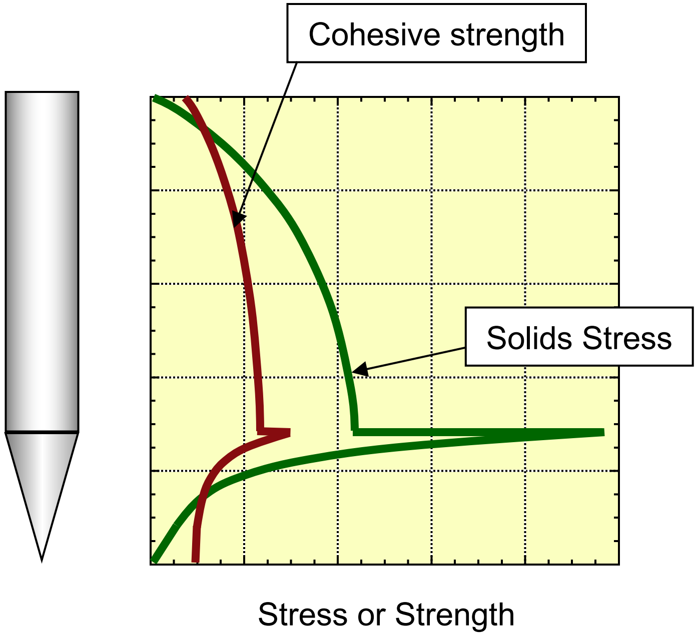



# Solids stress profile

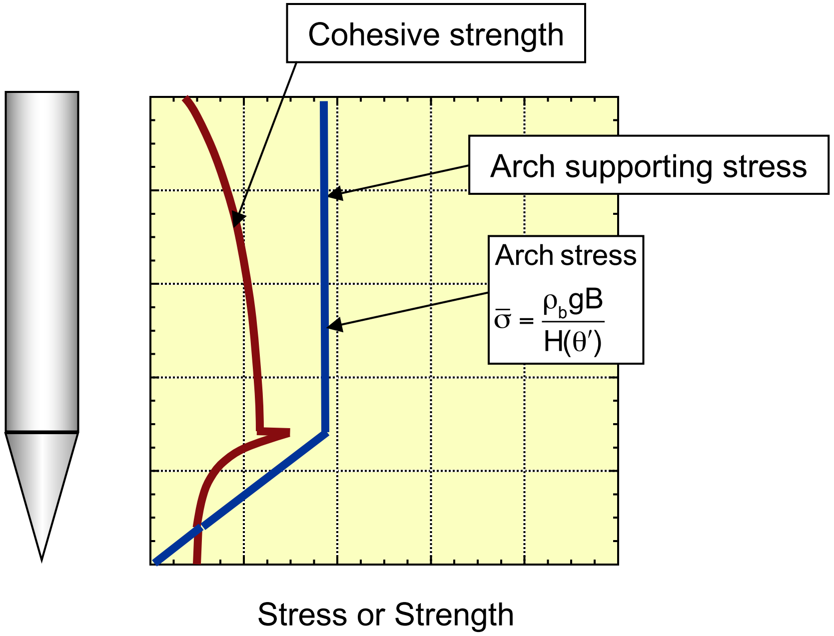


Consolidation Stress

# Solids stress profile



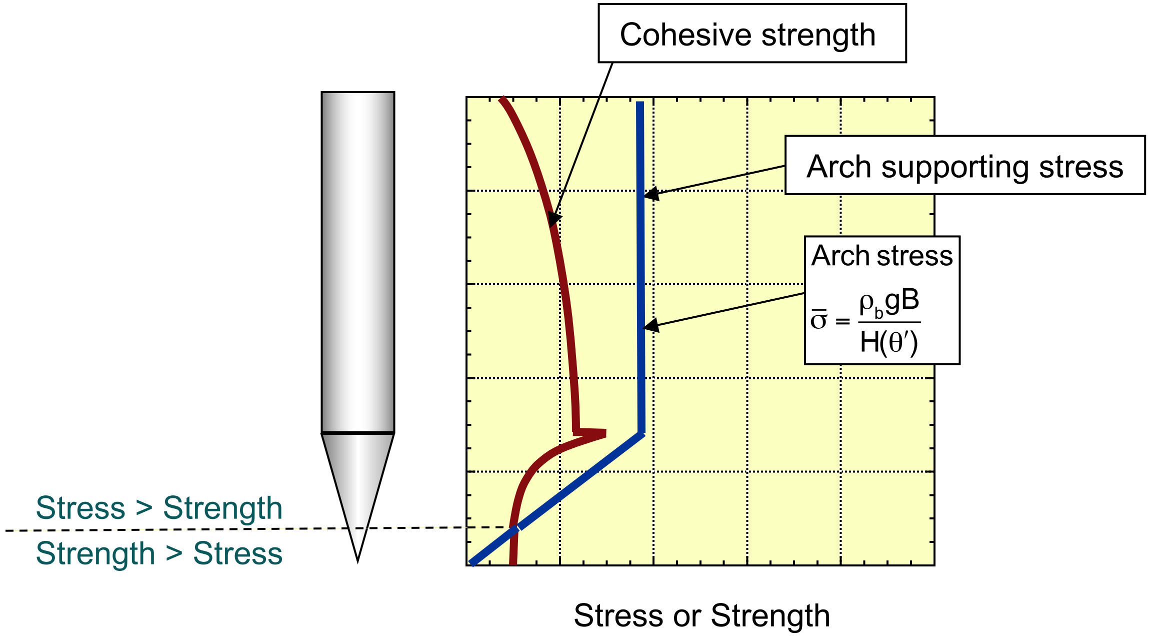
# Arch stress





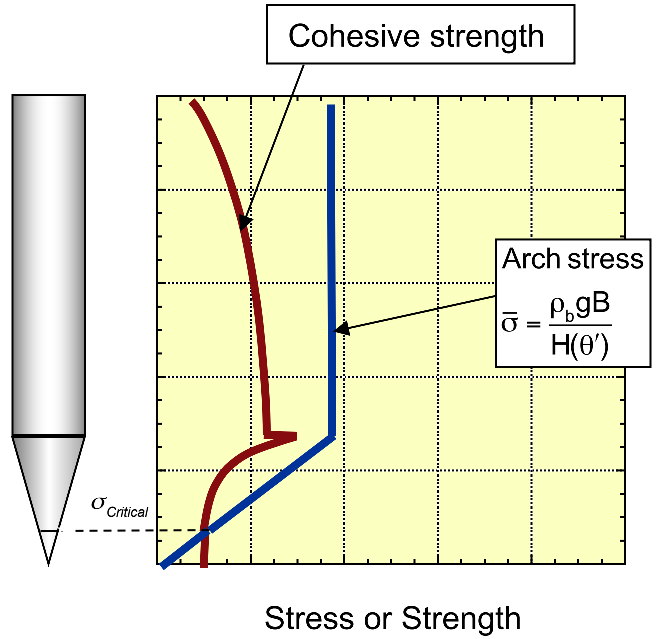

GM&A

# Arch stress



Cohesive strength
Arch supporting stress
Arch stress
$\bar{\sigma} = \frac{\rho_b g B}{H(\theta')}$
Stress > Strength
Strength > Stress
Stress or Strength

# Critical arching diameter

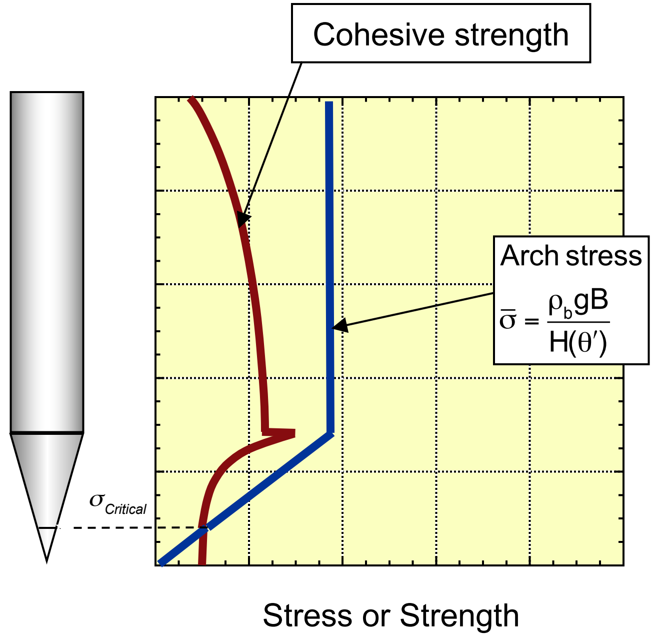



Critical stress
Stress = Strength

# Critical arching diameter

$$B_{min} = \frac{H(\theta')\sigma_{Critical}}{\rho_b g}$$

Critical stress
Stress = Strength



# Flow factor

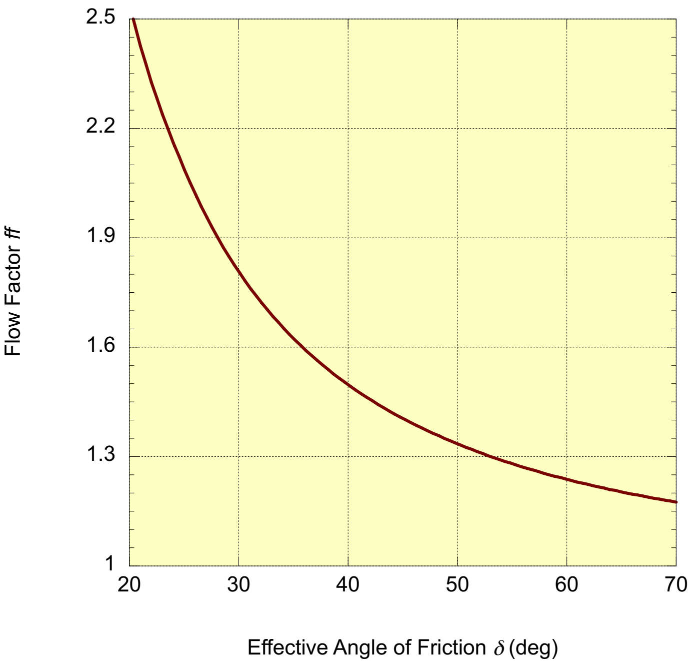
- Flow function (*FF*)

  Relationship between major principal stress and cohesive strength

- Flow factor (*ff*)

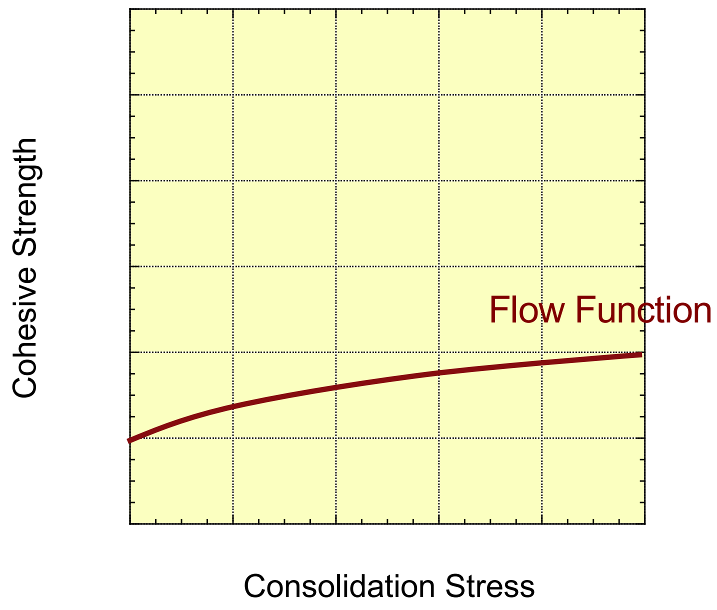
  Ratio of major principal stress and arch supporting stress

$$\text{ff} = \frac{\sigma_1}{\bar{\sigma}_1} = \frac{\text{major principle stress}}{\text{arch stress}}$$

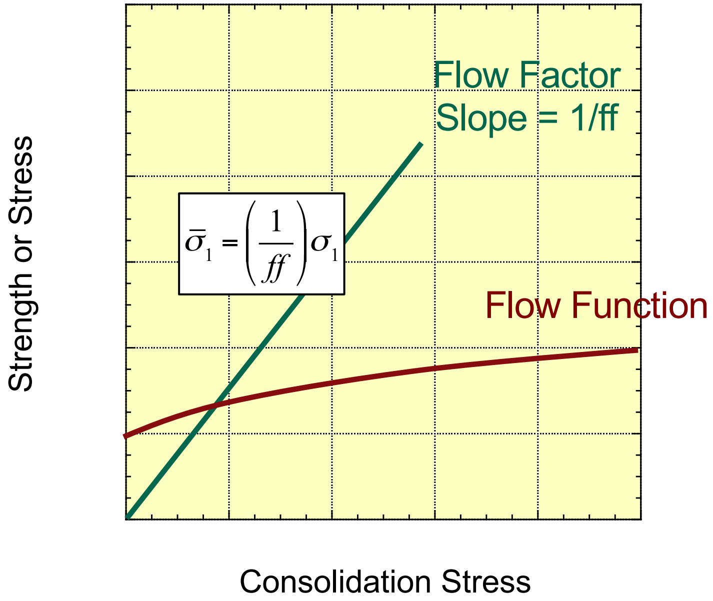



$$ff = 1.118 + \frac{0.285}{(\tan\delta)^2}$$

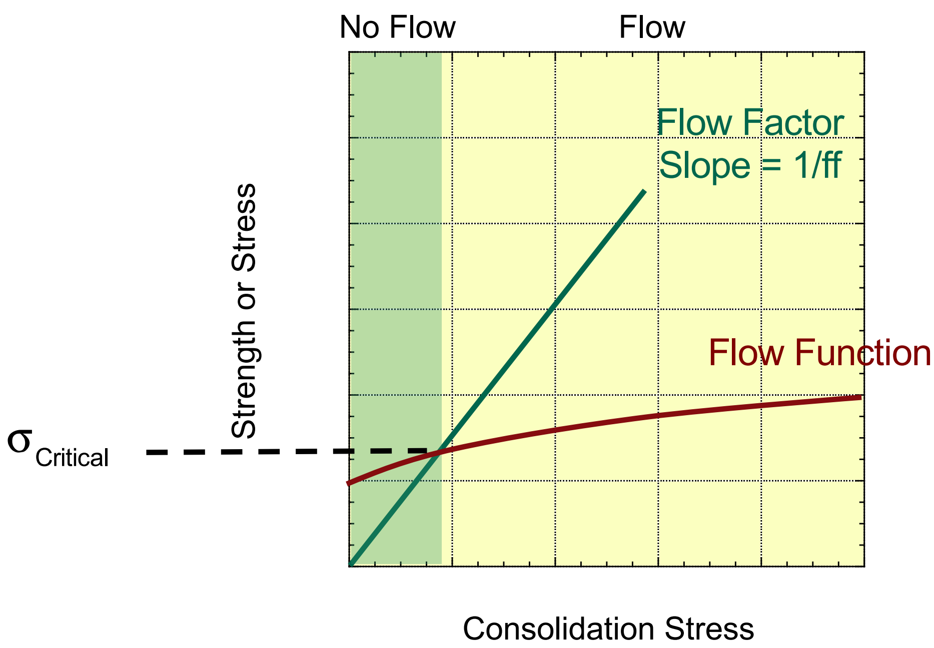
# Flow function



# Flow factor


Flow Factor
Slope = 1/ff
$\bar{\sigma}_1 = \left(\frac{1}{ff}\right)\sigma_1$
Flow Function
Strength or Stress
Consolidation Stress

# Critical arching diameter




$$B_{min} = \frac{H(\theta')\sigma_{Critical}}{\rho_b g}$$

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# Critical arching diameter

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- Uniform gas flow
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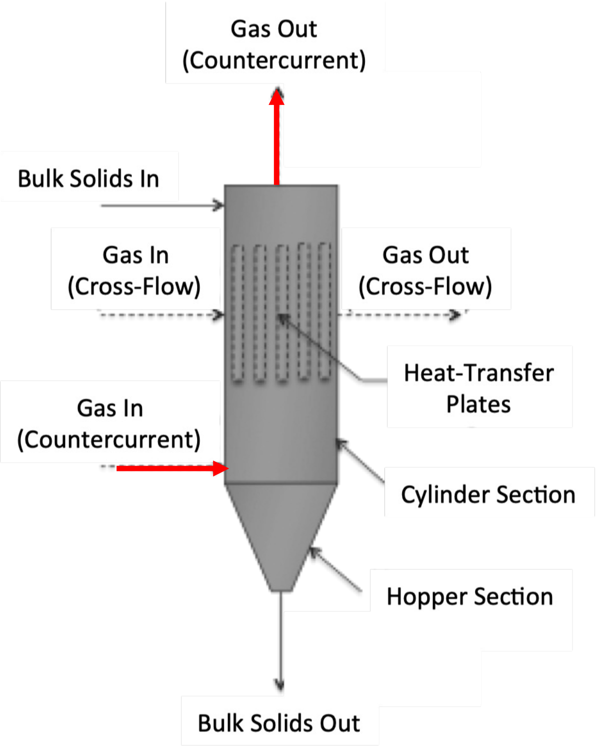
- Necessary volume/ residence time



# Gas Injection

- Nozzles
- Screens
- Sparge rings
- Inserts
- Annulus
- Crossbeams
- Gas permeable walls

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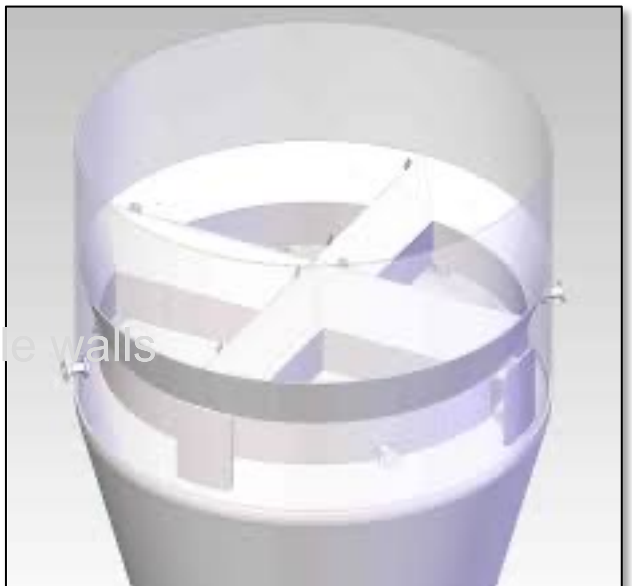

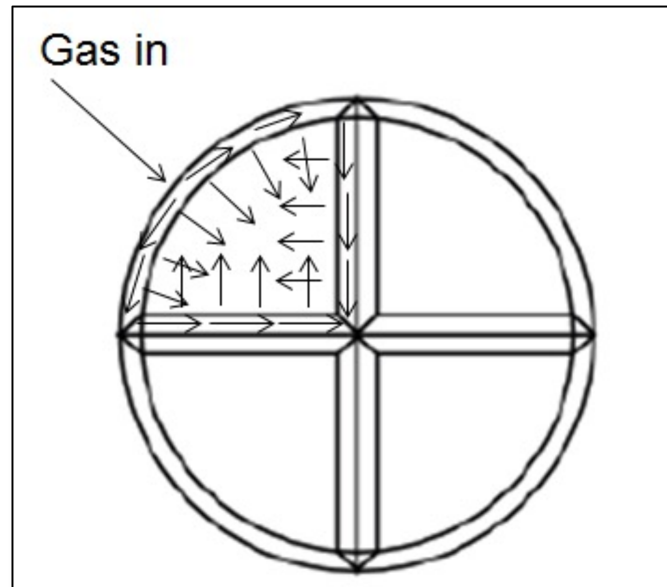


Jenike & Johanson J-Purge™

# Gas Injection

- Nozzles
- Screens
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Zeppelin Systems

# Gas Injection

- Nozzles
- Screens
- Sparge rings
- Inserts
- Annulus
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Young Industries
SilentFlow

# Requirements

- Plug flow of solids
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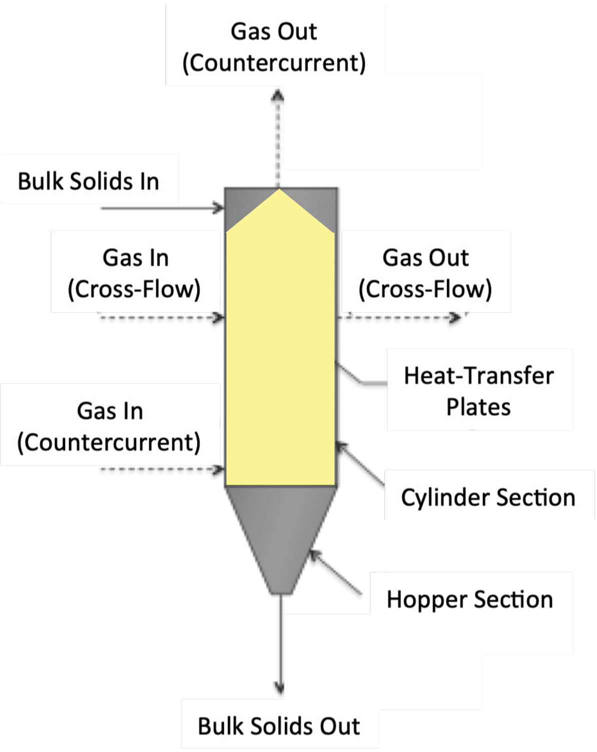
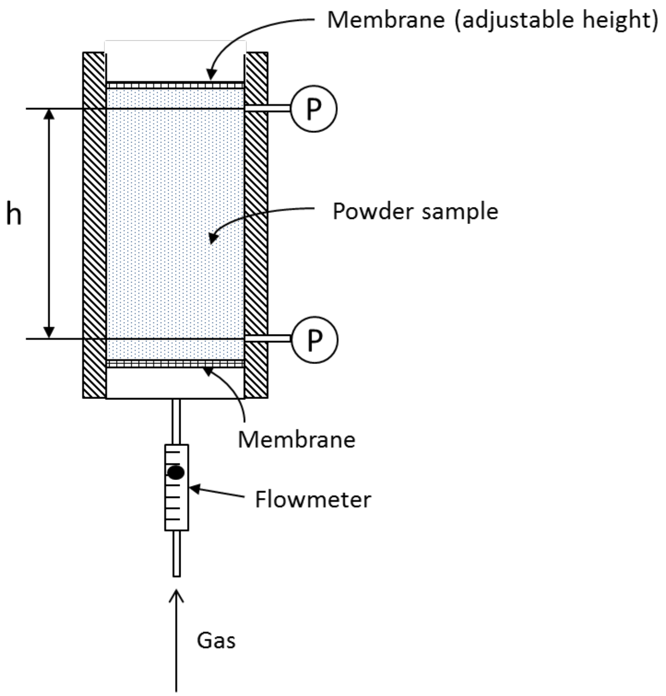
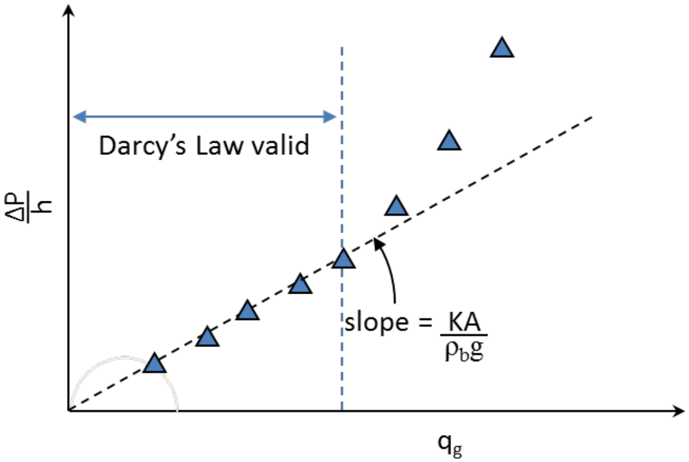


# Permeability




## Darcy's Law:

$$q_g = \frac{KA}{\rho_b g}\frac{\Delta P}{h} = \frac{kA}{\eta}\frac{\Delta P}{h}$$



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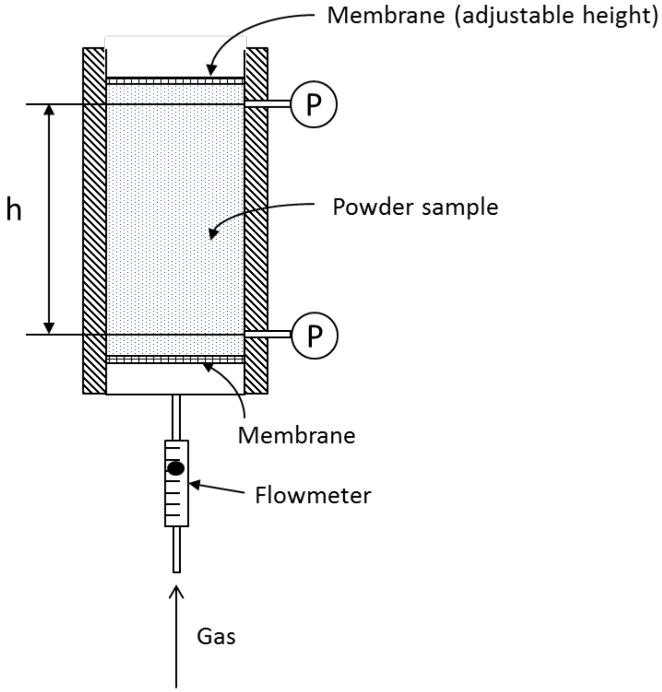



Darcy's Law:

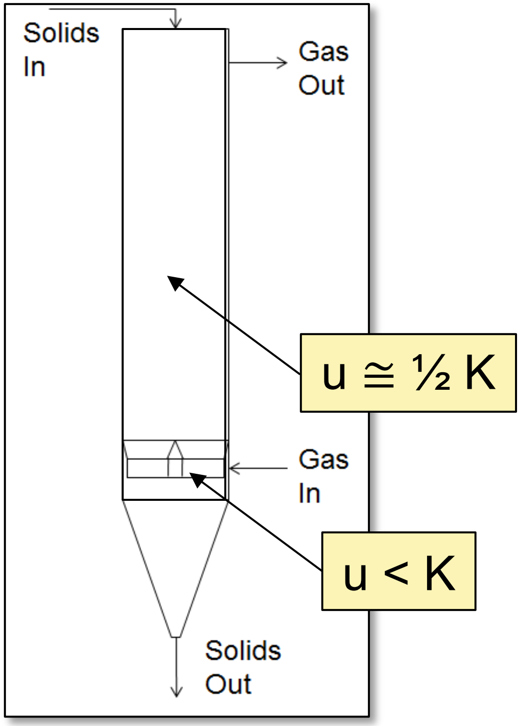
$$q_g = \frac{KA}{\rho_b g}\frac{\Delta P}{h} = \frac{kA}{\eta}\frac{\Delta P}{h}$$

$$u = \frac{K}{\rho_b g}\frac{dP}{dz}$$

$$\text{when } \rho_b g = \frac{dP}{dz}$$

$$u = K = u_{mf}$$

# Allowable gas velocity



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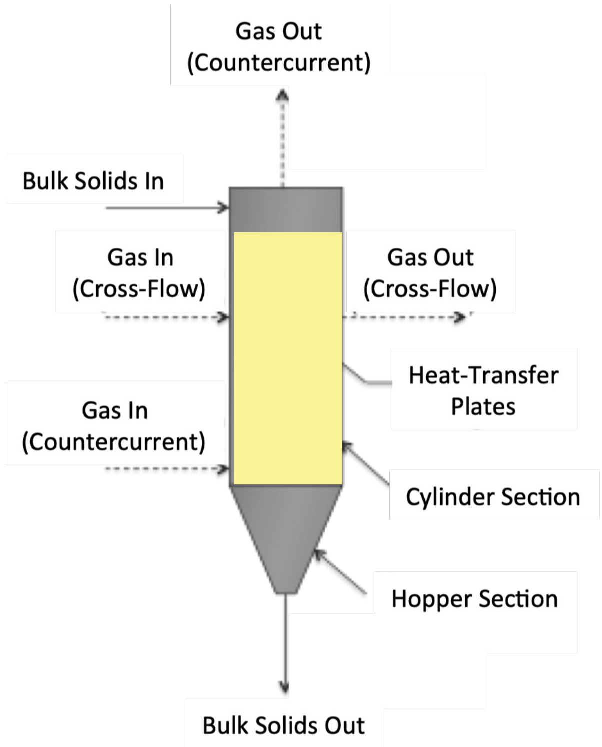
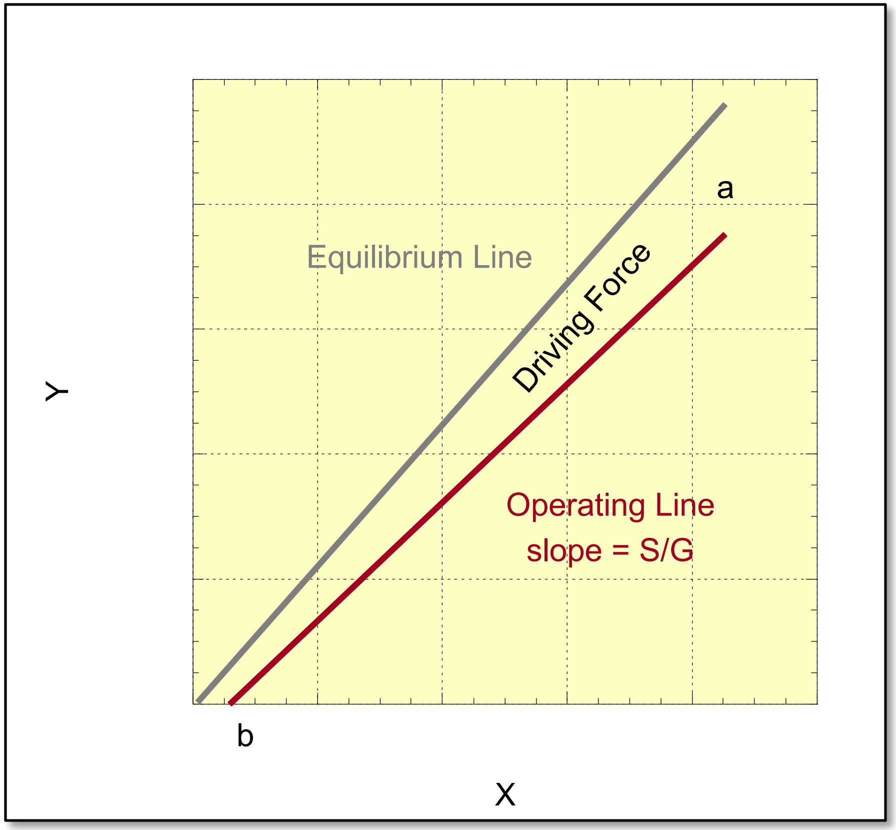
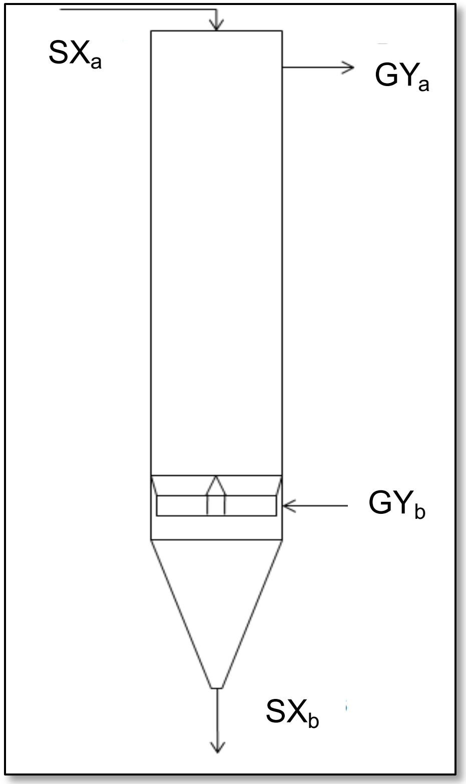


# Minimum gas rate

*Purge column or gravity dryer*



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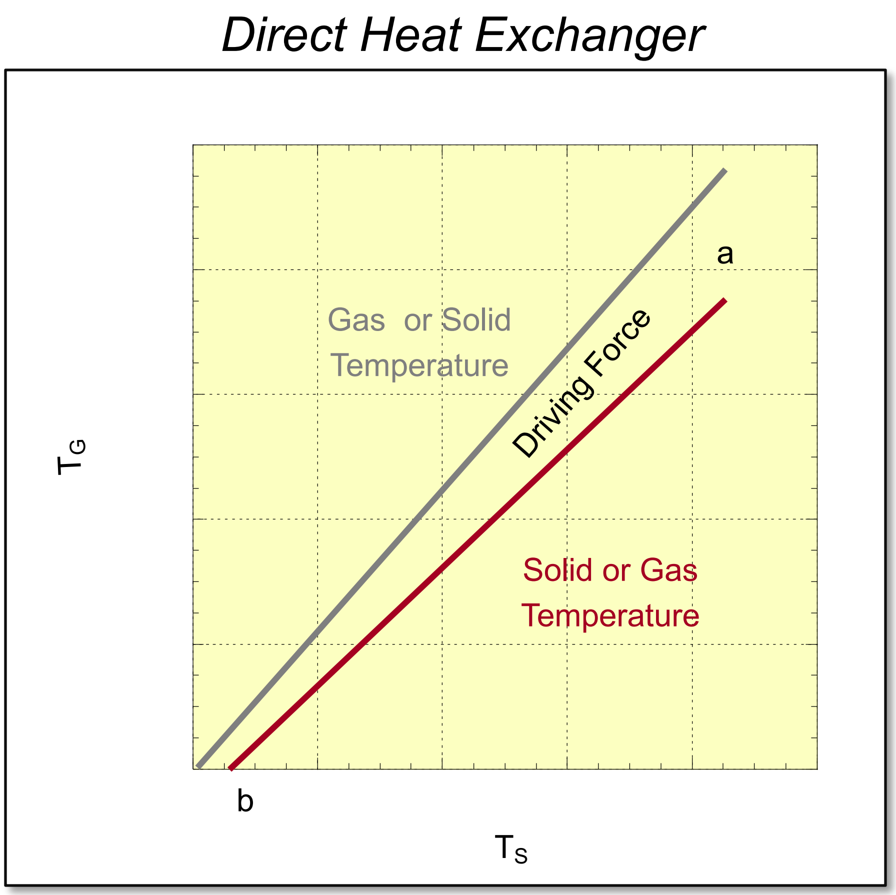


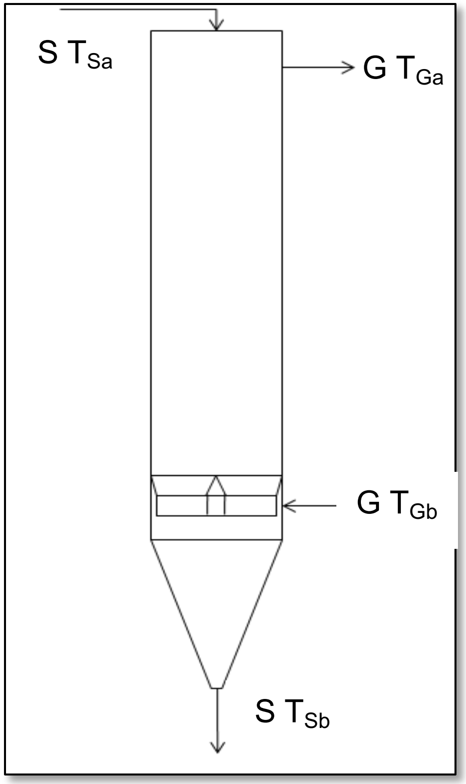

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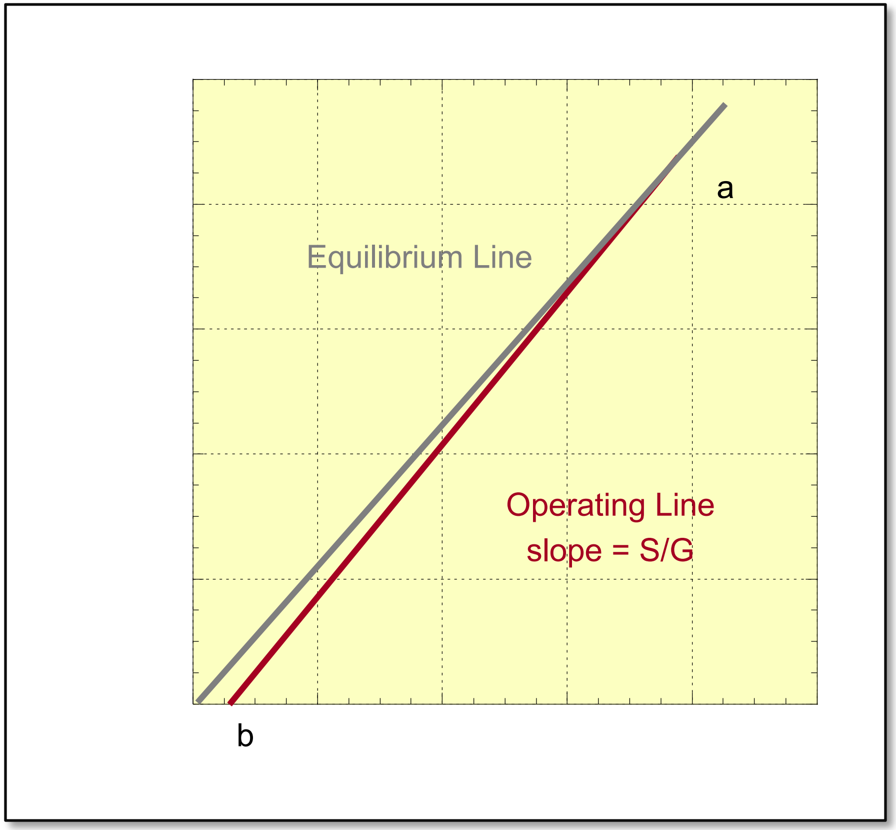
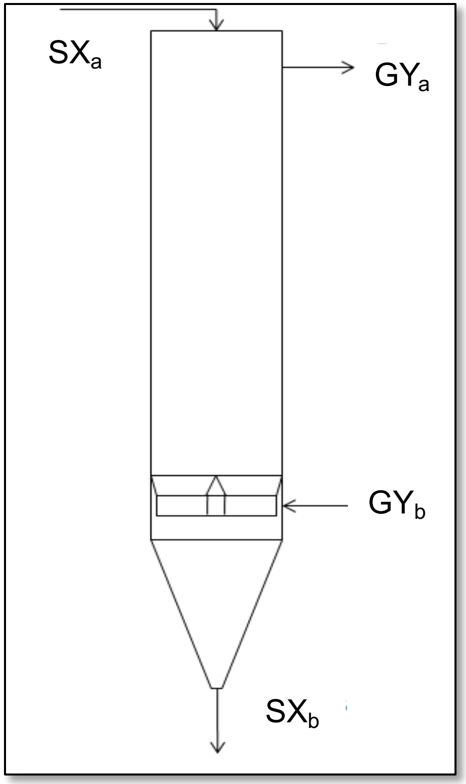


# Kinetics

- Purge columns/gravity dryers

$$N_A = k_y a_v (y_A^* - y_A)$$

- Direct contact heat exchangers

$$q = h a_v (T_s - T_g)$$

Flux

Coefficient

Driving force

# Kinetics

- Purge columns/gravity dryers

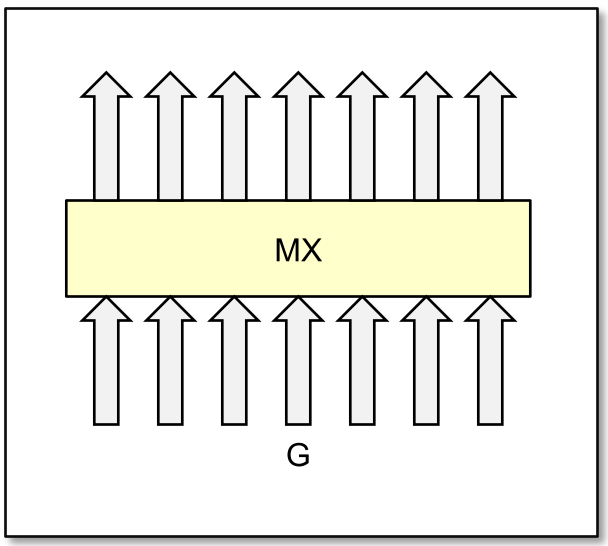
$$N_A = k_y a_v (y_A^* - y_A)$$

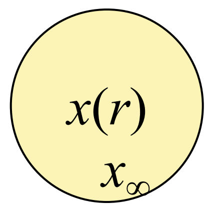
$$\frac{\partial X_A}{\partial t} = \frac{\mathcal{D}}{r^2} \frac{\partial}{\partial r}\left( r^2 \frac{\partial X_A}{\partial r} \right)$$

- Direct contact heat exchangers

$$q = h a_v (T_s - T_g)$$

# Kinetics



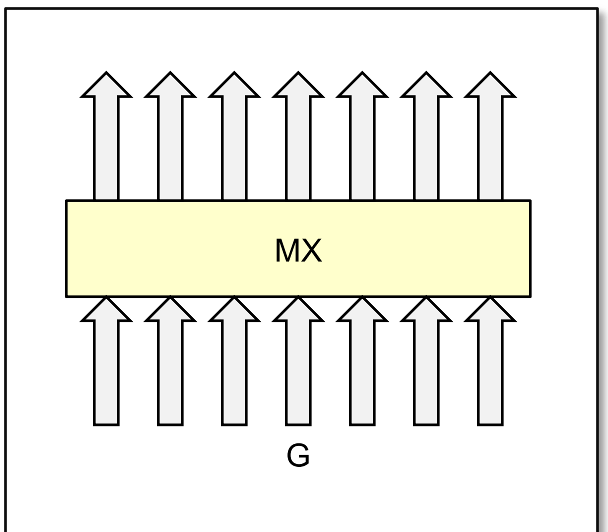

$$\frac{\partial x}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_{eff}r^2\frac{\partial x}{\partial r}\right)$$

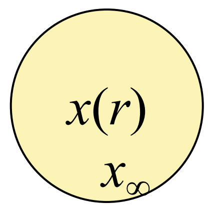
$$x(r,0) = x_{init}$$

$$\frac{\partial x(0,t)}{\partial r} = 0$$

$$x(r_o,t) = x_\infty$$

# Kinetics

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$$x(r,0) = x_{init}$$

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$$x(r_o,t) = x_{\infty}$$

$$\frac{\bar{x} - x_{\infty}}{x_{init} - x_{\infty}} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 D_{eff}\, t}{r_o^2}\right)$$

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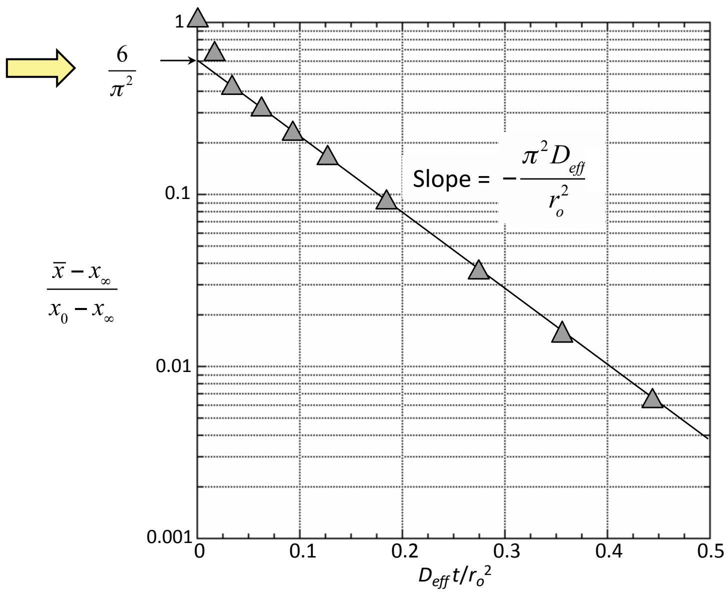
# Kinetics

## Diffusion controlled




$$\frac{\partial x}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_{eff} r^2 \frac{\partial x}{\partial r}\right)$$

$$x(r_o, t) = x_\infty$$

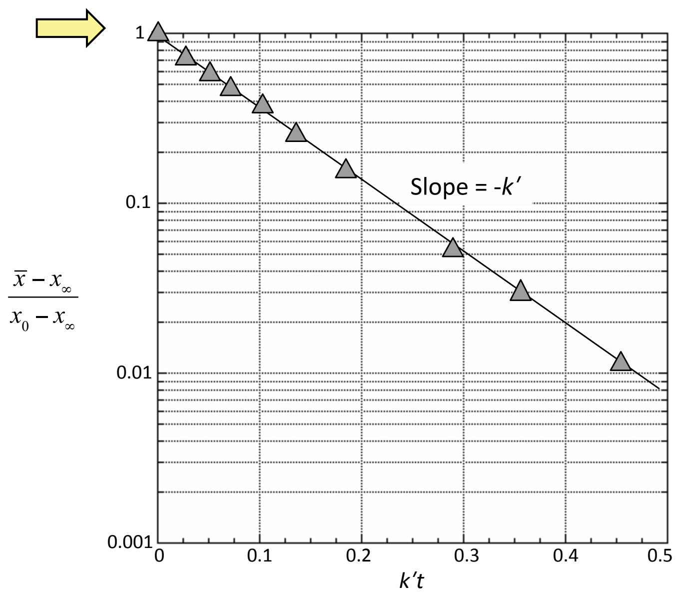
$$x(r, 0) = x_{init}$$

$$\frac{\partial x(0,t)}{\partial r} = 0$$

$$\frac{\overline{x} - x_\infty}{x_{init} - x_\infty} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 D_{eff} t}{r_o^2}\right)$$

# Kinetics

Controlled by convection in the gas phase



# Kinetics

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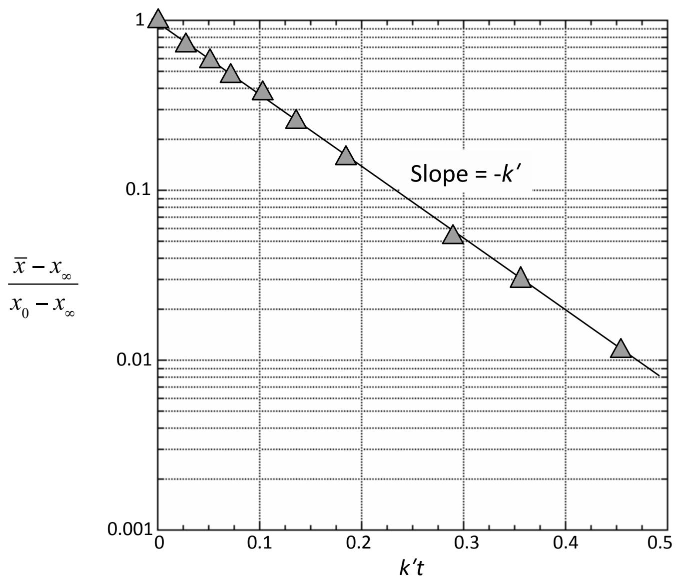



$$\frac{d\bar{x}}{dt} = -k'(\bar{x} - x_\infty)$$

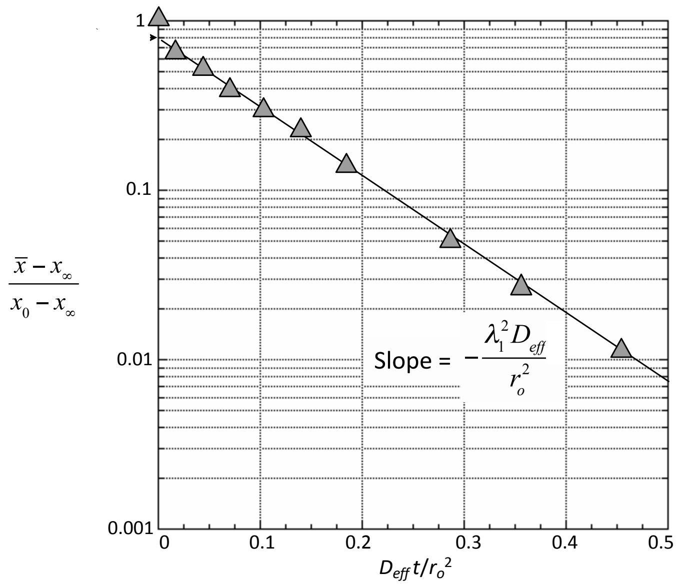
$$x(r_o, t) = x_\infty$$

$$x(r, 0) = x_{init}$$

$$\frac{\bar{x} - x_\infty}{x_{init} - x_\infty} = \exp(-k't)$$

# Kinetics

Controlled by both convection and diffusion

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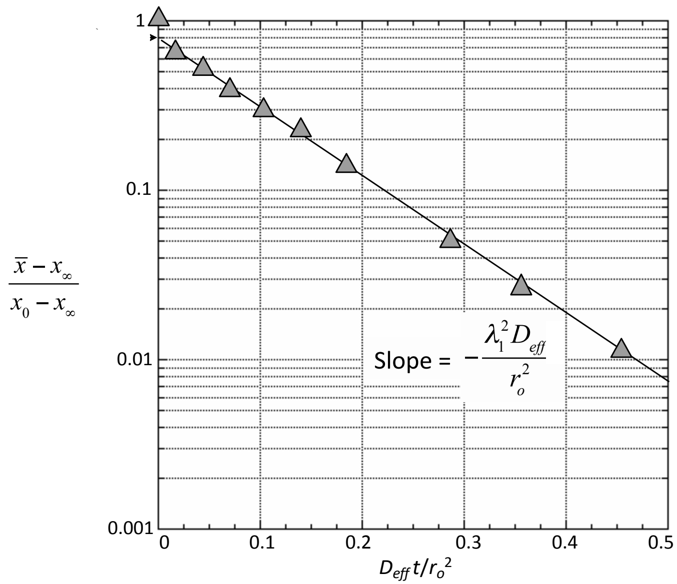
# Kinetics

Controlled by both convection and diffusion




$$\frac{\partial x}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left(D_{eff}r^2\frac{\partial x}{\partial r}\right)$$

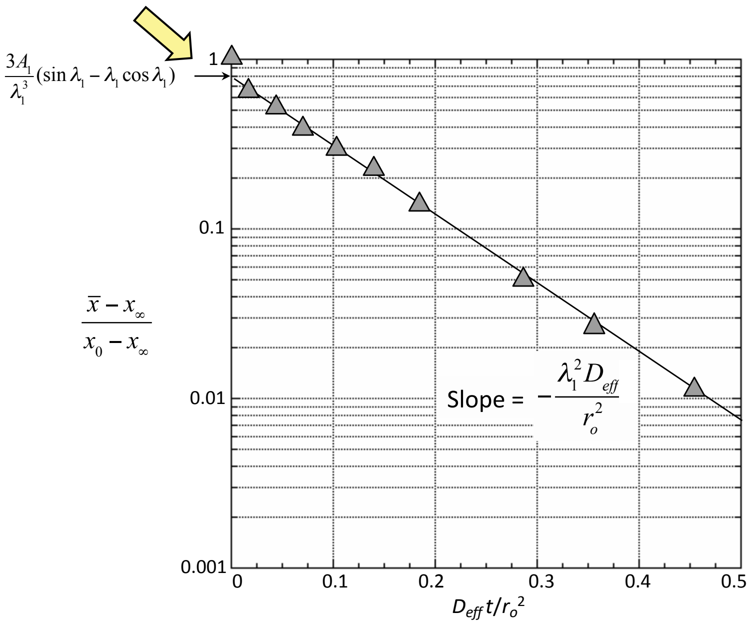
$$x(r_o,t)=x_\infty$$

$$\frac{\partial x(0,t)}{\partial r}=0$$

$$-D_{eff}\frac{\partial[x(r_o,t)]}{\partial r}=k_x(x-x_\infty)$$

# Kinetics

Controlled by both convection and diffusion

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$$x(r_o,t) = x_\infty$$

$$\frac{\partial x(0,t)}{\partial r} = 0$$

$$-D_{eff}\frac{\partial[x(r_o,t)]}{\partial r} = k_x(x - x_\infty)$$

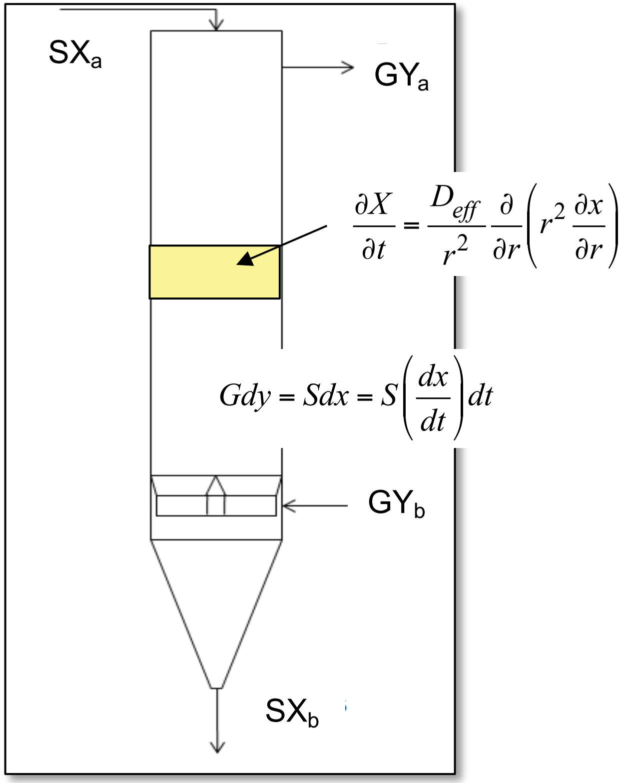
$$\frac{\overline{x}(t) - x_\infty}{x_{init} - x_\infty} = \frac{3A_1}{\lambda_1^3}(\sin\lambda_1 - \lambda_1\cos\lambda_1)\exp\left(-\lambda_1^2\frac{D_{eff}t}{r_o^2}\right)$$

$$1 - \frac{\lambda_1}{\tan\lambda_1} = \mathbf{Bi}$$

$$\mathbf{Bi} = \frac{k_x r_o}{D_{eff}}$$

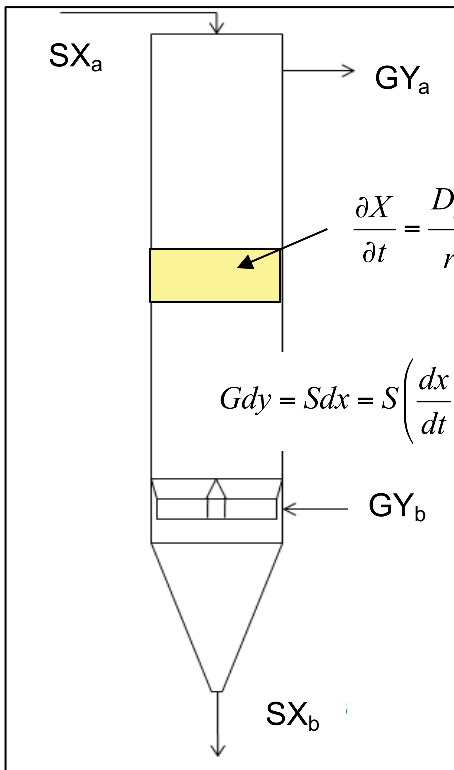
$$A_1 = \frac{4\sin(\lambda_1) - \lambda_1\cos(\lambda_1)}{2\lambda_1 - \sin(2\lambda_1)}$$

# Design



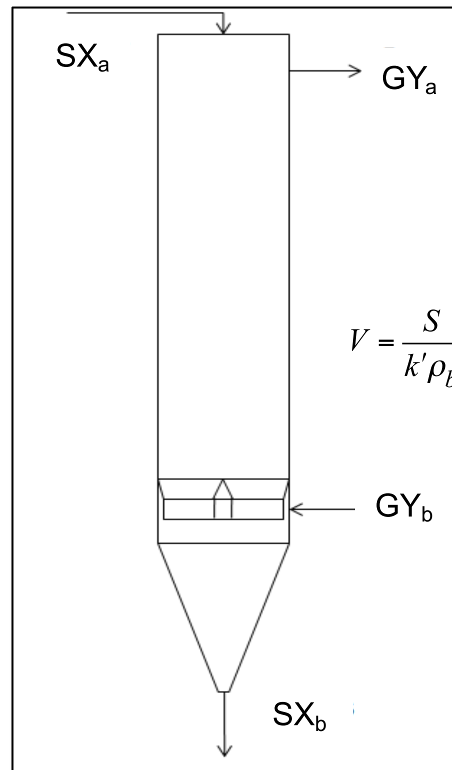

- Estimate $Y_A$
- Solve diffusion equation for time spent in short section in column
- Determine volatiles content entering section from mass balance
- Continue until bottom of column is reached
- Iterate until $Y_{ab} = 0$

# Design




$$\frac{\partial X}{\partial t} = \frac{D_{eff}}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial x}{\partial r}\right)$$

$$G dy = S dx = S\left(\frac{dx}{dt}\right)dt$$




$$V = \frac{S}{k'\rho_b}\frac{x_a - x_b}{(x^* - x)_{lm}} = H_S N_S$$

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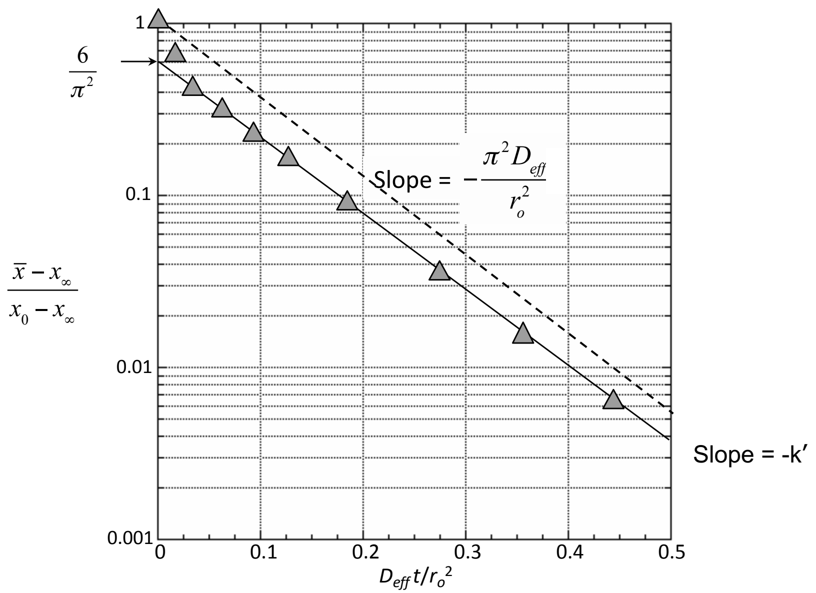
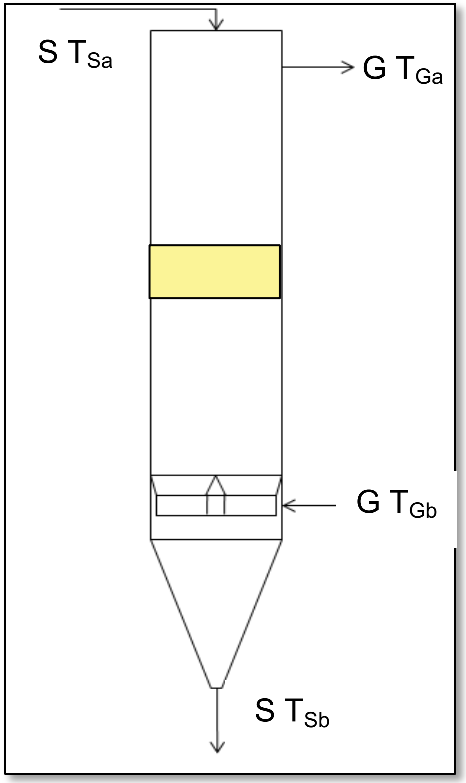
# Design



1
0.1
0.01
0.001
0
0.1
0.2
0.3
0.4
0.5
$\frac{6}{\pi^2}$
$\frac{\bar{x} - x_\infty}{x_0 - x_\infty}$
Slope = $-\frac{\pi^2 D_{eff}}{r_o^2}$
Slope = -k′
$D_{eff} t / r_o^2$

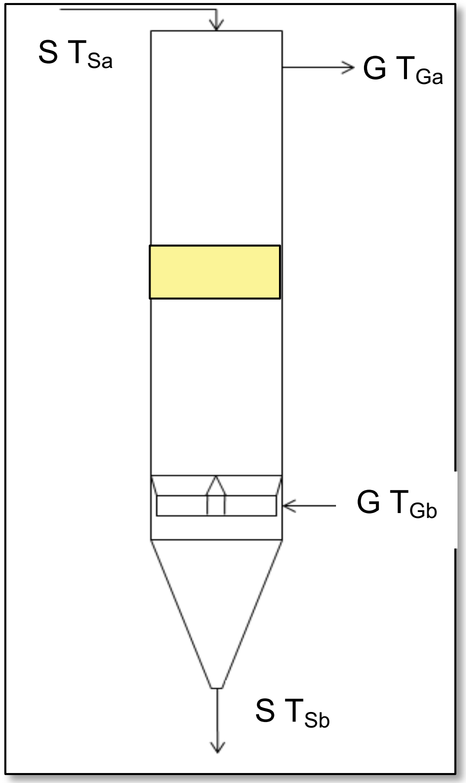
# Direct bulk solids heat exchangers




$$SC_{PS}\frac{dT_s}{dz} = ha_v(T_G - T_S)$$

$$SC_{GS}\frac{dT_s}{dz} = ha_v(T_S - T_G)$$

# Direct bulk solids heat exchangers



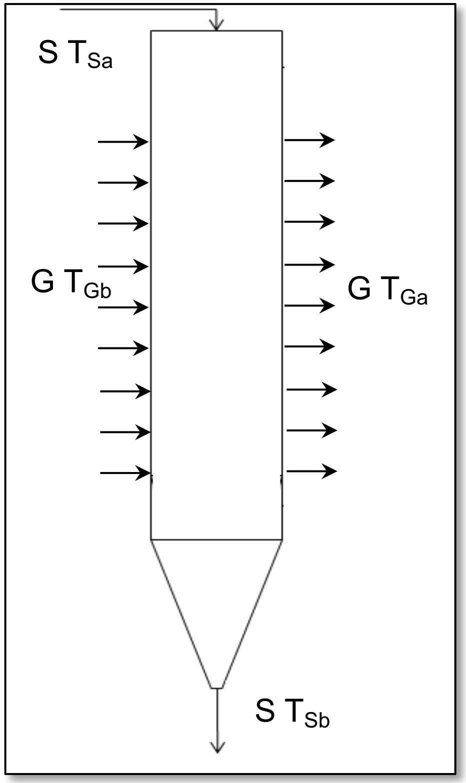

$$SC_{PS}\frac{dT_s}{dz} = ha_v(T_G - T_S)$$

$$SC_{GS}\frac{dT_s}{dz} = ha_v(T_S - T_G)$$

$$\ln\left(\frac{T_{Ga} - T_{Sa}}{T_{Gb} - T_{Sb}}\right) = -ha_v\left(\frac{1}{GC_{PG}} - \frac{1}{SC_{PS}}\right)V$$

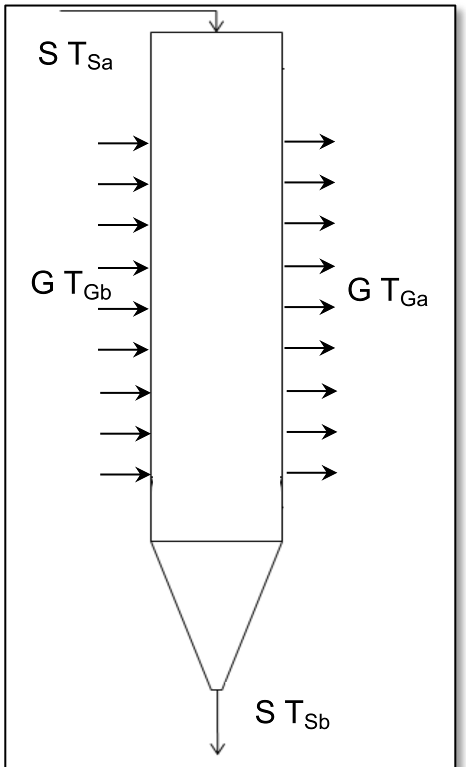
# Direct bulk solids heat exchangers

Cross-flow



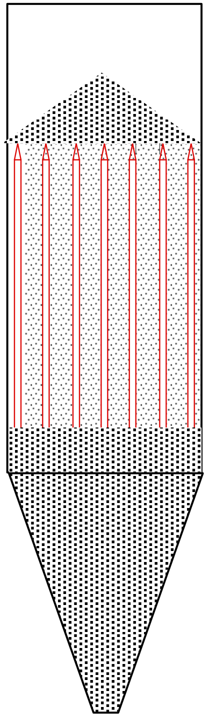
# Direct bulk solids heat exchangers

Cross-flow




$$\frac{T_s - T_{sin}}{T_{gin} - T_{sin}} = 1 - \exp\left(-\frac{A_z H h a_s}{\dot{m}_s C_{Ps}} - \frac{A_x x h a_s}{\dot{m}_g C_{Pg}}\right) \sum_{j=0}^{\infty} \frac{\left(\frac{A_x x h a_s}{\dot{m}_g C_{Pg}}\right)^j}{j!} \sum_{k=0}^{j} \frac{\left(\frac{A_z H h a_s}{\dot{m}_s C_{Ps}}\right)^k}{k!}$$

# Indirect moving bed heat exchangers



$$\rho_b u C_{Ps} \frac{\partial T}{\partial z} = -k_{eff} \frac{\partial^2 T}{\partial x^2}$$

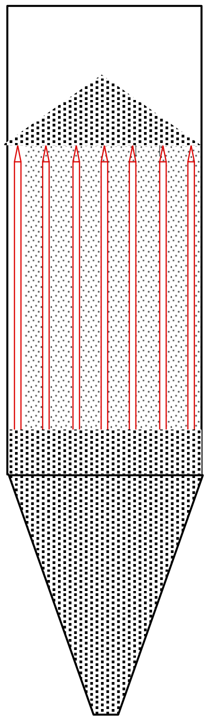
$$T(x,0) = T_0(x,0)$$

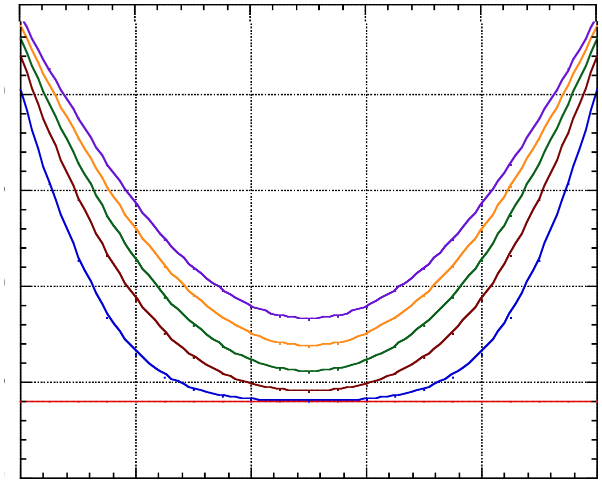
$$-k_{eff} \frac{\partial T(-\frac{b}{2}, z)}{\partial x} = h[T(-\tfrac{b}{2}, z) - T_f(z)]$$

$$-k_{eff} \frac{\partial T(\frac{b}{2}, z)}{\partial x} = h[T(\tfrac{b}{2}, z) - T_f(z)]$$

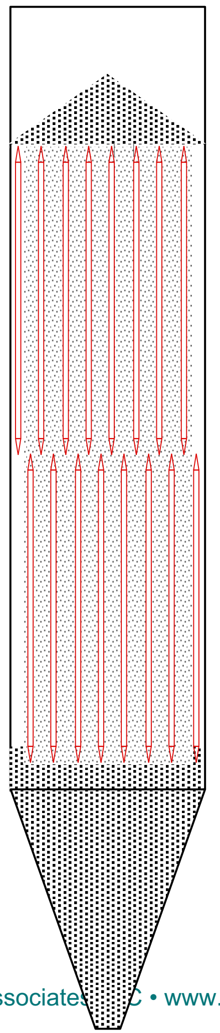
$$T_f(z) = T_{fb} + C\left[\bar{T}(z) - \bar{T}_a\right]$$

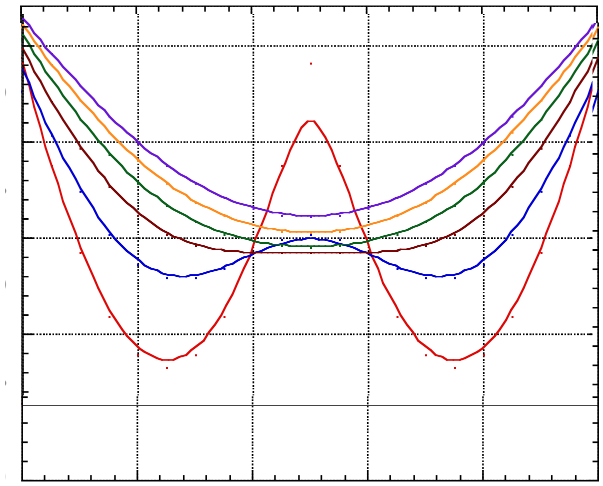
# Indirect moving bed heat exchangers





# Indirect moving bed heat exchangers

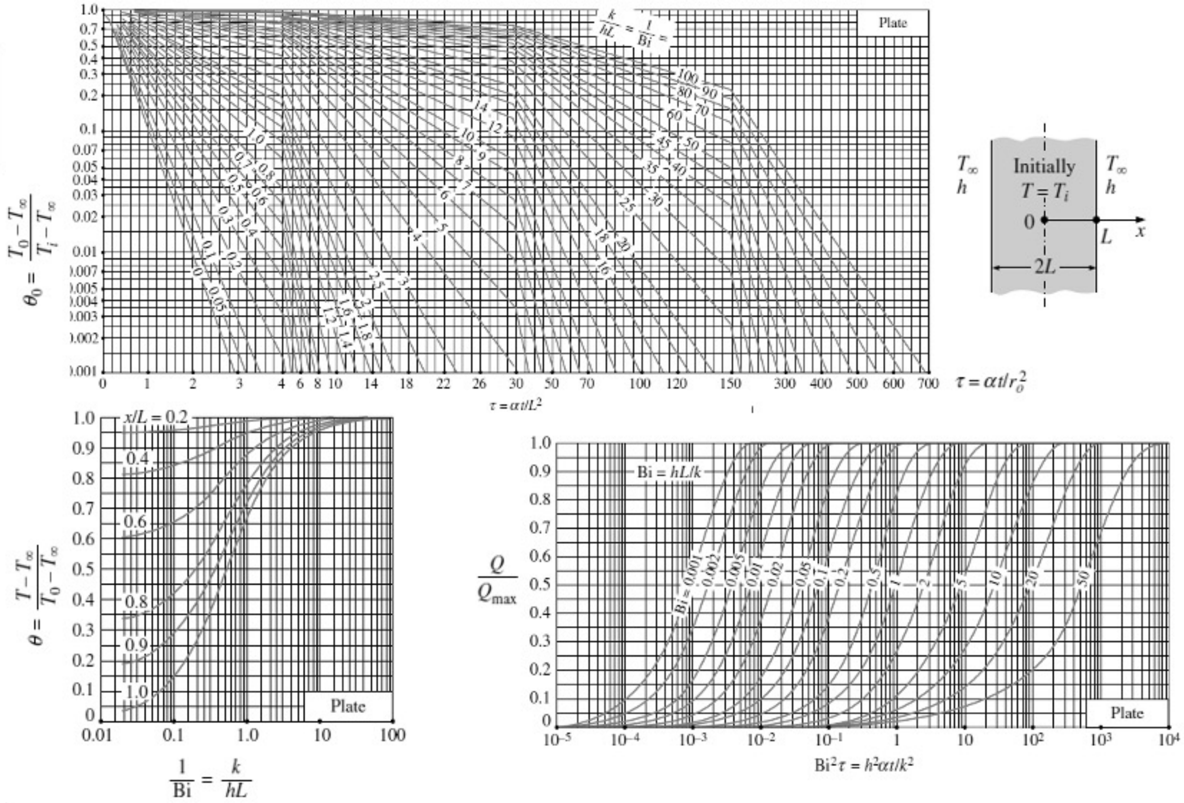




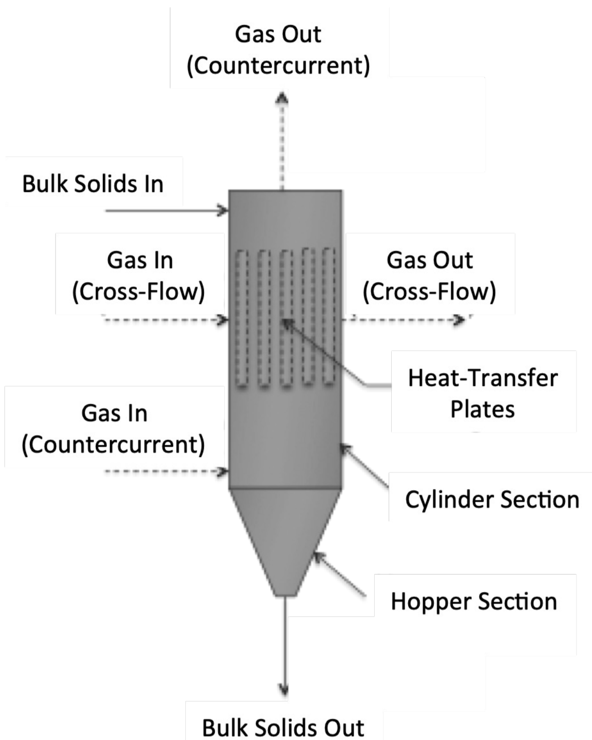
# Indirect moving bed heat exchangers

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t}$$

Transient temperature and heat transfer charts for a **plane wall of thickness 2*L*** initially at a uniform temperature $T_i$ subjected to convection from all sides to an environment at temperature $T_\infty$ with a convection coefficient of *h*.



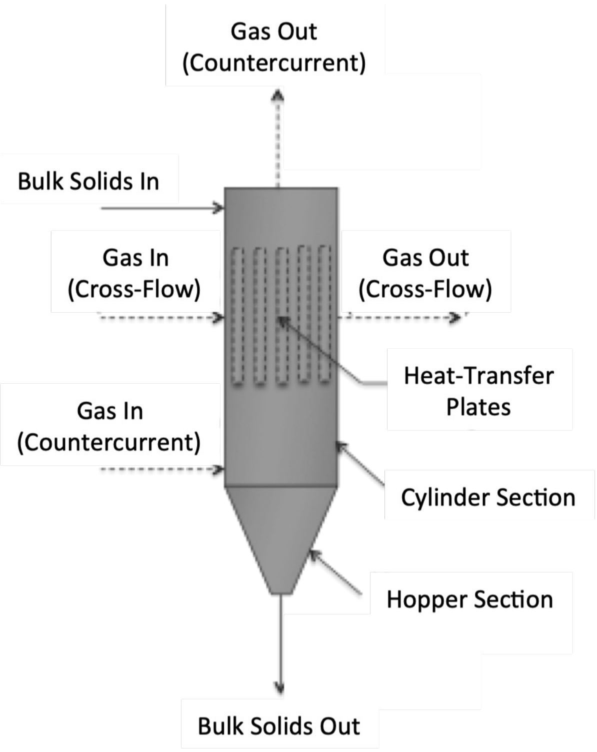
# Moving bed reactors




- Batch ⇨ Continuous
- Eqn's are the same!

# Requirements

- Plug flow of solids
- Proper outlet size
- Uniform gas flow
- Stable solids bed
- Necessary volume/ residence time



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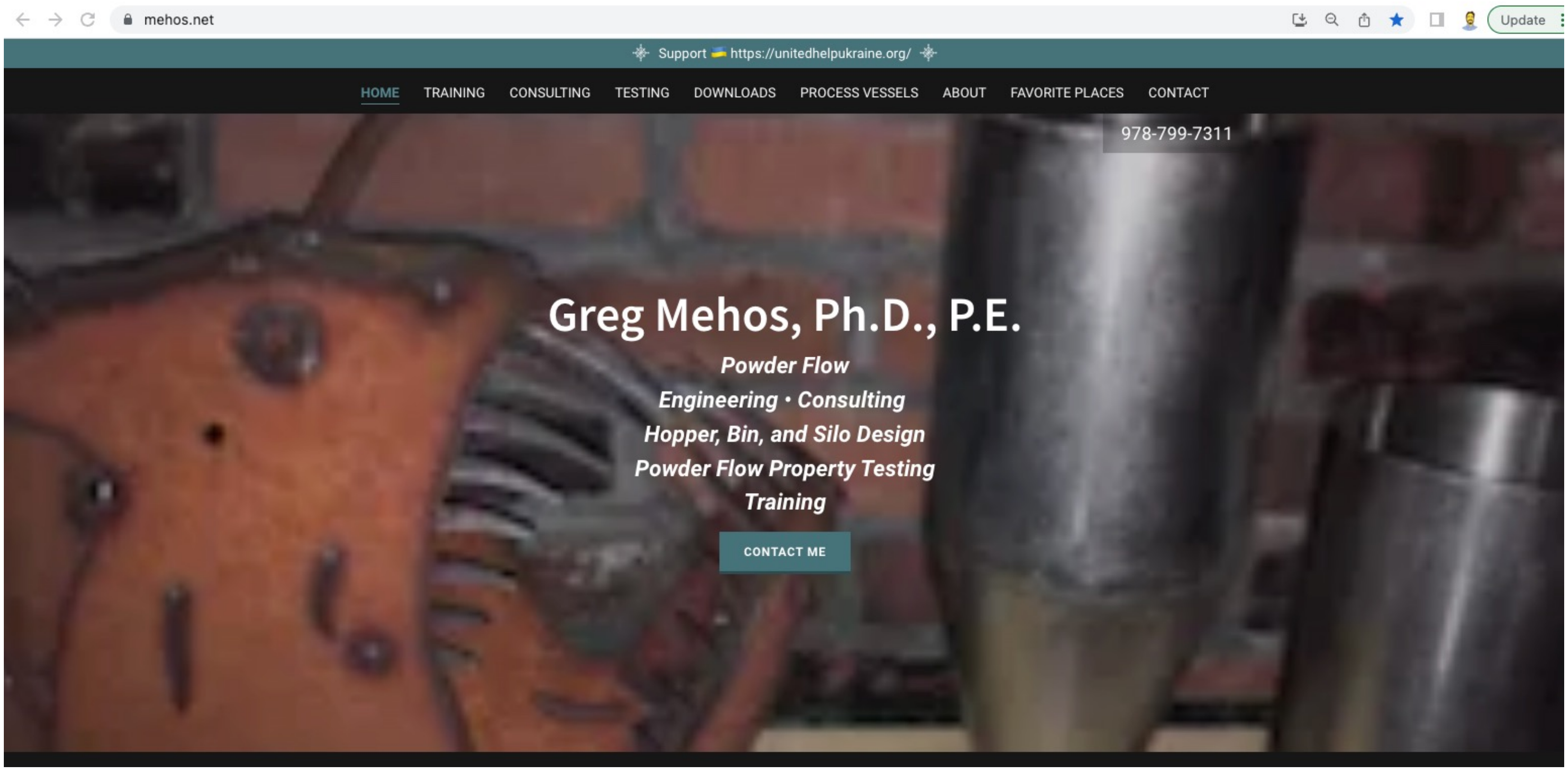

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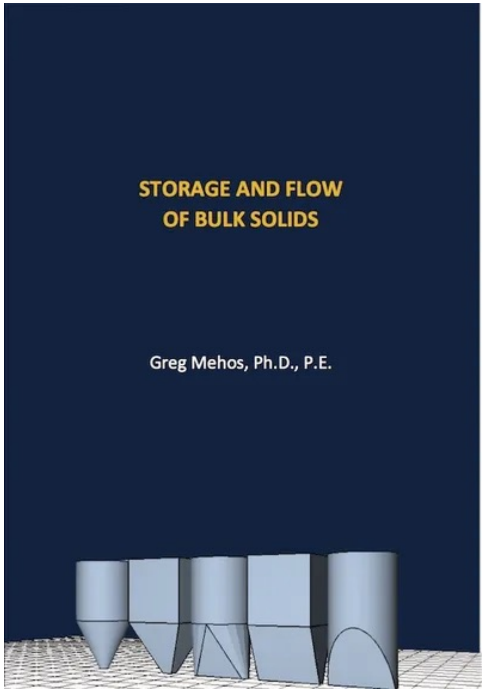

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