Nonmechanical Control of Solids Flow in Chemical Looping Systems

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NETL 2011 Workshop on Multiphase Flow Science

August 16 – 18, 2011
Pittsburgh, PA

Chemical Looping Systems

- There are Many Different Types of Chemical Looping Systems That are Being Developed or Proposed
- All Involve Substantial Flows of Solids Around the System

Chemical Looping Systems

- Typically, the Temperatures Involved in Chemical Looping Systems are too High to Easily Use Mechanical Valves for Control

- Therefore, Nonmechanical Means are Being Employed to Control the Solids Flow Rates Around the Systems

Chemical Looping Systems

- **How Are the Solids Being Controlled in These Systems Using Nonmechanical Means?**
- **This Depends on the Type of Flow System Used as Well as the Particle Size Used in the System**

Chemical Looping Systems

- To Evaluate the Different Nonmechanical Techniques it is Necessary to Understand the Principles Behind Nonmechanical Systems – but Often There is a Lack of Understanding About How They Operate

- Therefore, Several Basic Principles of Nonmechanical Systems will be Reviewed Before Evaluating Several Different Flow Systems

Nonmechanical Solids Flow Devices

- **Nonmechanical Solids Flow Devices Fall Into Two Categories:**

  1. **Solids Flow Control Devices (Valves)**

     Example: L-Valve

  2. **Solids Flow-Through Devices Which DO NOT CONTROL Solids Flow (They Automatically Pass Solids Through Them)**

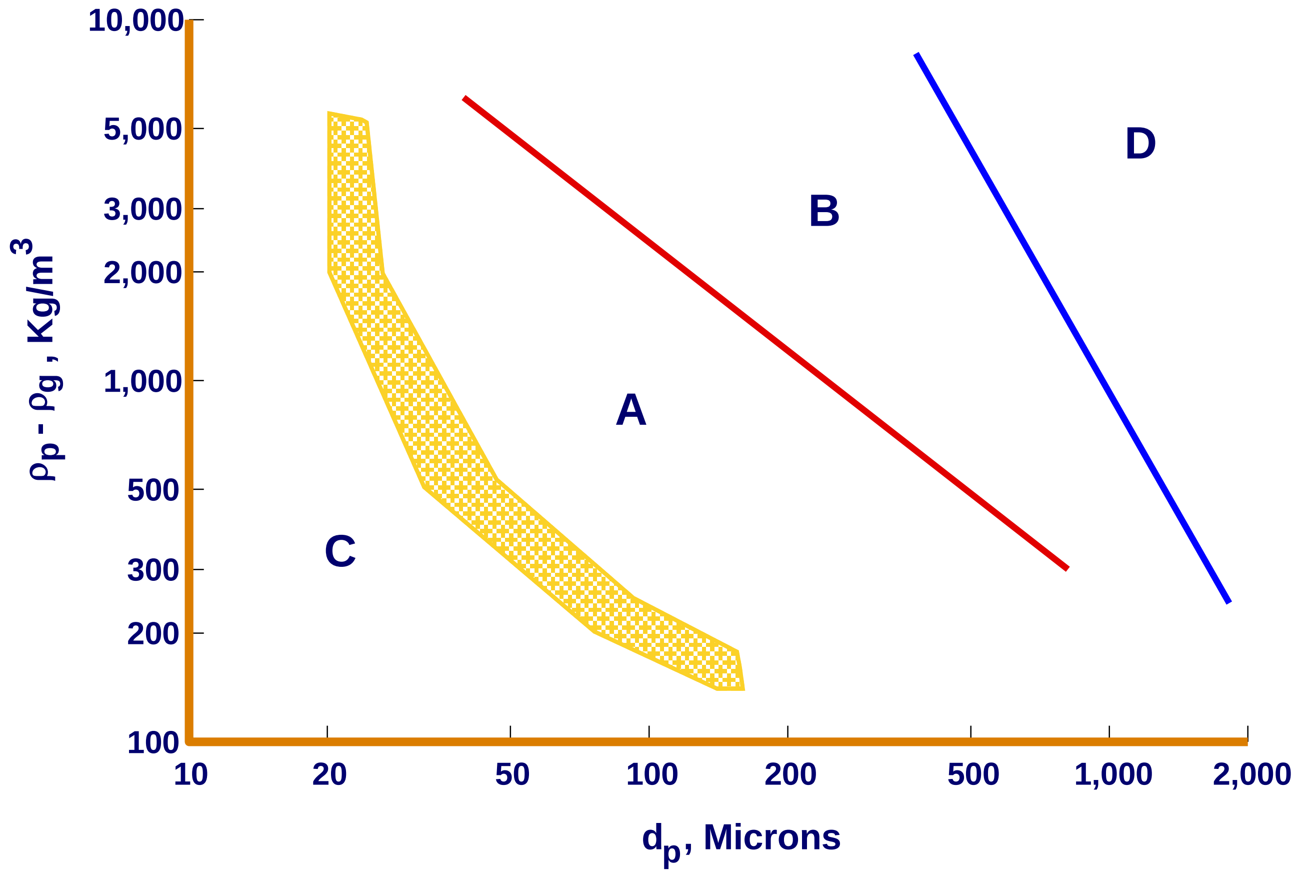
     Examples: Loop Seal

     Automatic "L-Valve"

GELDART'S POWDER CLASSIFICATION

(Geldart, D. Powder Technology, 1, 285, 1973)

Applies at Ambient Conditions



A: Aeratable ($U_{mb} > U_{mf}$) Material Has a Significant Deaeration Time *(FCC Catalyst)*

B: Bubbles Above U_{mf} ($U_{mb} = U_{mf}$) *(500-micron Sand)*

C: Cohesive *(Flour, Fly Ash)*

D: Spoutable *(Wheat, 2000-micron Polyethylene Pellets)*

Nonmechanical Solids Flow Devices

- **Nonmechanical Valves Used for Control Require Particle Sizes Greater Than About 100 Microns (Group B or D Materials)**
- **Nonmechanical Devices in Automatic (Non-Control) Operation Can be Used With Group A as Well as With Groups B and D**

Nonmechanical Solids Flow Devices

- Why do Nonmechanical Valves Not Work Well With Group A Materials?
- This is Because Group A Materials Do Not Defluidize Instantaneously When Gas is Shut Off to a Fluidized Bed, and They Retain Their Fluidity for a Few Seconds
- Thus, When Group A Solids are Poured Into a Nonmechanical Valve, the Solids Retain Their Fluidity and Flow Through the Valve Like Water (Uncontrollably)

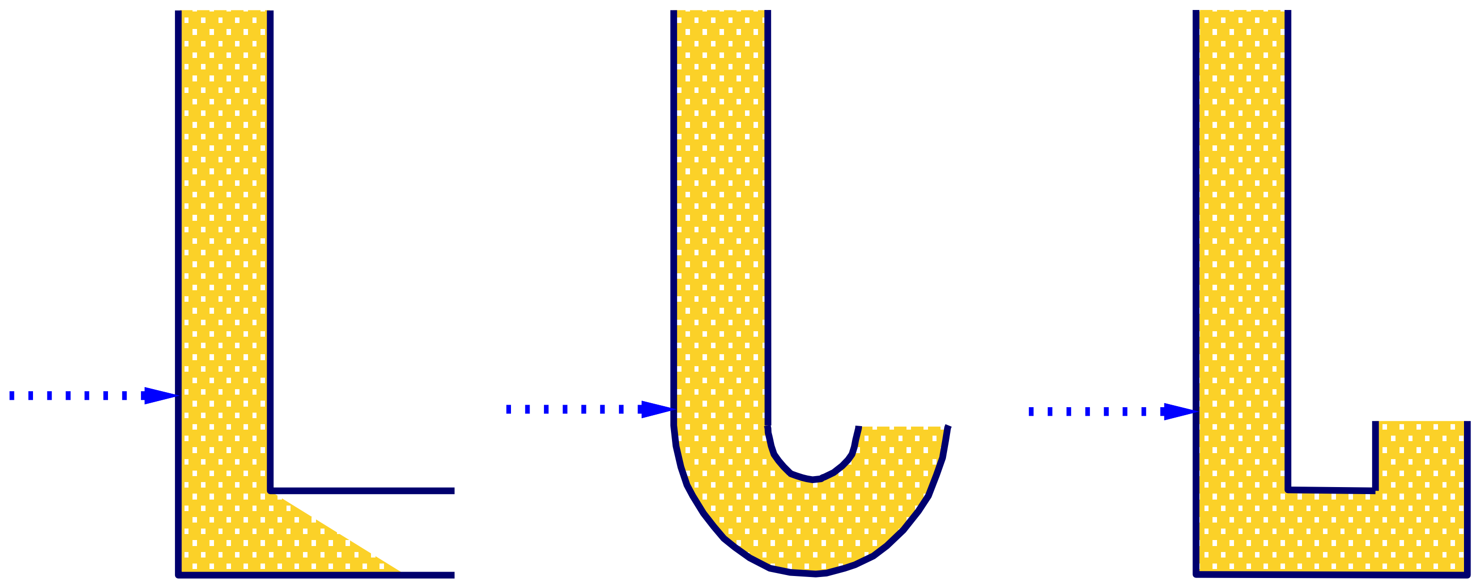
NONMECHANICAL VALVES USED FOR SOLIDS FLOW CONTROL

- **Nonmechanical Valves are Devices That Use Only Aeration Gas in Conjunction With Their Geometrical Shape to Control the Flow Rate of Solids Through Them**

1. **Have no Moving Parts** ***(Other than the Solids)***
2. **Are Very Inexpensive**
3. **Can Feed Solids Into a Dense-Phase or Dilute-Phase Environment**

NONMECHANICAL VALVE OPERATION

- The Most Common Nonmechanical Valve Used to Control Solids Flow is the L-Valve

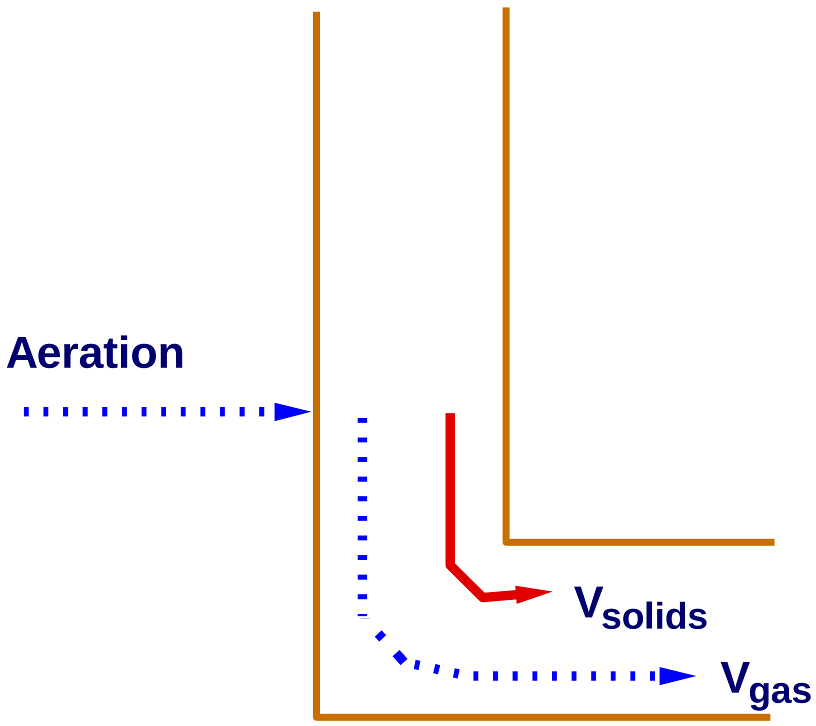


L-Valve J-Valve Approximated J-Valve

The Most Common Nonmechanical Valves

NONMECHANICAL VALVE OPERATION

- **Solids Flow Rate Through a Nonmechanical Valve is Controlled By the Amount of Aeration Gas That is Added to It**

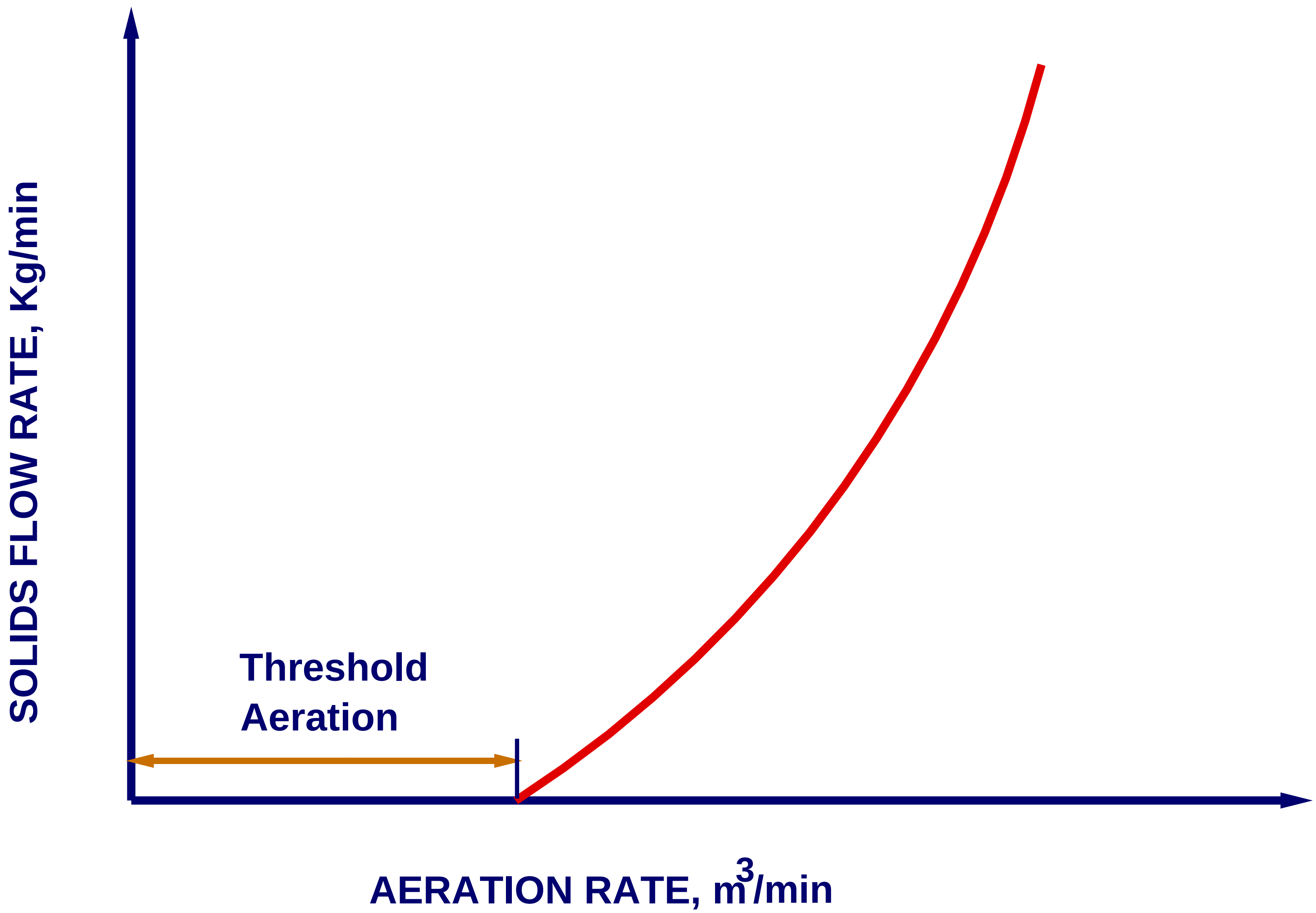


- **Solids Flow Through Nonmechanical Valves Because Gas Drags the Solids Around the Constricting Bend**

- **When Aeration Gas is Added to a Nonmechanical Valve, Solids Do Not Begin to Flow Immediately.**

  There is a Certain Threshold Amount of Aeration Which Must Be Added Before Solids Begin to Flow.

- **Solids Flow Through a Nonmechanical Valve Because of Drag Forces on the Particles Produced By the Aerating Gas.**


SOLIDS FLOW RATE, Kg/min
Threshold
Aeration
AERATION RATE, m3/min

NONMECHANICAL VALVE OPERATION

- Where Should Aeration be Added to an L-Valve?

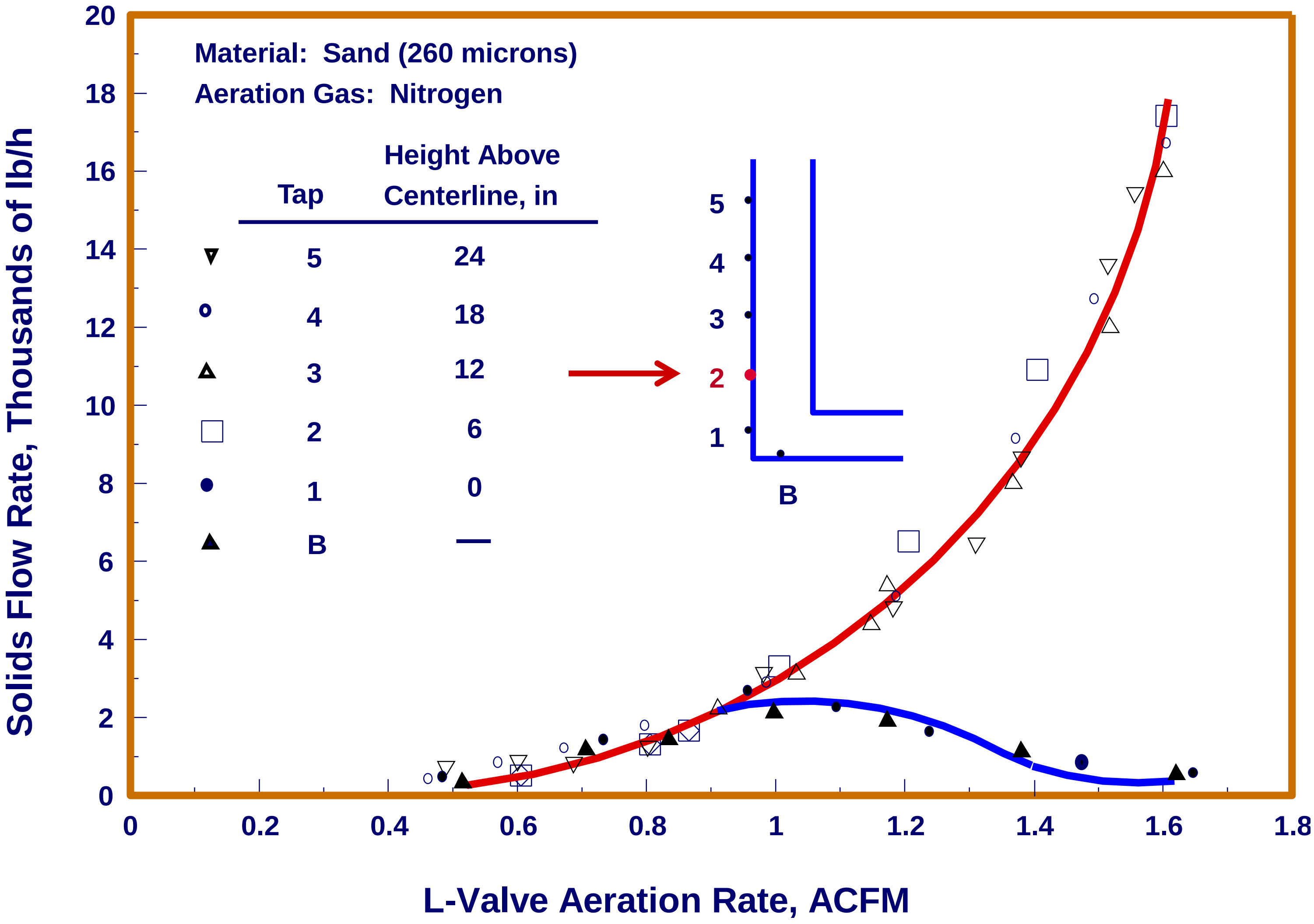
AERATION TAP LOCATION

- Add Aeration to a Nonmechanical Valve as Low in the Standpipe as Possible, But Above the Bend

  1. Will Give Maximum Standpipe Length
  2. Minimum Nonmechanical Valve ΔP

- Both Factors Result in Increasing the Maximum Solids Flow Rate Through the Valve

- If Aeration is Added at too Low a Point, However, (especially in an L-valve) Gas Bypassing Results and Solids Flow Control is Not Effective


Material: Sand (260 microns)
Aeration Gas: Nitrogen
Tap
Height Above Centerline, in
5 24
4 18
3 12
2 6
1 0
B —
5
4
3
2
1
B
Solids Flow Rate, Thousands of lb/h
L-Valve Aeration Rate, ACFM
0
2
4
6
8
10
12
14
16
18
20
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

Nonmechanical Solids Flow Devices

- **Understanding the Operation of Nonmechanical Valves Depends Primarily on Two Things:**

  1. **The Pressure Balance in the System**
  2. **Understanding Packed-Bed Standpipe Operation**

Standpipes

- A Standpipe is a Length of Pipe Through Which Solids Flow by Gravity
- The Primary Purpose of a Standpipe is to Transfer Solids From a Low Pressure Region to a Higher Pressure Region

- **Solids Can Be Transferred From Low to High Pressure in a Standpipe if Gas Flows Upward Relative To The Solids Thus Generating The Required Sealing ΔP**

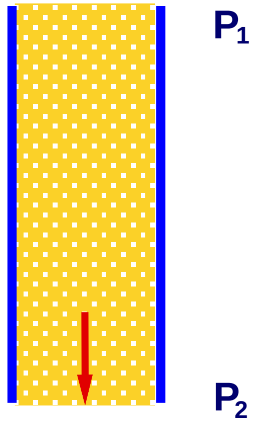
Relative Velocity $= V_r = V_s - V_g$

$$V_r = \frac{W_s}{\rho_p (1-\varepsilon) A} - \frac{W_g}{\rho_g \varepsilon A}$$

where: V_s & V_g are the Interstitial solids and gas velocities, respectively
W_s & W_g are the mass flows of solids and gas, respectively
ρ_p and ρ_g are the particle and gas densities, respectively
ε is the solids voidage, and A is the pipe area

- **Gas Flowing Upward Relative To The Solids Causes A Frictional ΔP To Be Generated**

Positive Direction is Downward

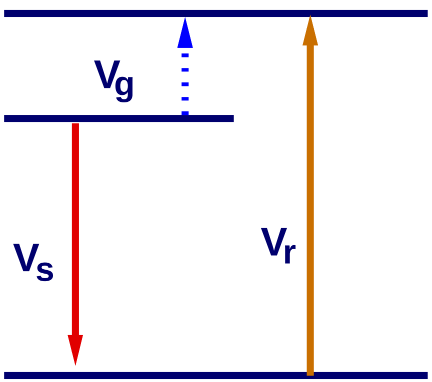


$P_2 > P_1$

+

Case I

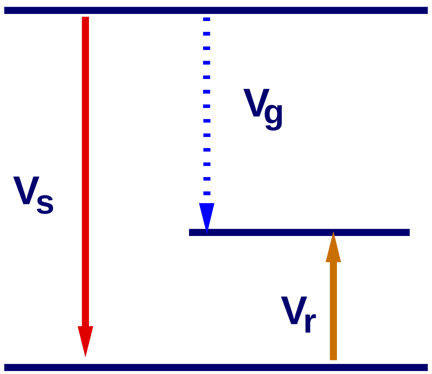
Gas Flowing **Upward** Relative to Pipe Wall



$$V_r = |V_s - V_g|$$
$$V_r = |V_s - (-V_g)|$$
$$V_r = |V_s + V_g|$$

Case II

Gas Flowing **Downward** Relative to Pipe Wall

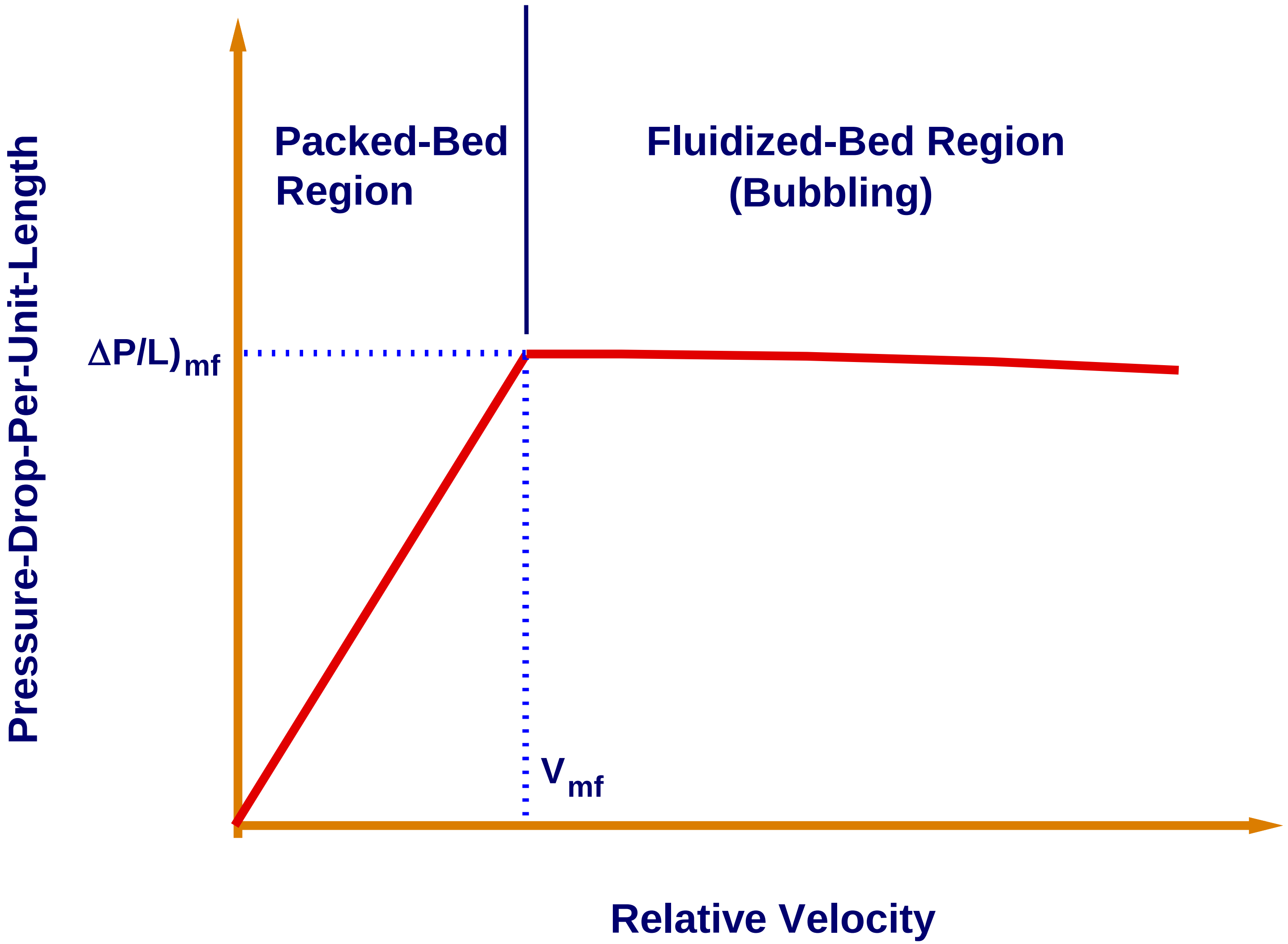


$$V_r = |V_s - V_g|$$

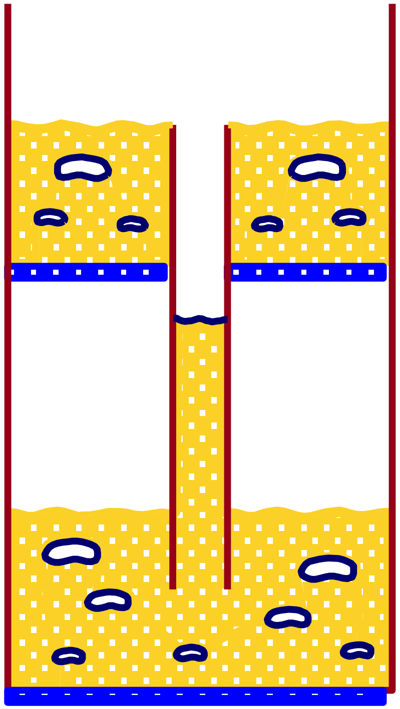
Standpipes

- The Relationship Between $\Delta P/L$ And V_r is Determined By the Fluidization Curve
- This Curve is Usually Generated In A Fluidization Column, But It Also Applies In Standpipes

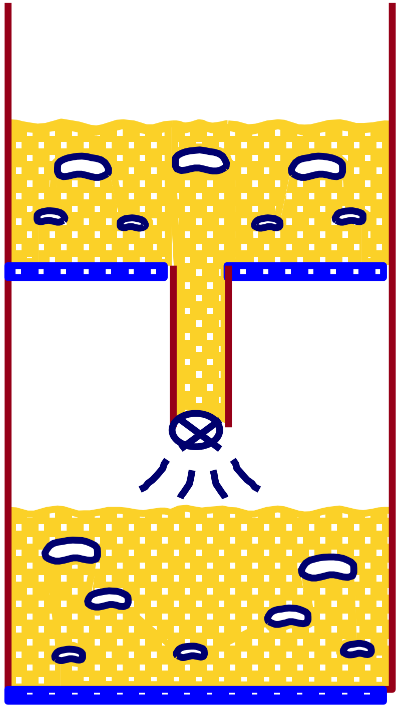
Fluidization Curve - Group B Solids



Underflow and Overflow Standpipes



OVERFLOW



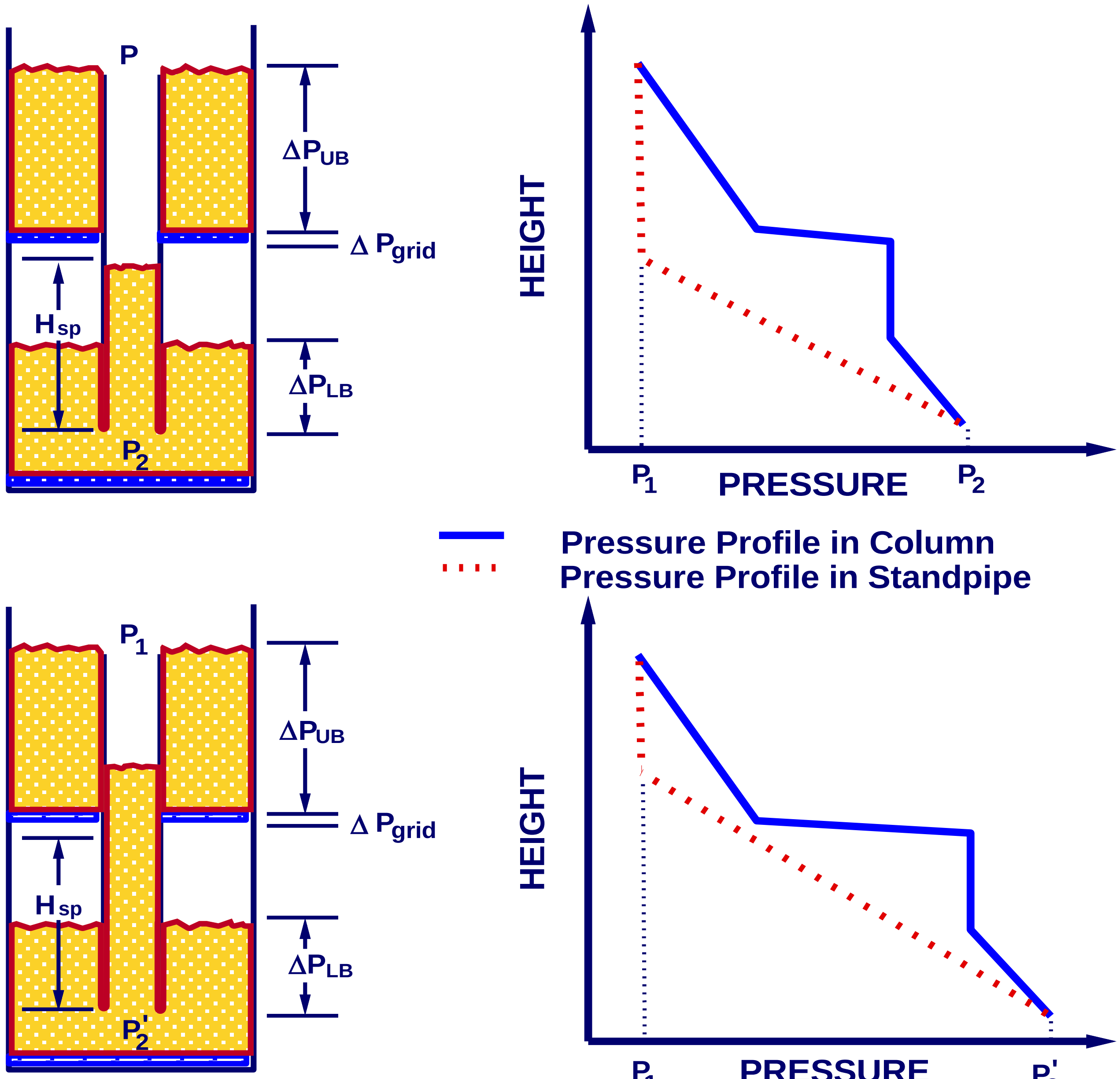
UNDERFLOW

Standpipes

- Many Standpipes are Fluidized Overflow Standpipes

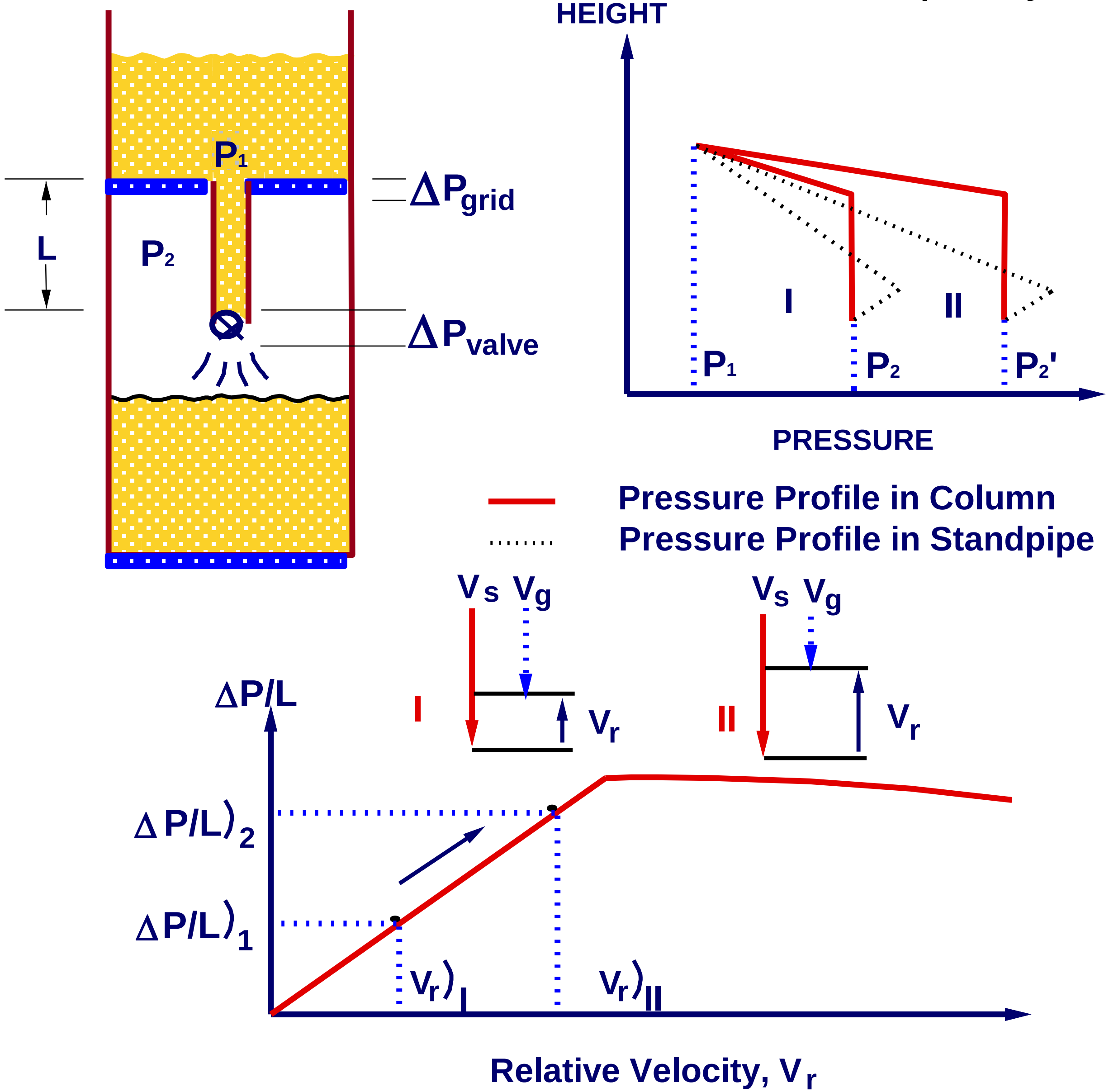
- Operation of These Standpipes is Easy to Understand, and Non-Control Nonmechanical Devices (Loop Seals, Seal Pots, etc.) Operate with This Type of Standpipe Above Them

Operation of Fluidized Overflow Standpipe



Standpipes

- **However, Nonmechanical Valves (Used to Control the Solids Flow Rate) MUST Operate With a *Packed Bed Underflow* Standpipe Above Them**
- **How Does This Type of Standpipe Operate?**

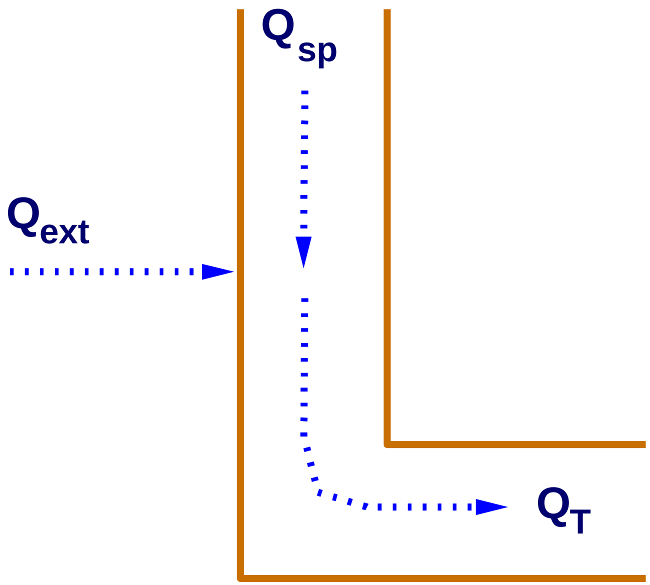


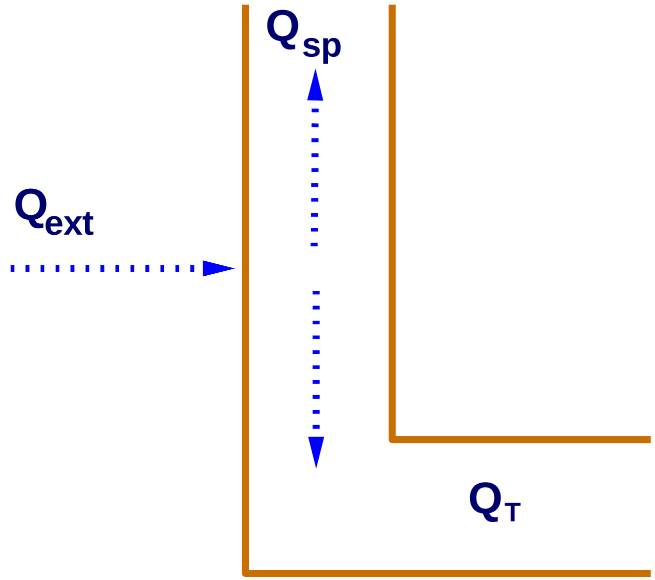
Underflow Packed-Bed Standpipe Operation

Nonmechanical Valves for Solids Flow Control

- **Gas Can Flow Either Upward or Downward (Relative to the Pipe Wall) in the Packed Flow Standpipe Above the L-Valve**

- **The Direction of This Flow Depends on Particle Size and the $\Delta P/L$ in the Standpipe Above the Valve**





$$Q_T = Q_{ext} + Q_{sp}$$

$$Q_T = Q_{ext} - Q_{sp}$$

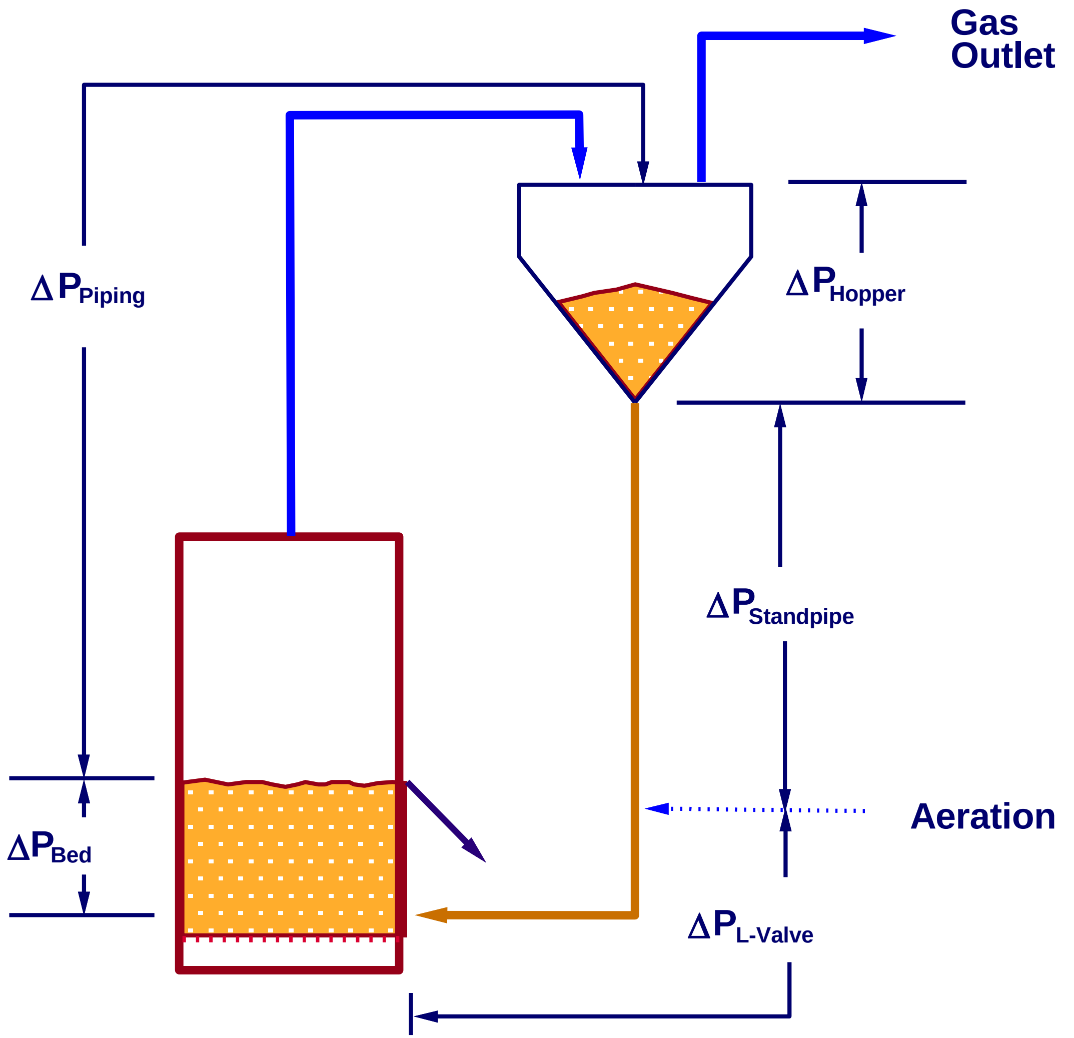
- Occurs With Small Particle Sizes and/or At High Solids Flow Rates
- Most Common Situation

- Occurs With Large Particle Sizes and/or At Low Solids Flow Rates

Nonmechanical Valves for Solids Flow Control

- **Nonmechanical Valve Operation Also Depends on the Pressure Balance Around the System**
- **Not Designing the Pressure Balance Correctly can Limit Nonmechanical Valve Operation by Affecting the Solids Flow Rate**

L-Valve System Pressure Balance

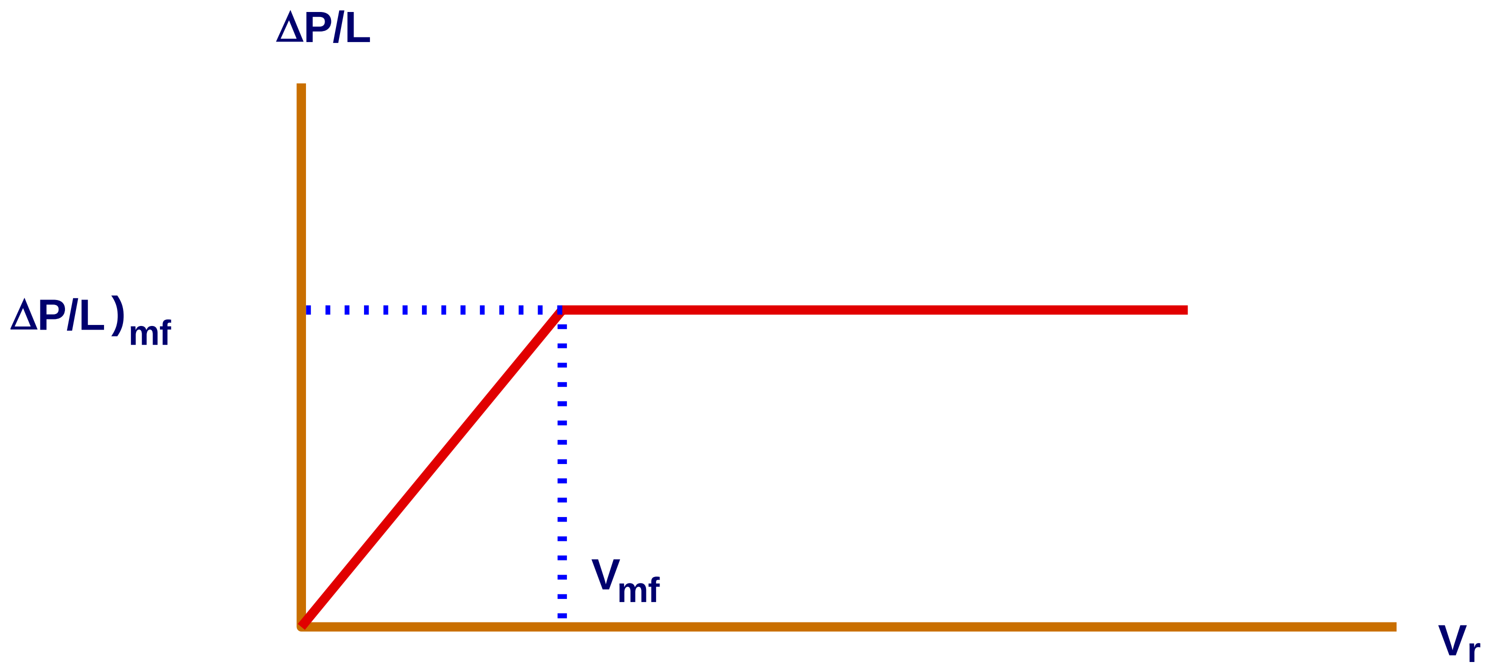


$$\Delta P_{Standpipe} + \overset{0}{\Delta P_{Hopper}} = \overset{K}{\overline{\Delta P_{Bed} + \Delta P_{Piping}}} + \Delta P_{L\text{-}Valve}$$

$$\Delta P_{Standpipe} = K + \Delta P_{L\text{-}Valve}$$

Maximum $\Delta P/L$ in Standpipe is:

$\Delta P/L)_{mf}$



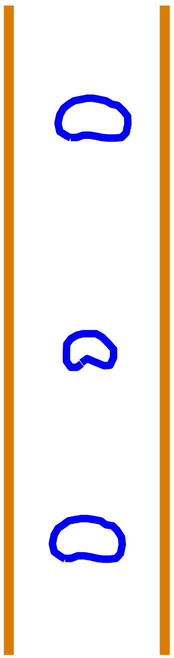
- **There is a Maximum $\Delta P/L$ That the Packed-Bed Standpipe Can Develop -- $(\Delta P/L)_{mf}$**

- **If Increase Solids Flow Rate, L-Valve ΔP Increases and Standpipe ΔP Increases Until $\Delta P/L$ Reaches $(\Delta P/L)_{mf}$**

- **A Short Standpipe Will Reach Its Maximum ΔP/L At a Lower Solids Flow Rate Than a Longer Standpipe**

- **Therefore, the Maximum Solids Flow Rate Through an L-Valve Depends on the Length of the Standpipe Above it**

- After $\Delta P/L)_{mf}$ is Reached, More Aeration Produces Bubbles in the Standpipe, Which Hinder Solids Flow

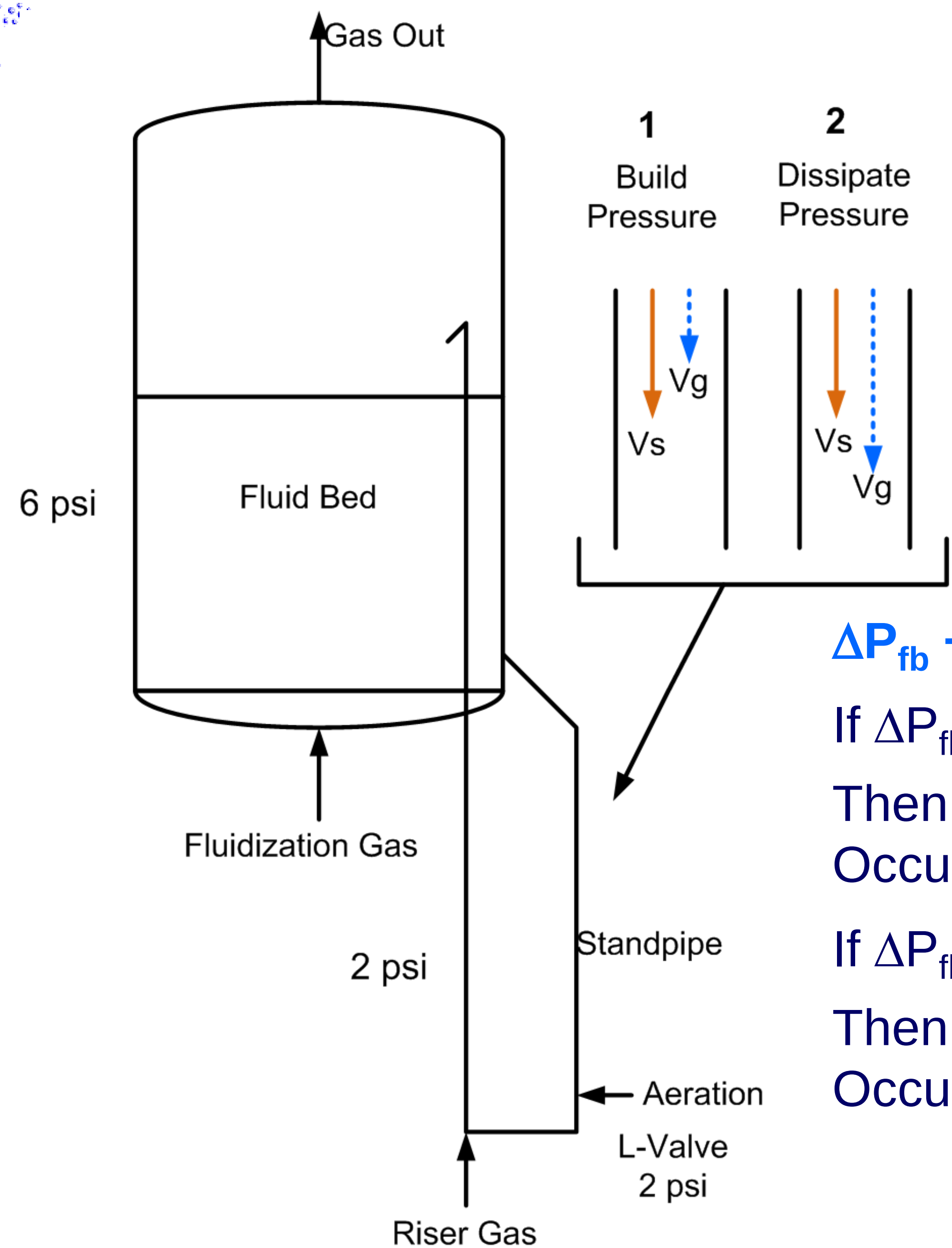


Pressure Balance is Critical

- Pressure Balance is Critical in Designing a System Containing a Nonmechanical Valve:

  1. If the Pressure Balance is Not Correct, the Valve Will Not Operate Correctly

  2. Example on Next Slide Shows Actual Case of Someone Designing an L-Valve That Could Have, But Did Not Work



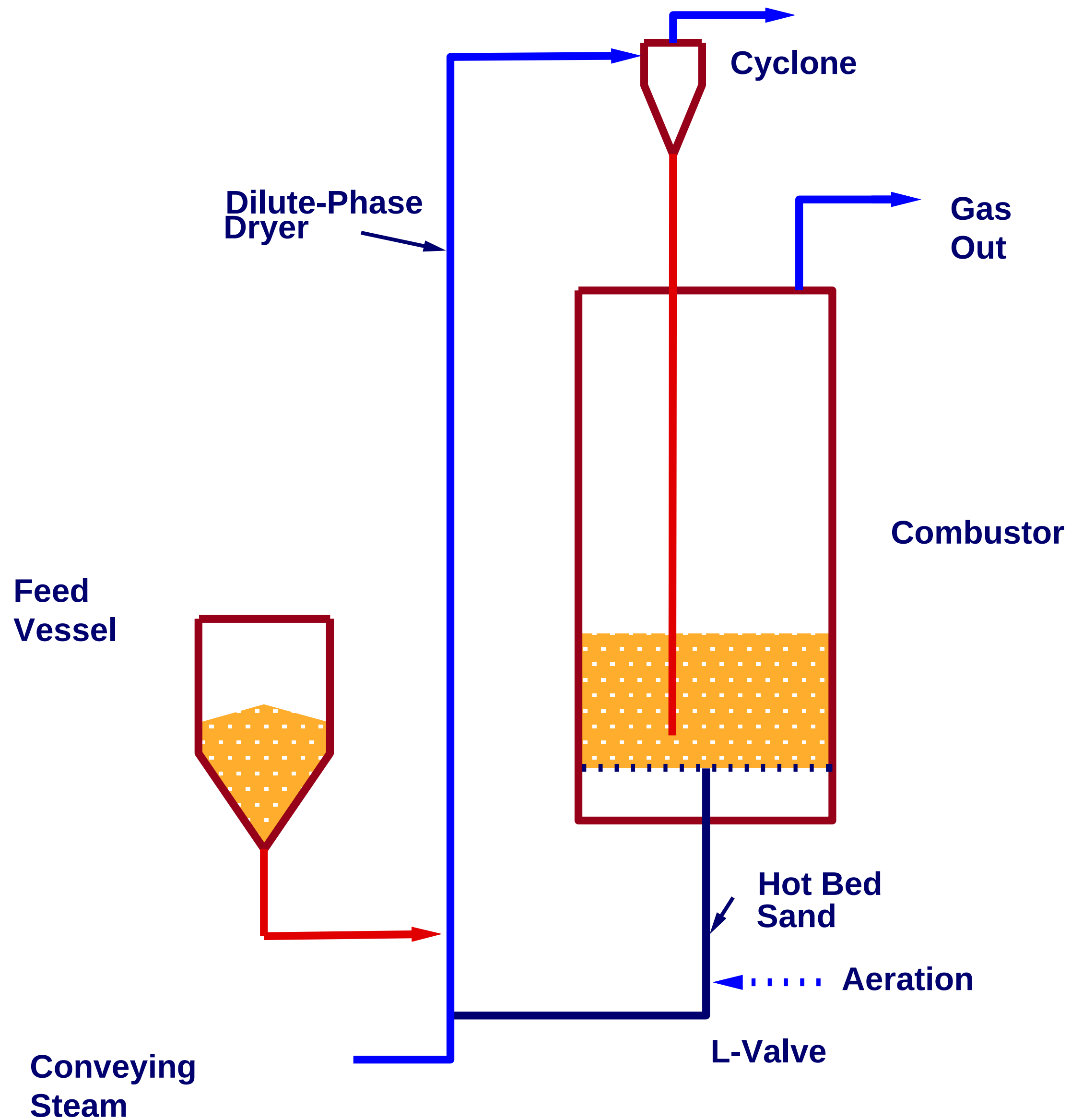
$$\Delta P_{fb} + \Delta P_{sp} = \Delta P_{L\text{-}valve} + \Delta P_{riser}$$

If $\Delta P_{fb} < \Delta P_{L\text{-}valve} + \Delta P_{riser}$

Then Relative Velocity as in 1 Occurs

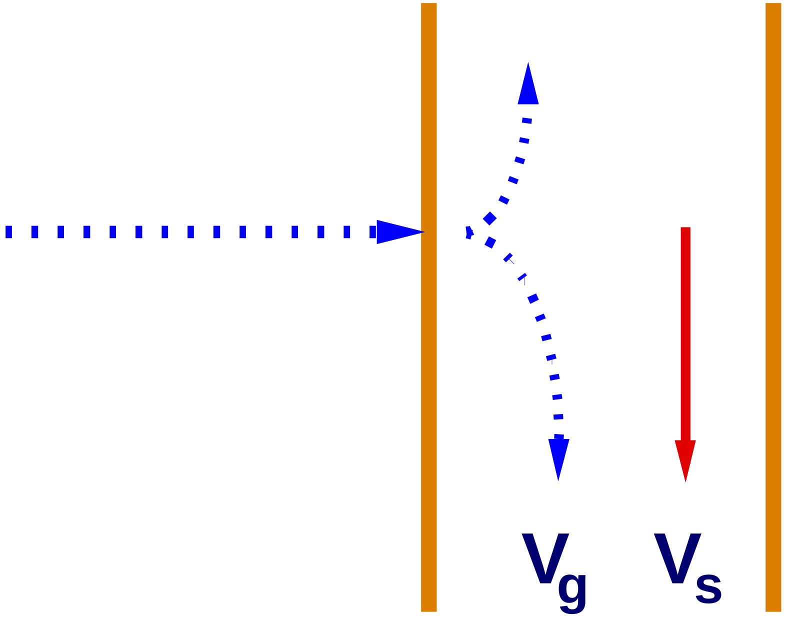
If $\Delta P_{fb} > \Delta P_{L\text{-}valve} + \Delta P_{riser}$

Then Relative Velocity as in 2 Occurs

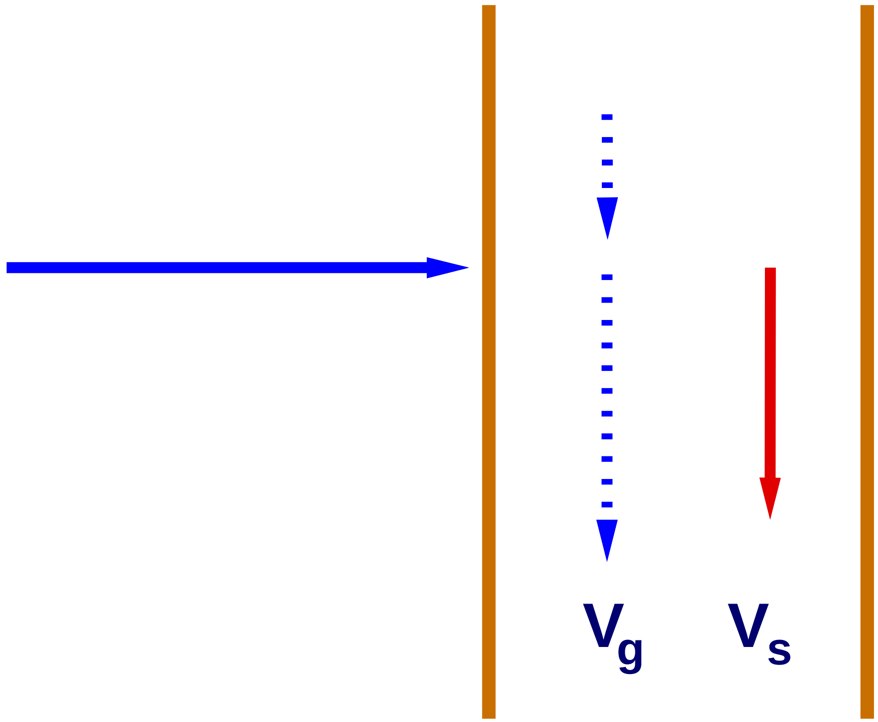


FEEDING A DRYER WITH AN L-VALVE (FORTUM)

The L-Valve Can be Designed to Prevent System Gas from Exiting the Reactor



It is also Possible to Prevent Aeration Gas from Entering the Reactor



NON-CONTROL (AUTOMATIC) NONMECHANICAL SOLIDS FLOW DEVICES

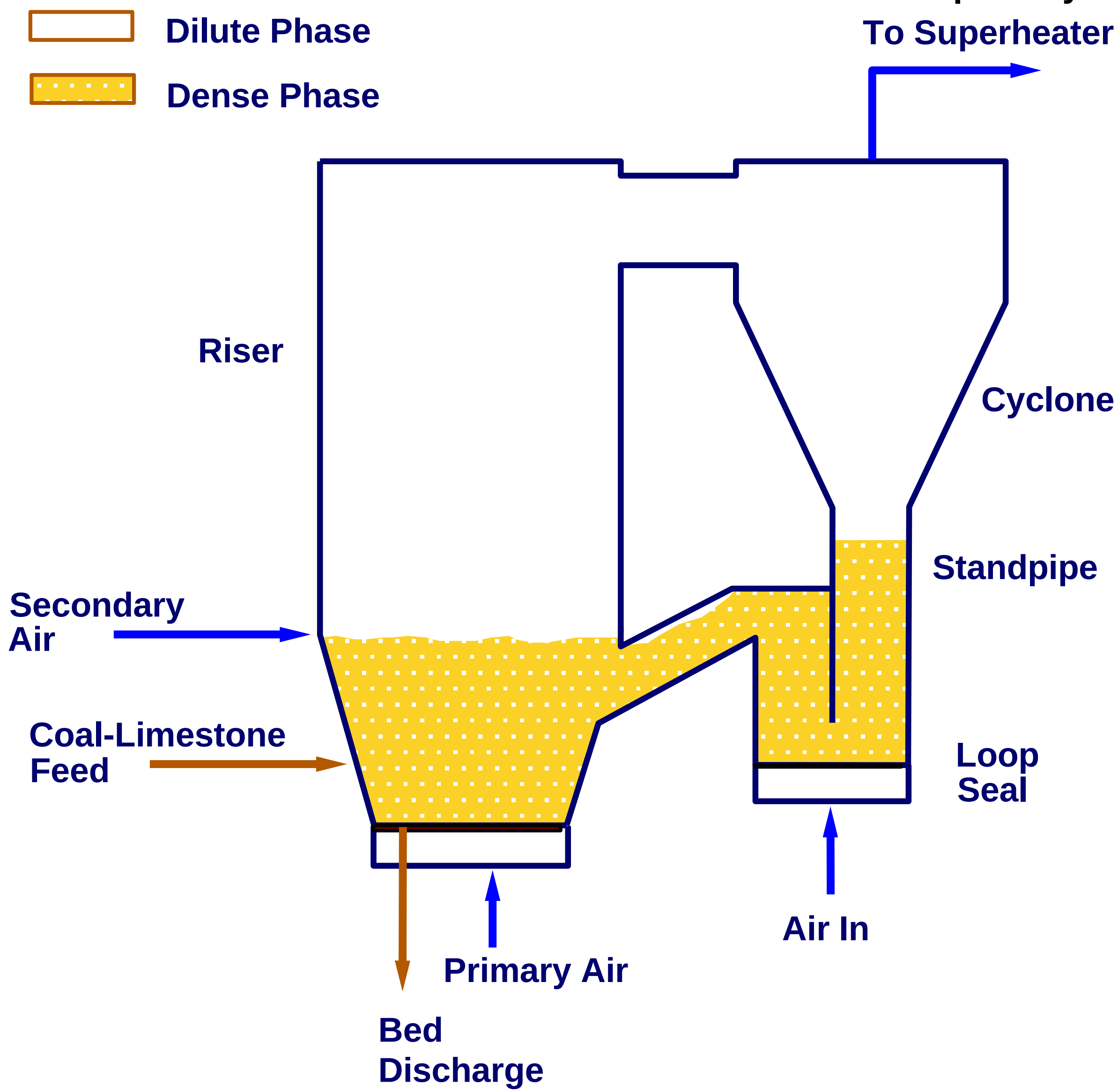
- Provide a Pressure Seal (In Conjunction With a Standpipe)

- Operate With an Overflow Fluidized Bed Standpipe Above Them

AUTOMATIC NONMECHANICAL SOLIDS FLOW DEVICES

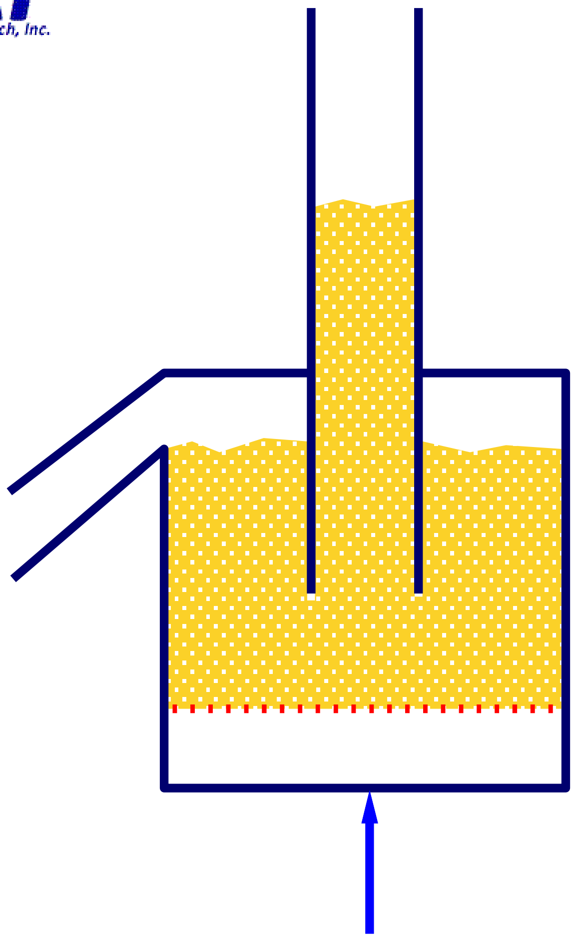
- Do Not Control Solids Flow
- Automatically Adjust to Changes in the Solids Flow Rate

- **One of the Most Frequent Applications of Automatic Nonmechanical Devices is in CFB Systems Where a Loop Seal is Used to Recycle Collected Solids from the Cyclone Back to the CFB**



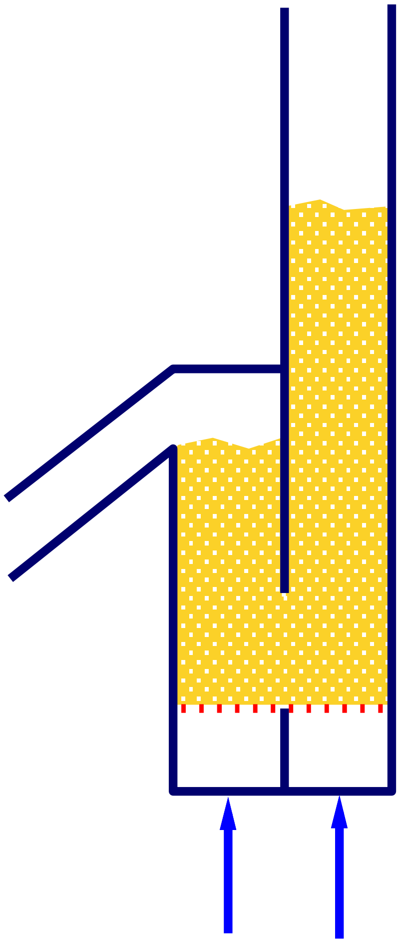
Circulating Fluidized Bed Combustor

(Foster-Wheeler Type)



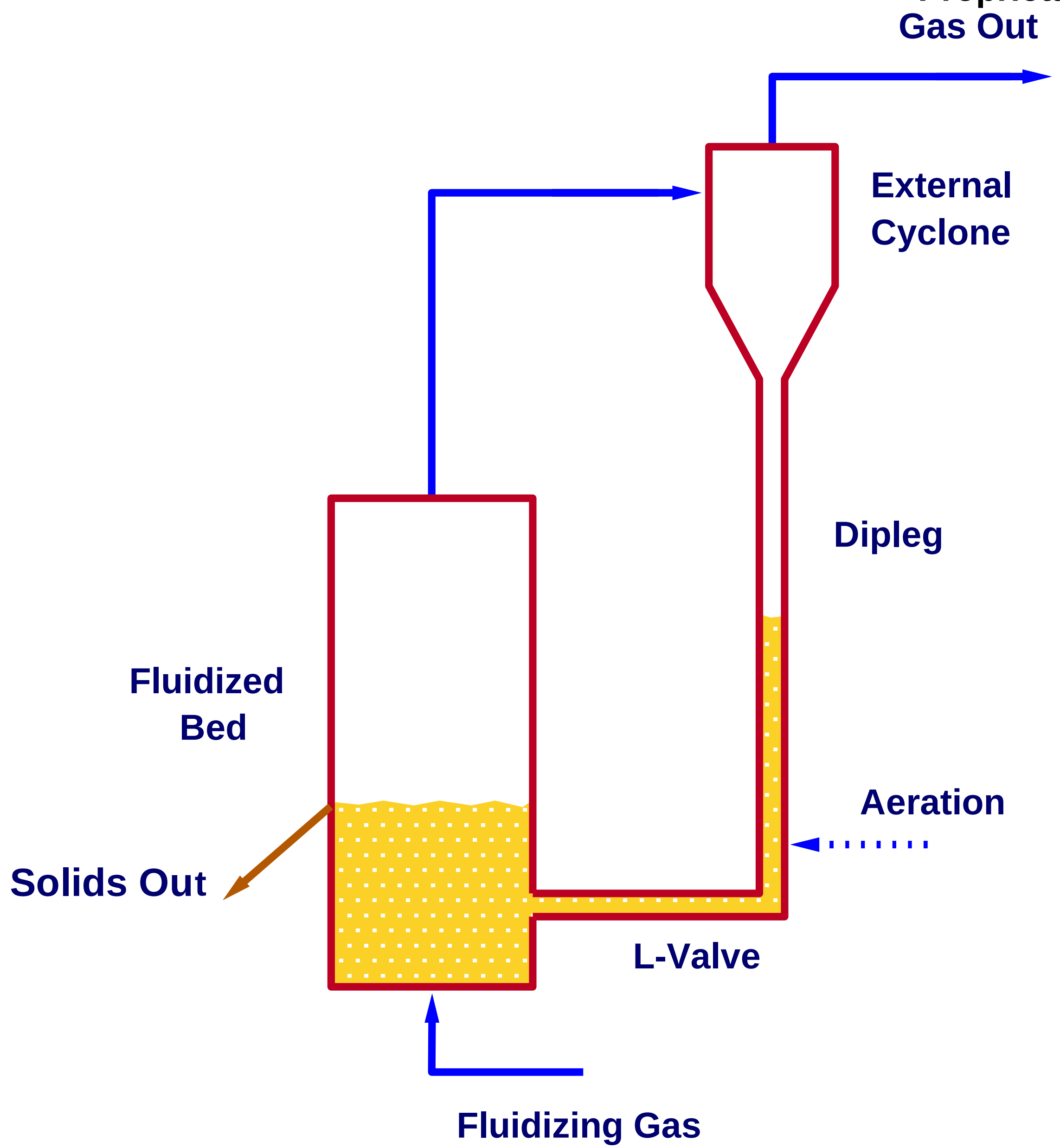
Fluidizing Gas

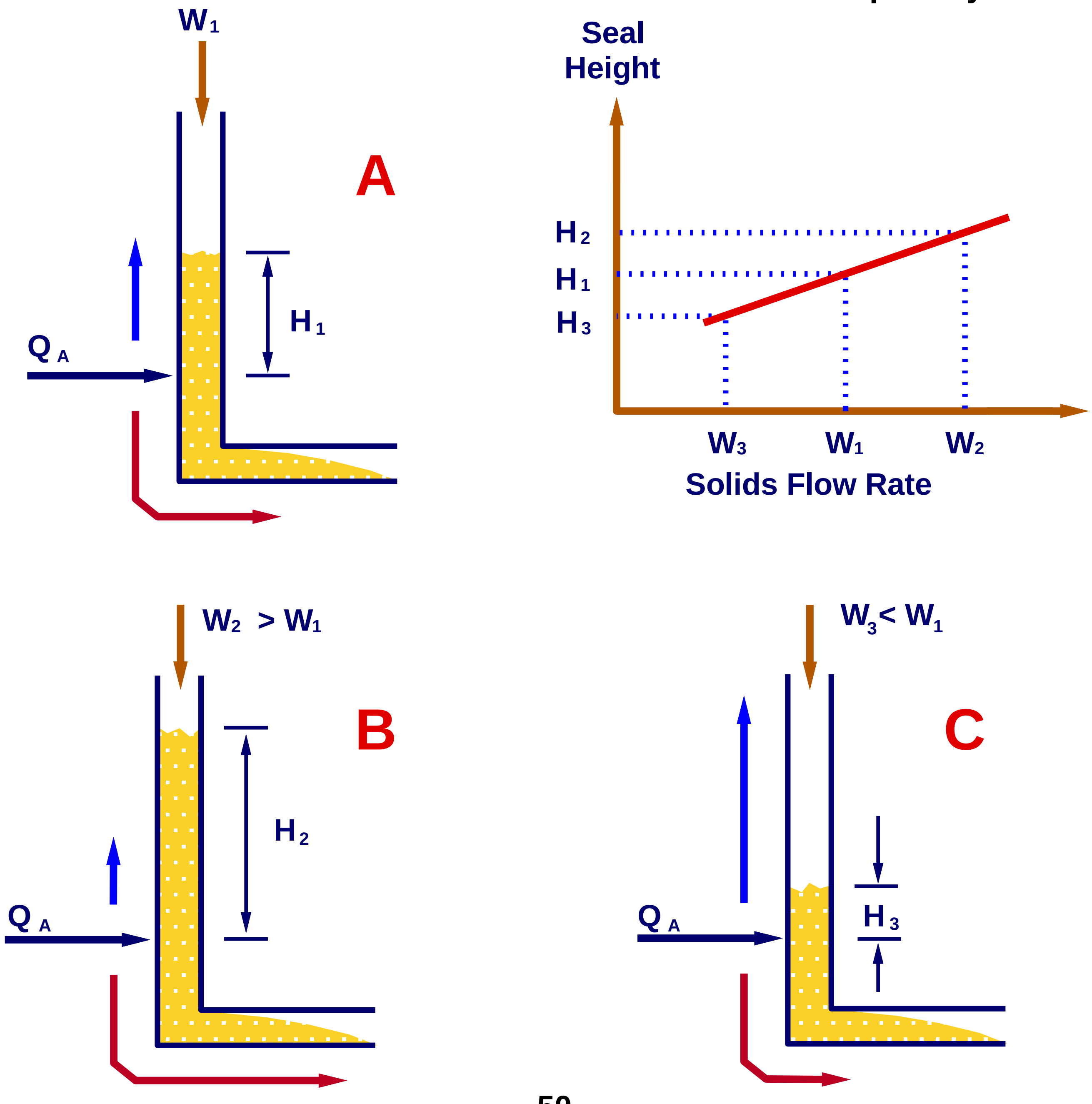
Seal Pot



Fluidizing Gas

Loop Seal


Gas Out
External
Cyclone
Dipleg
Fluidized
Bed
Aeration
Solids Out
L-Valve
Fluidizing Gas


W1
A
Q A
H1
Seal
Height
H2
H1
H3
W3
W1
W2
Solids Flow Rate
W2 > W1
B
Q A
H2
W3< W1
C
Q A
H3

Chemical Looping Systems

- In the Following Slides, Several Different Types of Proposed Solids Flow Systems for Chemical Looping are Shown

- The Techniques Used to Control the Solids Flow Rate Around Each of the Systems Are Different

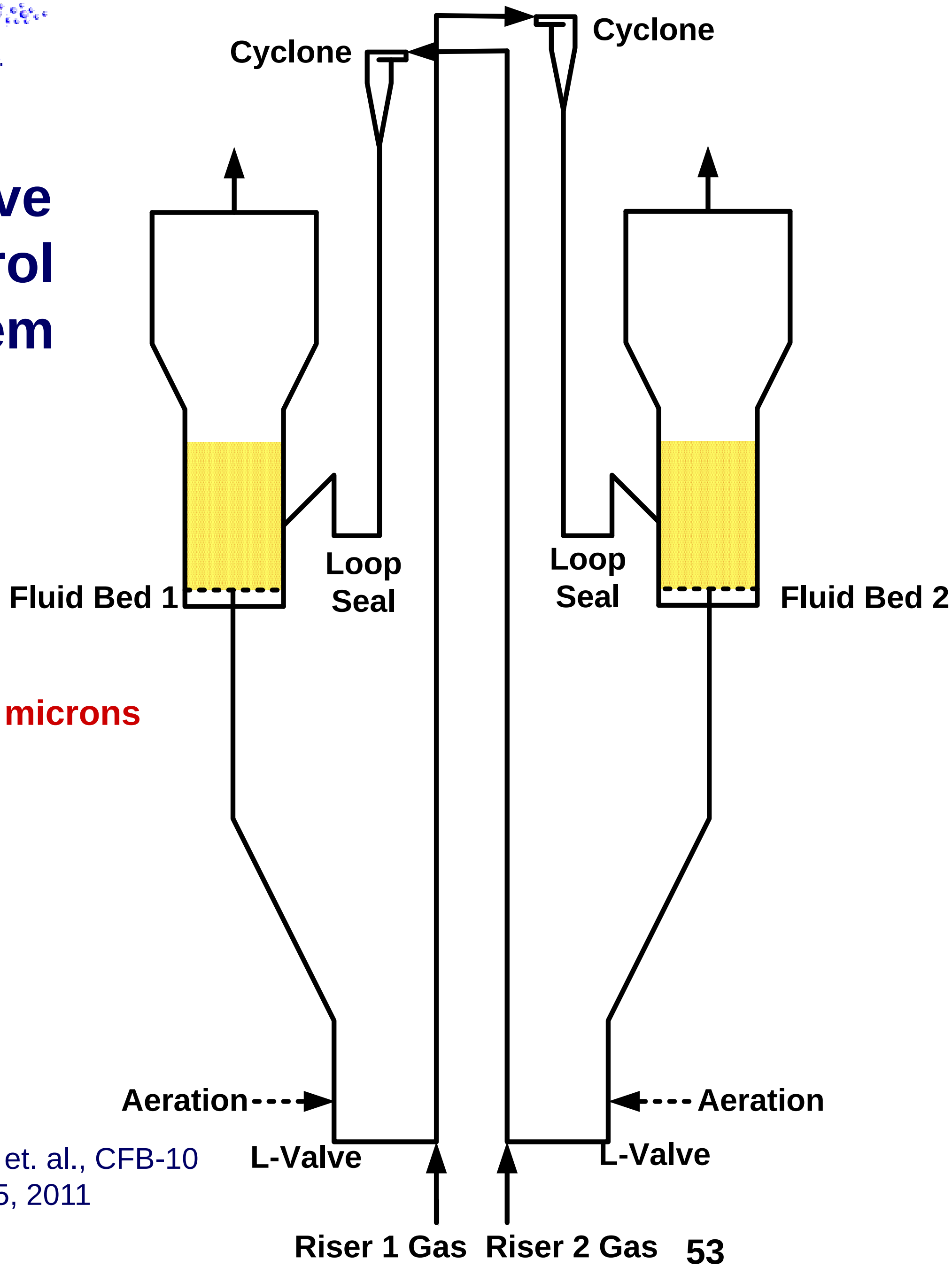
CONTROL OF NONMECHANICAL SYSTEMS

- There are Four Ways to Control the Solids Flow Rate in Nonmechanical Systems:

  1. Using a Nonmechanical L-Valve Below a Packed Bed Standpipe
  2. Operating the Riser at the Choking Velocity to Control the Solids Flow Rate
  3. Using Inventory Control to Change the Level in an Overflow Fluidized Bed Standpipe
  4. A Combination of Methods 2 and 3

L-Valve Control System

d_p = 320 microns



Yazdanpanah et. al., CFB-10 Proc., May 2-5, 2011

Advantage(s):

1. Good Solids Flow Control
2. Do Not Need to Change Inventory for Control

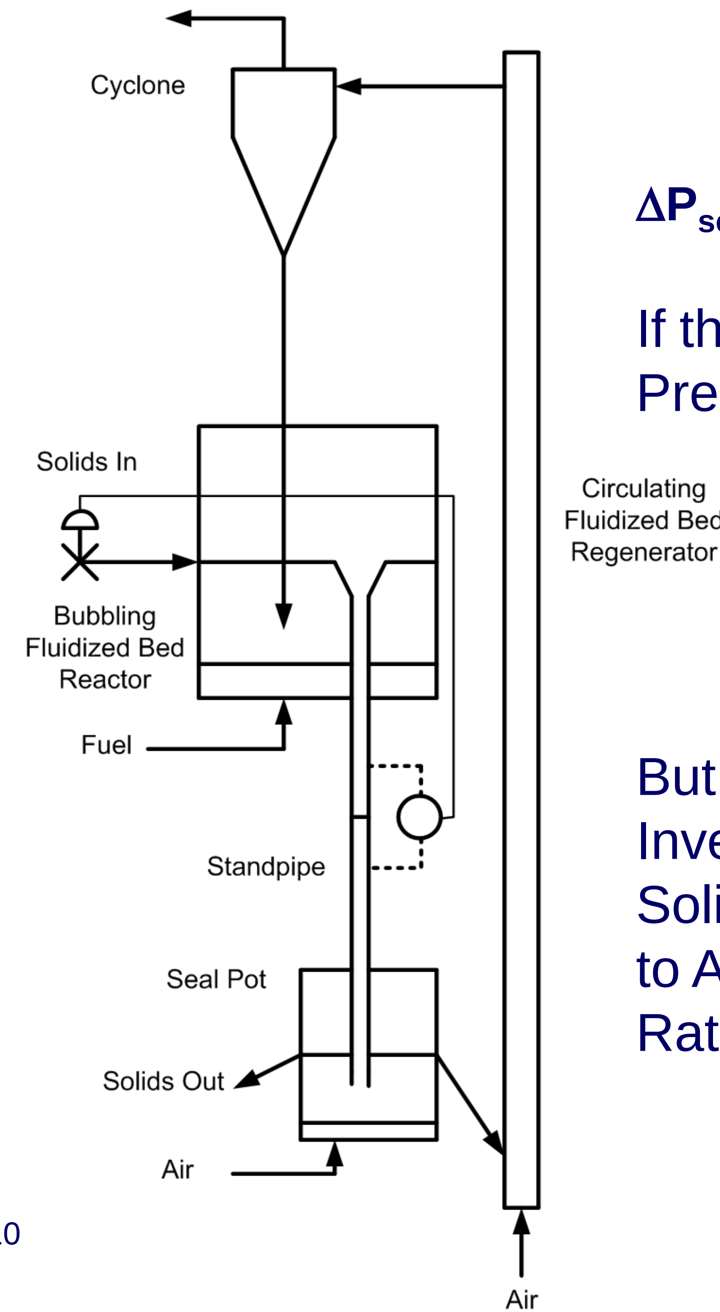
Disadvantage(s):

1. Works With B/D Geldart Groups Only

Conclusion:

Good, Solid Design

Inventory Control System



$$\Delta P_{sealpot} + \Delta P_{riser} + \Delta P_{cy} = \Delta P_{SP} = H_{SP} * \rho_{SP}$$

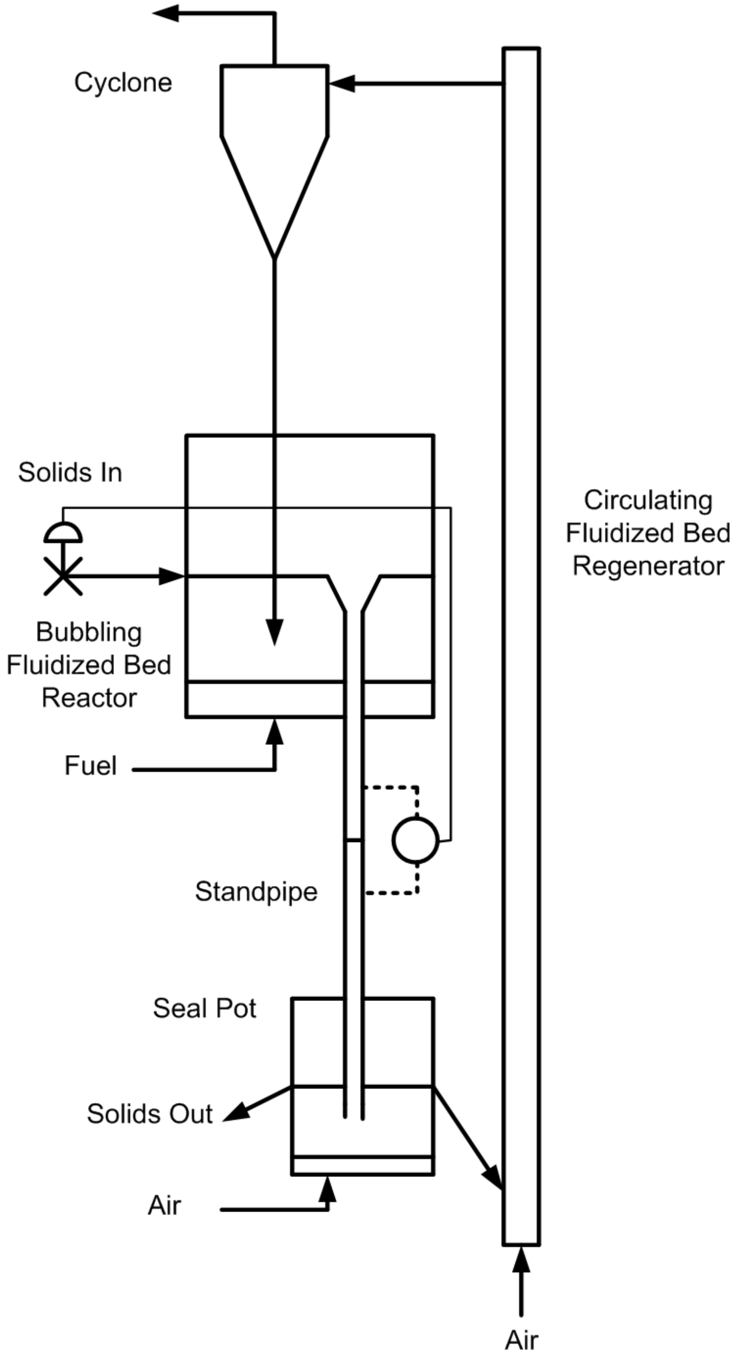
If the Solids Flow Rate Increases, the Pressure Drop Across the Riser Will Increase (if the Gas Velocity in the riser is constant). Therefore, the Solids Level in the Standpipe Must Increase.

But, It Cannot Increase for a Constant Inventory in the System. Therefore, Solids MUST be added to the System to Allow the Increased Solids Flow Rate.

d_p = 150 microns

Shimizu et. al., CFB-10 Proc., May 2-5, 2011

Inventory Control System



d_p = 150 microns

Shimizu et. al., CFB-10
Proc., May 2-5, 2011

Advantage(s):

1. Can be Used With Group A Particles

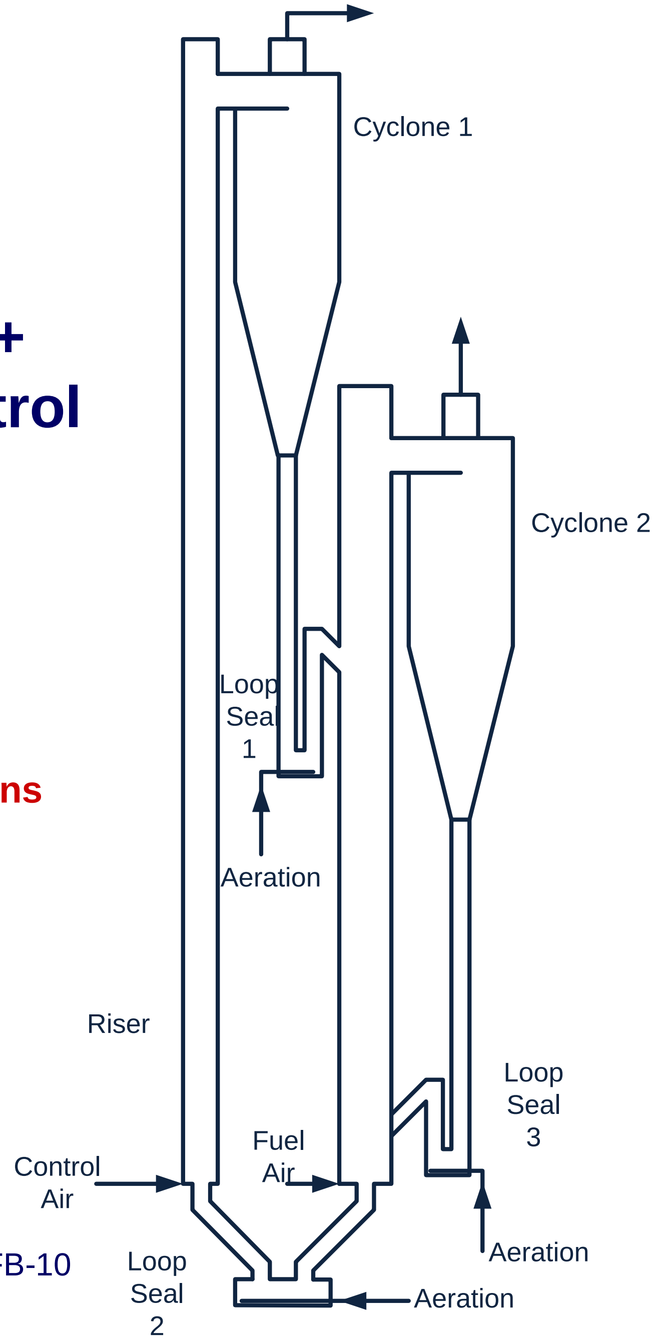
Disadvantage(s):

1. At High P Will be Hard to Add and Remove Solids
2. Solids Flow Rate Change Not "Immediate"

Conclusion:

More Complex and Less Responsive System

Inventory + Riser Control System



d_p = 161 microns

Guio-Perez et. al., CFB-10 Proc., May 2-5, 2011

Advantage(s):

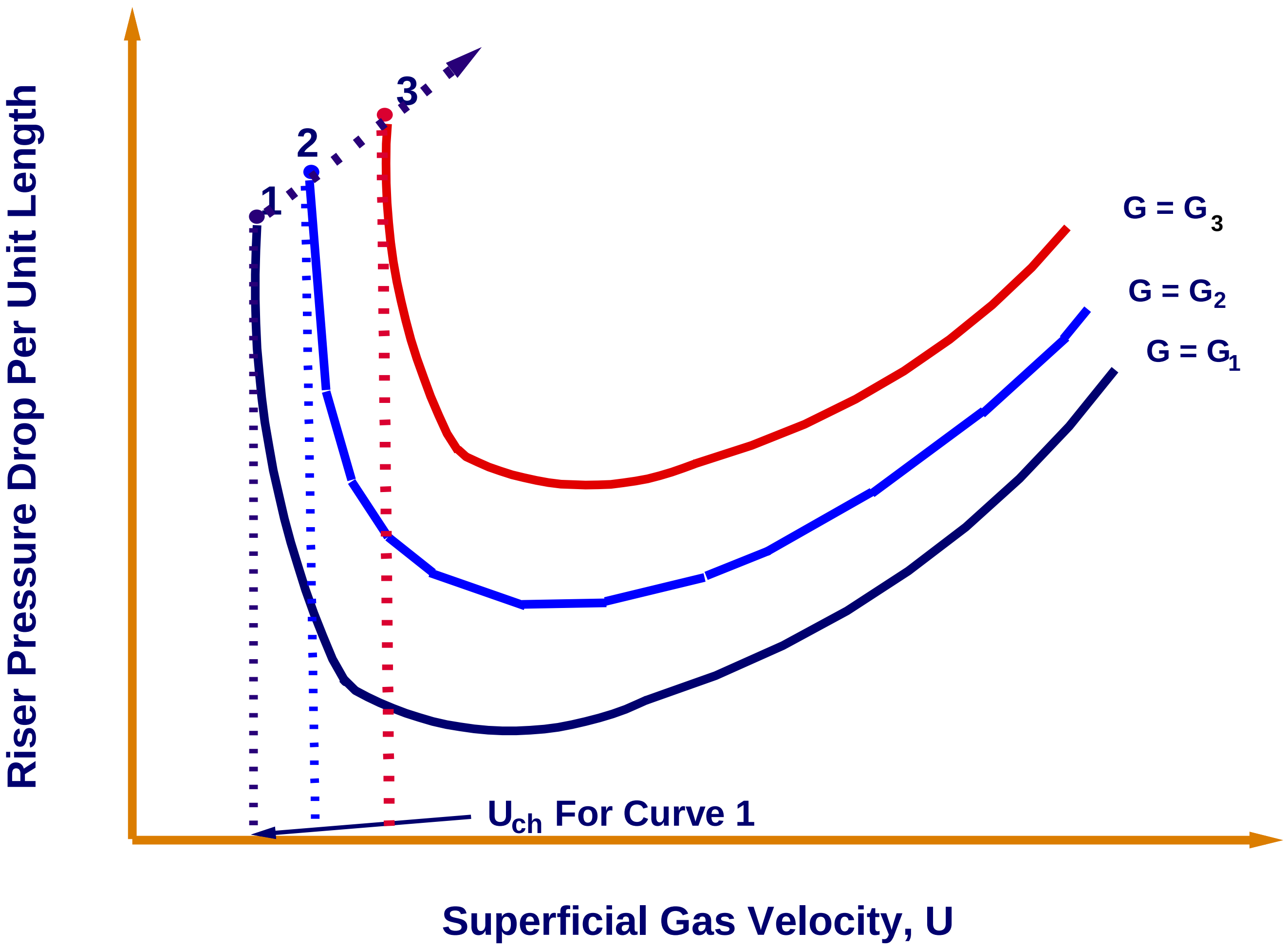
1. Can be Used With Group A Particles

Disadvantage(s):

1. At High P Will be Hard to Add and Remove Solids
2. Solids Flow Rate Change Not "Immediate"

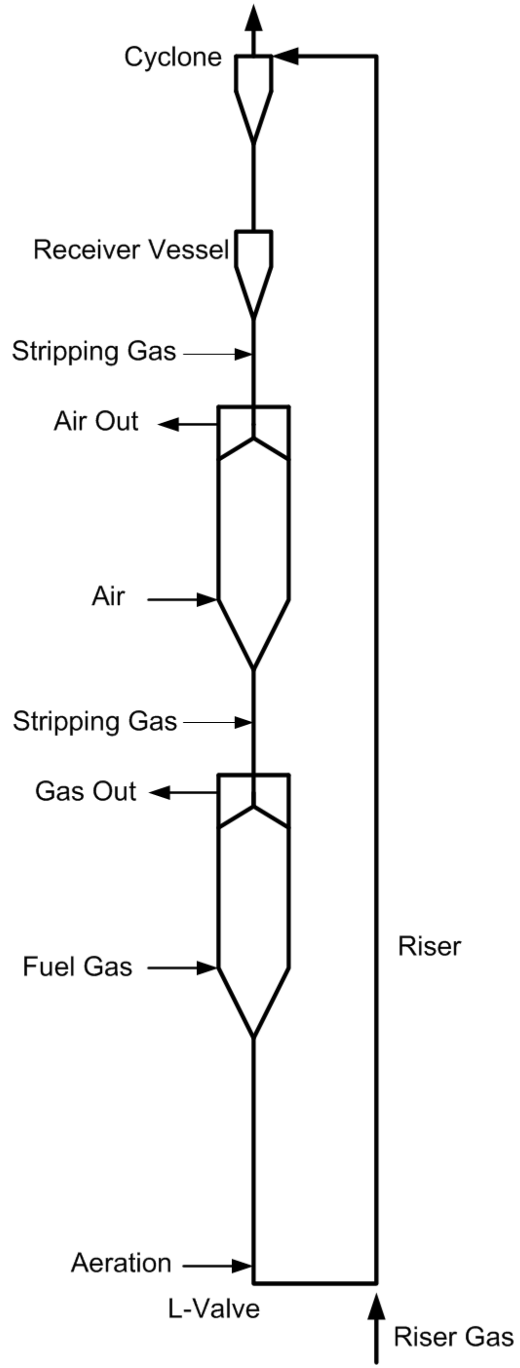
Conclusion:

More Complex and Less Responsive System


Riser Pressure Drop Per Unit Length
1
2
3
G = G3
G = G2
G = G1
Uch For Curve 1
Superficial Gas Velocity, U

L-Valve Control

Large Group B and Group D Particles



Advantage(s):

1. Good Solids Flow Control
2. Do Not Need to Change Inventory for Control

Disadvantage(s):

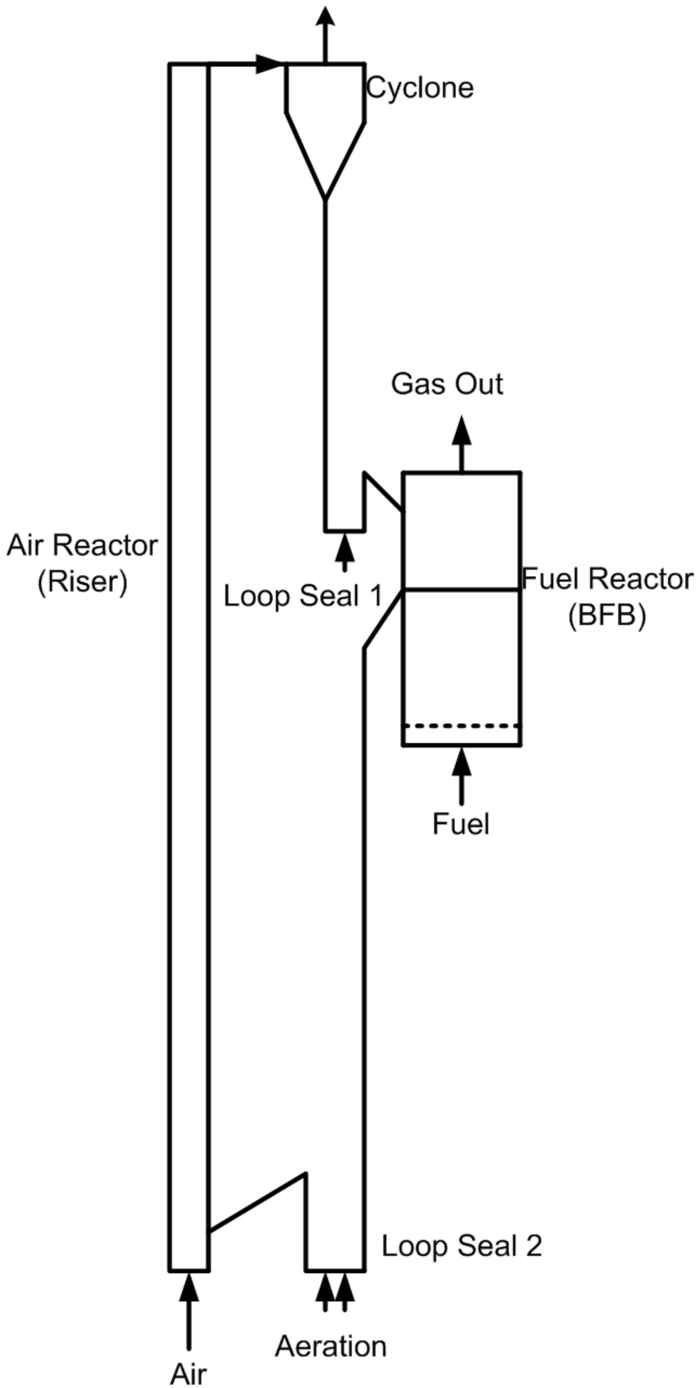
1. Cannot be Used With Group A Solids

Conclusion:

Good, Solid Design

The Ohio State University,
L.S. Fan and Colleagues

Riser Control



Varied

Advantage(s):

1. **Can be Used With Group A Particles**

Disadvantage(s):

1. **At High P Will be Hard to Add and Remove Solids**
2. **Solids Flow Rate Change Not "Immediate"**

Conclusion:

Less Responsive System

Chalmers Univ. of Tech., A. Lyngfeldt, 1st Intl Conf on Chem Looping, Lyon March 17-19, 2010

Thank You!

Questions?