PRESSURE BUILDUP IN STANDPIPES

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Abstract

Standpipes are an important element in Fluidized Catalytic Cracking (FCC) units. They supply the pressure buildup required to “drive” the solids through a controlling slide valve at the catalyst flux required. Most operators assume that the buildup in a fluidized underflow standpipe (the type used in FCC units) should be equivalent to the material’s fluidized density multiplied by the length of the standpipe. Certainly, this is the maximum buildup possible in the standpipe, but standpipes do not always operate at this maximum pressure buildup condition.

One reason that the standpipe does not always operate at its optimum pressure buildup condition is that the standpipe also serves another function in the pressure balance loop. The standpipe is the only element that can adjust itself to automatically balance the pressure drop in the circulation loop. Because of this, the standpipe does not always operate at optimum (maximum pressure buildup) conditions – it is constrained by the parameters of the pressure drop loop. If these constraints occur, standpipe pressure profiles and gas flows in the standpipe will be adjusted automatically to allow the pressure balance to occur, and negative standpipe buildups are even possible in certain limiting situations.

Background

Standpipes are designed to build pressure in a catalyst circulation system to generate the driving force required to force the solids through a controlling slide valve at the maximum catalyst flux desired. Often problems in FCC circulation systems are traced to poor standpipe pressure-drop-per-unit-length ($\Delta P/L$) buildups. Because FCC standpipes are designed for fluidized operation, the $\Delta P/L$ values in the standpipe are often referred to as standpipe densities. The apparent poor standpipe buildup may be due to too much or too little aeration. It may also be a result of the pressure balance produced by the operation of the circulation system. The latter situation has not been adequately understood in the literature.

FCC Standpipes: Theory and Operation

A standpipe is essentially a length of pipe through which solids flow. Solids can flow through a standpipe in either dilute or dense-phase flow. Standpipes can be vertical, angled, or a mixture of angled and vertical pipes called a hybrid standpipe.

The purpose of a standpipe is to transfer solids from a region of low pressure to a region of higher pressure. This is shown in Figure 1, where solids are being transferred from a fluidized bed at pressure P_1 to another fluidized bed operating at P_2 (higher than P_1).

Solids can be transferred by gravity from a low pressure to a higher pressure if gas flows upward *relative* to the downward flowing solids. This relative gas-solids flow will then generate the sealing pressure drop required for the system. The direction of the actual gas flow in the standpipe relative to the standpipe wall can be either up or down and still have the relative gas-solids velocity, v_r, directed upwards. This is sometimes difficult to understand, but it can be explained with the aid of Figure 1, and the definition of the relative gas-solids velocity. The relative gas-solids velocity, v_r, is defined as:

$$v_r = \left| v_s - v_g \right| \tag{1}$$

where v_s is the solids velocity, and v_g is the interstitial gas velocity ($v_g = U/\varepsilon$).

It is generally easier to visualize what is occurring in a solids transfer system by mentally traveling along with the solids. Therefore, the positive reference direction for determining v_r will be taken to be the direction that the solids are flowing – downward.

In Figure 1 solids are being transferred downward in a standpipe from pressure P_1 to a higher pressure P_2. Solids velocities in Figure 1 are denoted by the length of the bold arrows, gas velocities by the length of the dashed arrows, and the relative gas-solids velocity by the length of the thin-lined arrows. For Case 1 in Figure 1, solids are flowing downward, and gas is flowing upward relative to the standpipe wall. The relative velocity is directed upward, and is equal to the sum of the solids velocity and the gas velocity, i. e.:

$$v_r = v_s - \left(-v_g\right) = v_s + v_g \tag{2}$$

For Case 2, solids are flowing down the standpipe relative to the standpipe wall. Gas is also flowing down the standpipe relative to the standpipe wall, but at a velocity less than that of the solids. For this case, the relative velocity is also directed upward, and is equal to the difference between the solids velocity and the gas velocity, i. e.:

$$v_r = v_s - v_g \tag{3}$$

In both cases, if one were riding down the standpipe with the solids, the gas would appear to be moving upward relative to your reference point.

The gas flowing upward relative to the solids generates a frictional pressure drop. The relationship between the pressure-drop-per-unit-length (ΔP/Lg) and the relative velocity for a particular material is determined by the fluidization curve for that material. This fluidization curve is generated in a fluidization column where the solids are not flowing. However, the relationship also applies for solids flowing in a standpipe.

For FCC catalyst (a Geldart Group A material), as v_r is increased above v_{mf} the solids expand without bubble generation over a certain velocity range. Because of this bubbleless expansion, the ΔP/L decreases over this velocity range. The velocity where bubbles begin to form in FCC catalyst is called the minimum bubbling velocity, v_{mb}. A typical fluidization curve for FCC catalyst is shown in Figure 2.

Standpipes generally operate in three basic flow regimes - packed-bed flow, fluidized-bed flow, and a dilute-phase flow called streaming flow. The differences between these types of flow are discussed below:

1. **Packed Bed Flow** In packed-bed flow v_r is less than v_{mf}, and the voidage in the standpipe is more or less constant. As v_r is increased, ΔP/L increases linearly in packed-bed flow. When a standpipe is operating in the moving packed-bed flow regime, a flow condition is sometimes reached which causes the solids to momentarily stop and then start again. This causes the standpipe to vibrate, and a loud "chattering" noise can often be heard. This type of flow is called stick-slip flow. It should be avoided, but no method presently exists to predict when it will occur.

2. **Fluidized-Bed Flow** In fluidized-bed flow, v_r is equal to or greater than v_{mf}. The voidage in the standpipe changes along the length of the standpipe, and ΔP/Lg does not change with increasing v_r. There are two kinds of fluidized-bed flow:

   a) bubbling fluidized-bed flow, and
   b) non-bubbling, fluidized-bed flow.

   For FCC catalyst, there is an operating window corresponding to a relative velocity between v_{mf} and v_{mb}, where the solids are fluidized but no bubbles are formed in the standpipe. A standpipe operating with FCC catalyst and with a relative velocity above v_{mb} operates in the bubbling fluidized-bed mode.

   Large bubbles are undesirable in a standpipe. If a standpipe is operating in the bubbling fluidized bed mode such that the solids velocity, v_s, is less than the bubble rise velocity, u_b, then bubbles will rise and grow by coalescence. Bubbles rising against the downflowing solids hinder and limit the solids flow rate (Knowlton and Hirsan, 1978; Eleftheriades and Judd, 1978) because the solids flow area is reduced by the presence of bubbles. The larger the bubble, the greater is the hindrance to solids flow.

   When the solids velocity in a standpipe is greater than the bubble rise velocity, the solids will carry the bubbles down the standpipe relative to the standpipe wall. It is also possible for bubbles to coalesce and hinder solids flow when they flow downward. In this case, the small bubbles are carried downward faster than the larger bubbles. When they catch up to a larger bubble, they coalesce which results in even larger bubbles and a greater hindrance to solids flow.

   Bubbles also reduce the ΔP/Lg or "density" of the solids in the standpipe. Thus, a standpipe operating in the bubbling regime will require a longer length to seal the same ΔP than a standpipe in which the same solids are slightly above minimum fluidizing conditions. For optimum fluidized-bed FCC catalyst standpipe operation, v_r should be maintained in a range just slightly below v_{mb} to just slightly above v_{mb}. However, because v_{mb} is so close to v_{mf} operating in this narrow range can lead to standpipes slipping into packed bed flow – an unwanted occurrence. Therefore, FCC catalyst standpipes are more reliably operated by maintaining them in the fluidized state a short distance "above" v_{mb}. The relative velocity range where it is best to operate FCC catalyst standpipes is shown schematically in Figure 3. In both cases, operation in these areas will either reduce the formation of bubbles, or allow standpipe operation with only small bubbles.

   Because it is difficult to prevent small bubbles from occurring in standpipes, small standpipes are more difficult to operate than large standpipes. In small standpipes, small bubbles have a diameter that is a large fraction of the diameter of the standpipe and can hinder solids flow in small standpipes. In large standpipes, small bubble diameters will not significantly affect solids flow (Figure 4).

3. **Streaming Flow** Underflow standpipes (especially cyclone diplegs) sometimes operate in a dilute-phase streaming flow characterized by high voidage. A substantial amount of gas can be carried down the standpipe when operating in this mode (Geldart and Broodryk, 1991). Excessive gas flow down a dipleg is usually undesirable.

There are two basic types of standpipe configurations - the overflow standpipe (Figure 5A) and the underflow standpipe (Figure 5B). The overflow standpipe is so named because the solids “overflow” from the top of the fluidized bed into the standpipe, and there is *no bed of solids above the standpipe*. In the underflow standpipe, the solids are introduced into the standpipe from the underside of a bed or hopper, and *a bed of solids is present above the standpipe*. With this definition, a cyclone dipleg is classified as an overflow standpipe *because there is no bed of solids* above the entrance to the dipleg.

With two types of standpipe configurations and two typical flow regimes (fluidized and packed bed), there are four different types of standpipes:

1. An underflow packed-bed standpipe
2. An underflow fluidized-bed standpipe
3. An overflow fluidized-bed standpipe
4. An overflow packed-bed standpipe

All standpipe types are used extensively except for the overflow packed-bed standpipe. This type of standpipe is much harder to control than the others and is not used. Each type of standpipe can be constrained (solids flow limited) at either the top or the bottom. However, top-constrained standpipes are rare, and nearly all standpipes used in fluidized bed standpipe systems are constrained at the bottom.

In any gas-solids flow system, a pressure-drop loop can be defined such that the sum of the pressure drop components around the loop is zero. In many (but not all) pressure-drop loops, the standpipe is the *dependent* part of the loop. This means that the pressure drop across the standpipe will automatically adjust to balance the pressure drop produced by the other *independent* components (which do not automatically adjust their pressure drops) in the loop. How the standpipe pressure drop adjustment is made is different for different types of standpipes.

Consider the overflow standpipe system shown in Figure 6A. Solids are being transferred at a low rate from the upper fluidized bed to the lower fluidized bed against the pressure differential P_2-P_1. This pressure drop consists of the pressure drop in the lower fluidized bed from the standpipe exit to the top of the bed (ΔP_{lb}), the pressure drop across the distributor supporting the upper fluidized bed (ΔP_d), and the pressure drop across the upper fluidized bed (ΔP_{ub}), i. e.:

$$P_2 - P_1 = \Delta P_{lb} + \Delta P_d + \Delta P_{ub} \qquad (4)$$

This pressure drop must be balanced by the pressure drop generated in the overflow standpipe. If the standpipe is operating in the fluidized-bed mode at a $\Delta P/L$ equal to $(\Delta P/L)_{mf}$, the solids height in the standpipe, H_{sp}, will adjust so that the differential pressure buildup generated in the standpipe, ΔP_{sp}, will equal the product of $(\Delta P/L)_{mf}$ and H_{sp}, i. e.:

$$\Delta P_{sp} = P_2 - P_1 = \Delta P_{lb} + \Delta P_d + \Delta P_{ub} = (\Delta P/L)_{mf}\,(H_{sp}) \qquad (5)$$

If the gas flow rate through the two beds is increased, ΔP_d increases while the pressure drops across the two fluidized beds essentially remain constant. Therefore, P_2-P_1 increases to P'_2-P_1. The pressure drop across the overflow standpipe also increases to P'_2-P_1. The standpipe ΔP increases because the height of fluidized solids in the standpipe increases from H_{sp} to H'_{sp}, i. e.:

$$\Delta P_{sp} = P'_2 - P_1 = (\Delta P/L)_{mf}\,(H'_{sp}) \qquad (6)$$

This is shown schematically in Figure 6B, and the change is also reflected in the pressure diagram. If the increase in the pressure drop across the distributor is so great that H_{sp} must increase to a value greater than the standpipe height available to seal the pressure differential, the standpipe will not operate.

In fluidized catalytic crackers, fluidized underflow standpipes are used. This type of standpipe is one of the most widely used standpipes in industry. Because it is an underflow standpipe and full of solids, changes in the bed height to balance the pressure drop are not possible. This type of standpipe is designed so that its length is long enough to generate more pressure than required. The excess pressure generated by the standpipe is then “burned up” across the slide valve to balance pressure drop changes in the other loop components.

With the fluidized underflow standpipe, aeration gas is added to the standpipe to maintain the solids in a fluidized state. As the solids flow down the fluidized underflow standpipe from a low pressure to a higher pressure, the gas in the standpipe is compressed and causes the solids to move closer together. When the standpipe is operating at low pressures, the percentage change in gas density from the top of the standpipe to the bottom is significant. If aeration is not added to the standpipe to prevent this, the solids can defluidize near the bottom of the standpipe (Figure 7A**)**. Defluidization of solids in the standpipe results in less pressure buildup in the standpipe and a reduced solids flow rate around the loop.

To maintain the catalyst in a fluidized underflow standpipe in a fluidized state, aeration gas is added to the standpipe. Adding the correct amount of gas uniformly (every 1.5 to 3 meters) in a commercial fluidized underflow standpipe will prevent defluidization at the bottom of the standpipe (Figure 7B). If the material flowing in the standpipe is a Geldart Group A material such as FCC catalyst, aeration should be added uniformly along the standpipe. If the aeration is added at only one location (i. e., at the bottom of the standpipe) a large bubble will form in the standpipe at the aeration point (Figure 8A). If the bubble is large enough, it can restrict the flow of solids. The large bubble forms because it is difficult for the aeration gas to permeate into the very fine catalyst moving through the standpipe. Therefore, it requires a significant area for the gas to dissipate through the fine catalyst at the same rate that it is being added through the aeration tap. If the aeration gas is added at several locations, then the bubble size is significantly reduced, and standpipe operation is significantly improved (Figure 8B). Aeration bubbles extend downward from the aeration point in the direction of flow of the solids. This occurs because the momentum of the solids is much greater than the buoyancy force of the bubble and elongates the aeration bubble in the direction of flow.

The amount of aeration required to maintain solids in a fluidized state throughout the standpipe was presented by Karri and Knowlton (1993) to be:

$$Q = 1000\left[\frac{P_b}{P_t}\left(\frac{1}{\rho_{mf}} - \frac{1}{\rho_{sk}}\right) - \left(\frac{1}{\rho_t} - \frac{1}{\rho_{sk}}\right)\right] \quad (8)$$

In a commercial fluidized underflow standpipe, the amount of aeration theoretically required is added in equal increments via aeration taps located approximately 1.5 to 3 meters apart. Care should be taken not to overaerate the standpipe. If this occurs, large bubbles are generated that hinder solids flow. Thus, standpipes can be overaerated as well as underaerated.

Standpipes in Solid Recycle Systems

FCC units recirculate catalyst in a reaction/regeneration cycle. First the catalyst is used to supply heat or a reactant to the process, it is then transferred to a separate vessel to regenerate the catalyst, and is returned to the reactor. A cyclone collecting entrained solids above a fluidized bed and returning the solids to the bed via the cyclone dipleg is also a recirculating solid system. All of these recirculation systems employ standpipes.

There are two basic types of solids recirculation systems: 1) automatic and 2) controlled. In an automatic system, the solids are recirculated around a loop without being controlled. In the controlled recirculation system, a valve is used to control the solids flow rate. In automatic systems, overflow standpipes are usually employed. In the controlled recirculation systems the standpipe is an underflow standpipe.

Automatic Solid Recirculation Systems

One of the simplest types of automatic solids recirculation systems is the cyclone/dipleg system utilized to collect entrained solids and return them to the bed. This type of system is shown in Figure 9 for a fluidized bed containing both primary and secondary internal cyclones. External cyclones return systems are also automatic recycle systems. All solids entering the primary and secondary cyclones are returned to the bed automatically via the primary and secondary diplegs

The pressure balance around the system for returning solids to the bed via the secondary cyclone dipleg is:

$$\Delta P_{fluid\ bed} + \Delta P_{cy1} + \Delta P_{cy2} = \Delta P_{dip2} = \rho_{dip2} H_{dip2}\ g \quad (9)$$

For solids to be returned to the bed in the secondary cyclone dipleg, the secondary dipleg length, H_{dip2}, should be at least:

$$H_{dip2} = (\Delta P_{fluid\ bed} + \Delta P_{cy1} + \Delta P_{cy2})/(\rho_{dip2}\ g) \quad (10)$$

As shown above, if the primary or secondary cyclone pressure drop increases, the immersion of the secondary dipleg in the fluidized bed increases or the solids density in the secondary cyclone dipleg decreases, the solids level in the overflow standpipe (secondary cyclone dipleg) increases. Conversely, if the primary or secondary cyclone pressure drop decreases, the immersion of the secondary cyclone dipleg in the fluidized bed decreases or the solids density in the secondary cyclone dipleg increases, the solids level in the secondary cyclone dipleg decreases to adjust.

Controlled Solid Recirculation Systems

In a controlled solids recirculation system, a valve is used to control the solids flow rate in the system, and the standpipe is almost always an underflow standpipe.

The primary standpipes in FCC units are generally underflow fluidized bed standpipes. Many FCC units incorporate two standpipes in their loop systems. The solids flow rate around the system is usually controlled by a slide valve in each standpipe.

A typical FCC riser/recirculation system developed by UOP (called a side-by-side unit) is shown in Figure 10. A pressure drop balance around this unit gives:

$$\Delta P_{regen} + \Delta P_{sp1} - \Delta P_{sv1} - \Delta P_{riser} + \Delta P_{stripper} + \Delta P_{sp2} + \Delta P_{sv2} = 0 \qquad (11)$$

In this unit, hot catalyst is introduced into a dilute-phase riser where it is contacted with oil. The hot solids vaporize the oil and catalytically crack it into lower-molecular weight hydrocarbons in the riser. The catalyst reactivity is reduced by carbon deposition during this step. Therefore, the catalyst is transferred to a regenerator where the carbon is burned off of the catalyst. This heats up the catalyst and also restores its reactivity. However, before the catalyst is returned to the regenerator via an angled standpipe/slide valve combination, hydrocarbon vapors are removed from the catalyst in a steam stripper. From the regenerator, the catalyst is transferred down another angled standpipe/slide valve combination and is injected into the bottom of the riser.

Solids flow in standpipes in FCC units is generally controlled in the following manner. In Standpipe 1, Slide Valve 1 controls the temperature at the outlet of the riser by varying the flow of regenerated solids to the riser. The slide valve in Standpipe 2 controls the fluidized solids level in the stripper (King, 1992).

Underflow fluidized standpipes in FCC units are operated in either vertical, angled, or hybrid configurations (Figure 11). Angling a standpipe is a convenient way to transfer solids between two points separated horizontally as well as vertically. In angled standpipes, the gas and solids separate in the standpipe, with the gas bubbles flowing up along the top of the standpipe while the solids flow down along the bottom of the standpipe (Figure 12**).** The pressure buildup in a hybrid standpipe is lower than in a vertical standpipe. Karri and Knowlton (1993) reported that the maximum solids mass flux possible in a hybrid underflow fluidized standpipe was less than in a vertical underflow fluidized standpipe. The principal reason for this is that the rising bubbles in the angled section of the standpipe become large at low solids flow rates (and low aeration rate). At a certain solids mass flux, the bubbles become large enough to bridge across the vertical section at the top of the standpipe, hindering the solids flow.

Even though vertical standpipes can transfer solids more efficiently than hybrid standpipes, true angled standpipes are commonly operated satisfactorily in large FCC units. However for best operation, these standpipes are typically short and are designed so that the mass flux through them is high. Thus, when operating a hybrid standpipe or a true angled standpipe it is best to keep the standpipe as short as possible so that large gas slugs will not have a long length to form, and to use a high mass flux rate so that there is minimal deaeration of the solids as they flow through the standpipe.

As stated above, in a gas-solids flow system a pressure-drop loop can be defined such that the sum of the pressure drop components around the loop is zero. In FCC catalyst systems, the standpipe is the *dependent* part of the loop. This means that the pressure drop across the standpipe will automatically adjust to balance the pressure drop produced by the other *independent* components (which do not automatically adjust their pressure drops) in the loop.

Most operators assume that the buildup in a fluidized underflow FCC catalyst standpipe should be equivalent to the material's fluidized density multiplied by the length of the standpipe. This is the maximum buildup possible in the standpipe, but standpipes do not always operate at this maximum pressure buildup condition.

One reason that the standpipe does not always operate at its optimum pressure buildup condition is that the standpipe also serves another function in the pressure balance loop. The standpipe is the only element that can adjust itself to *automatically* balance the pressure drop in the circulation loop. Therefore, the standpipe does not always operate at maximum pressure buildup conditions if it is constrained by the parameters of the ΔP loop. If these constraints occur, standpipe pressure profiles and gas flows in the standpipe will be adjusted automatically to allow the pressure balance to occur, and negative standpipe buildups are possible in certain situations.

There are generally three element types in a pressure balance loop:

1. Fixed Element: An element with a constant ΔP at a fixed velocity and solids mass flux (riser, bed, cyclone, etc.)
2. Variable Element: An element with a ΔP that can vary because of a change in setting (slide valve, ΔP between reactor/regenerator)
3. Automatically Variable Element: An element with a ΔP that will *automatically* vary to balance the differential pressures around the loop (standpipe)

The fixed and variable elements typically make up what is called the *Independent* part of the pressure drop loop. The standpipe pressure drop constitutes the *Dependent* part of the pressure drop loop. Consider the circulation loop shown in Figure 13A in which the pressure data shown are from an actual operating unit. The pressure balance around this unit is:

$$\Delta P_{sv} + \Delta P_{riser} - \Delta P_{R/Reg} - \Delta P_{bed} = \Delta P_{sp} \qquad (12)$$

The left-hand side of Equation 12 is the Independent part of the pressure drop loop. The right-hand side of Equation 12 is the Dependent part of the pressure drop loop. The standpipe ΔP will adjust so that the pressure balance around the loop is satisfied. The standpipe ΔP can be positive (builds pressure) or negative (dissipates pressure). The standpipe in Figure 13A is dissipating pressure so that the pressure balance is satisfied. Therefore, a standpipe does not always build pressure as designed to do. If a standpipe is not building pressure at its fluidized density, it does not mean that it is operating poorly. The pressure balance needs to be checked.

When a standpipe ΔP/Lg is negative, it means that the standpipe is dissipating pressure. In this mode, most (or all) of the standpipe is operating in the defluidized mode. When this occurs, the gas is flowing faster than the solids (on average) over the standpipe. However, the actual pressure profile in the standpipe can take many forms as indicated in Figure 14. All of these standpipe pressure profiles result in a negative pressure drop across the standpipe. In general, the type of aeration pattern used will determine the actual pressure profile.

In Figure 13B, the solids flux around the unit has been increased. The riser pressure drop increases, and the standpipe ΔP must increase (it is now positive) to bring the ΔP loop into balance. In Figure 13C, the solids flux around the unit has been increased even more and the standpipe ΔP/Lg is now at a value that is more typical of the design standpipe ΔP/Lg values.

A standpipe operating in a negative pressure buildup mode is also shown in Figure 15. The standpipe in this example (the data are from an operating FCC unit) is operating in a catalyst cooler loop. As shown in the figure, the standpipe is dissipating pressure. This is required to in order to balance the pressure drops around the circulation loop. The primary reason that the standpipe is required to operate in a negative pressure buildup mode is that the fluidized catalyst cooler is so tall that it generates a large pressure drop. This large pressure drop cannot be dissipated through the slide valve, the riser or the fluidized bed. Therefore, the standpipe must dissipate the required pressure in order to balance the pressure drops.

Nomenclature

D	=	pipe diameter, m
g	=	gravitational constant, 9.81 m/s^2
H_{dip2}	=	secondary cyclone dipleg length, m
H_{dip2}	=	secondary cyclone dipleg length, m
H_{sp}	=	standpipe height, m
H'_{sp}	=	changed standpipe height, m
L	=	length, m
L_{sp}	=	standpipe length, m
P	=	pressure, Pa
P'	=	changed pressure, Pa
P_b	=	pressure at bottom of standpipe, Pa
P_t	=	pressure at top of standpipe, Pa
ΔP	=	pressure drop, Pa
ΔP_{cy}	=	cyclone pressure drop, Pa
ΔP_{cy1}	=	primary cyclone pressure drop, Pa
ΔP_{cy2}	=	secondary cyclone pressure drop, Pa
ΔP_d	=	distributor pressure drop, Pa
ΔP_{dip2}	=	pressure drop across secondary cyclone dipleg, Pa/m
$\Delta P_{fluid\ bed}$	=	fluidized-bed pressure drop, Pa
$\Delta P_{independent}$	=	independent part of pressure drop loop, Pa
ΔP_{lb}	=	lower fluidized bed pressure drop, Pa
ΔP_{regen}	=	regenerator pressure drop, Pa
ΔP_{riser}	=	riser pressure drop, Pa
ΔP_{sp}	=	standpipe pressure drop, Pa
ΔP_{sp1}	=	first standpipe pressure drop, Pa
ΔP_{sp2}	=	second standpipe pressure drop, Pa
$\Delta P_{stripper}$	=	stripper pressure drop, Pa
ΔP_{sv1}	=	first slide valve pressure drop, Pa
ΔP_{sv2}	=	second slide valve pressure drop, Pa
ΔP_{ub}	=	upper fluidized bed pressure drop, Pa
$\Delta P/Lg$		pressure-drop-per-unit-length, Pa/m
$\Delta P/Lg)_{mf}$	=	pressure-drop-per-unit-length at minimum fluidization, Pa/m

Q	=	aeration required to prevent defluidization, m^3/s
Q	=	volumetric flow rate of gas, m^3/s
U	=	superficial gas velocity, m/s
U_{mf}	=	superficial gas velocity at minimum fluidization, m/s
v_g	=	interstitial gas velocity, $U g/\varepsilon$, m/s
v_{mb}	=	minimum bubbling velocity, m/s
v_{mf}	=	interstitial minimum fluidization velocity, U_{mf}/ε
v_r	=	relative gas/solid velocity, m/s
v_s	=	solids velocity, m/s
ε	=	voidage
ε_{mf}	=	voidage at minimum fluidization
ρ_{dip2}	=	secondary cyclone dipleg density, kg/m^3
ρ_{mf}	=	fluidized-bed density at minimum fluidization, kg/m^3
ρ_p	=	particle density, kg/m^3
ρ_{sk}	=	skeletal density, kg/m^3
ρ_t	=	fluidized-bed density at top of standpipe, kg/m^3

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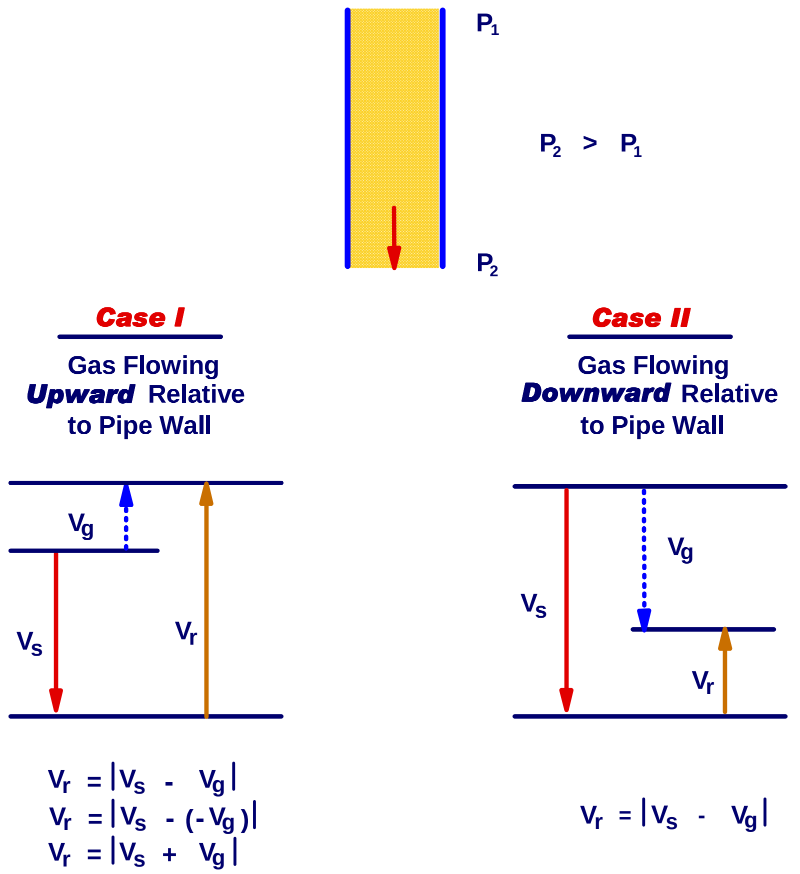

Figure 1. Illustration of Relative Gas-Solid Velocity

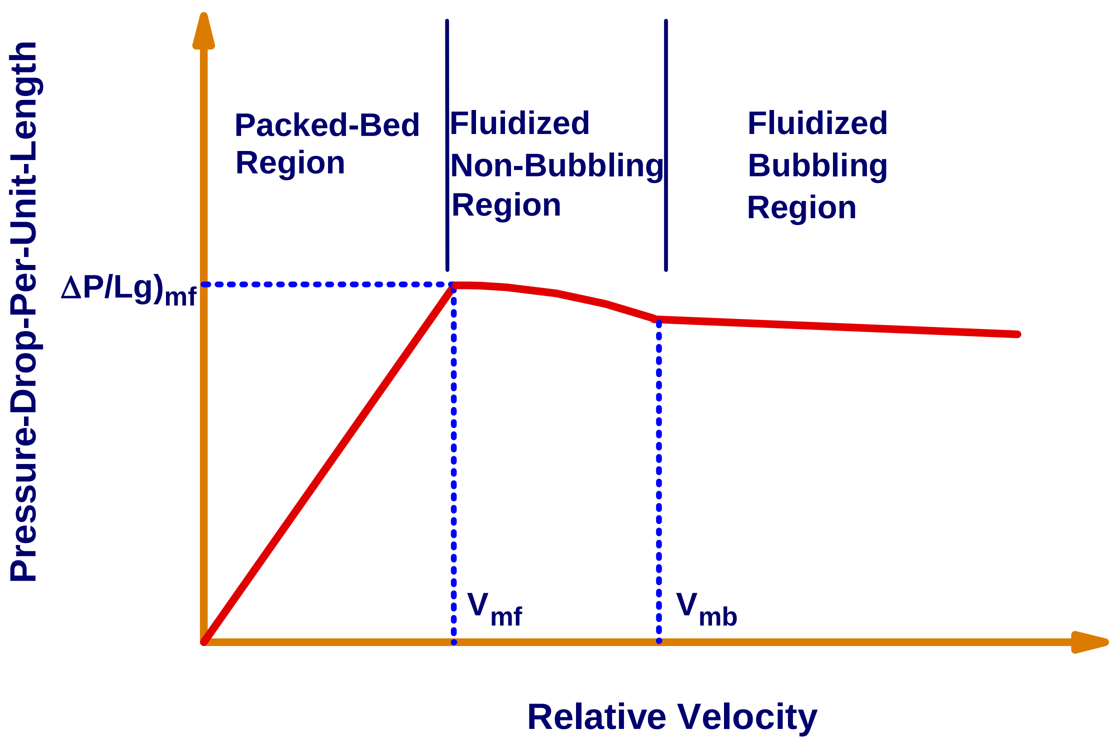

Figure 2. Typical Fluidization Curve for FCC Catalyst

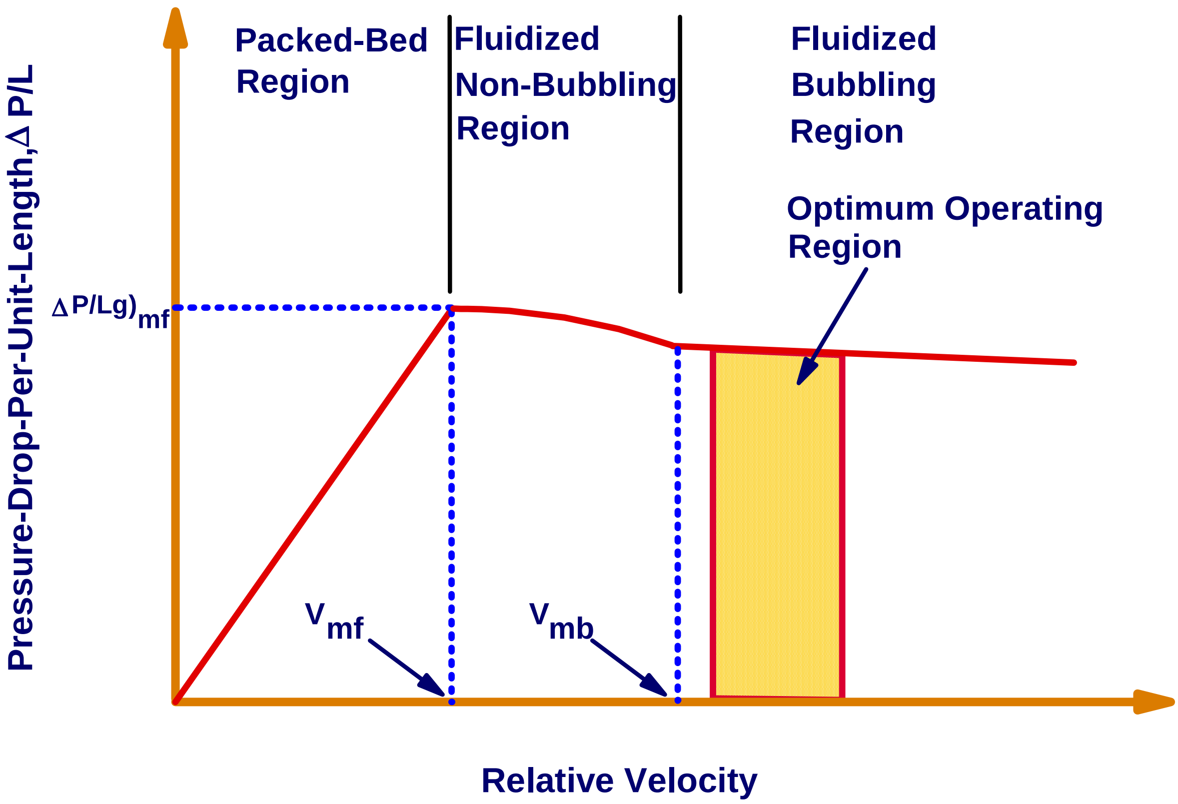

Figure 3. Optimum Standpipe Operating Region for FCC Catalyst

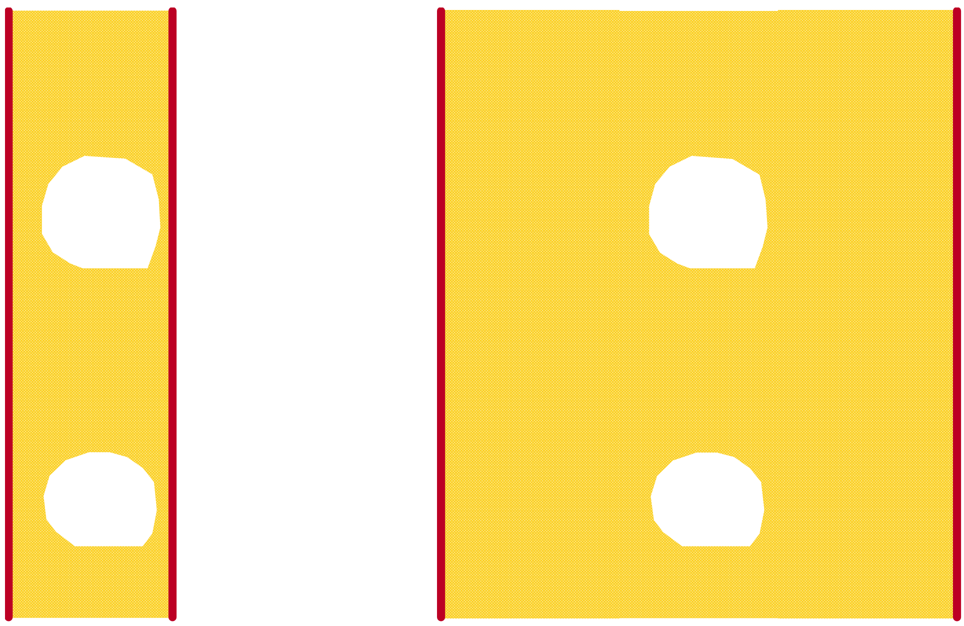

Figure 4. Small Bubbles Affect Small Standpipes More Than Large Standpipes

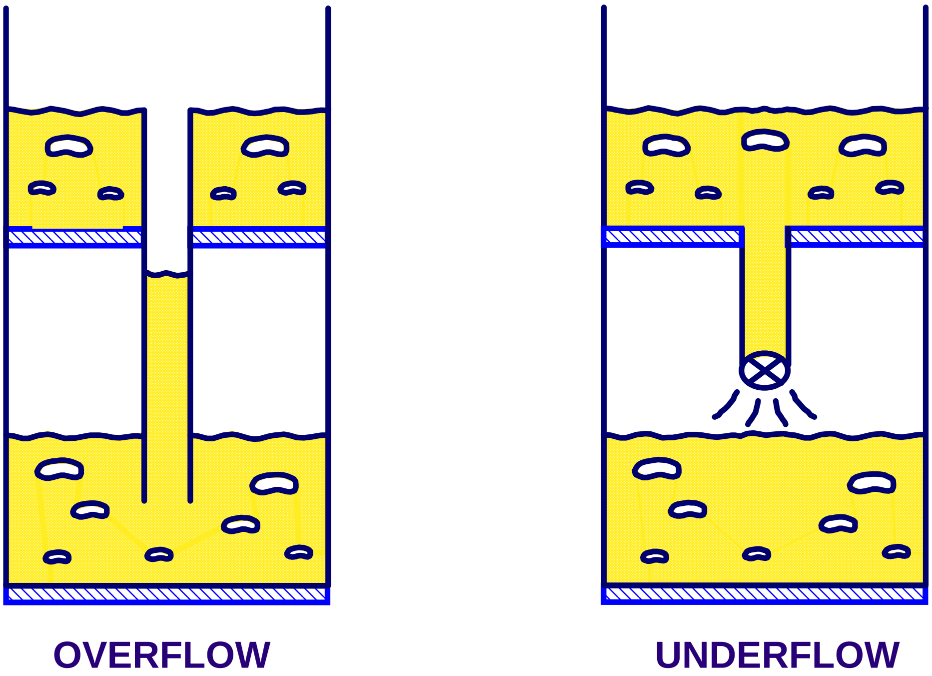

Figure 5. Overflow and Underflow Standpipes

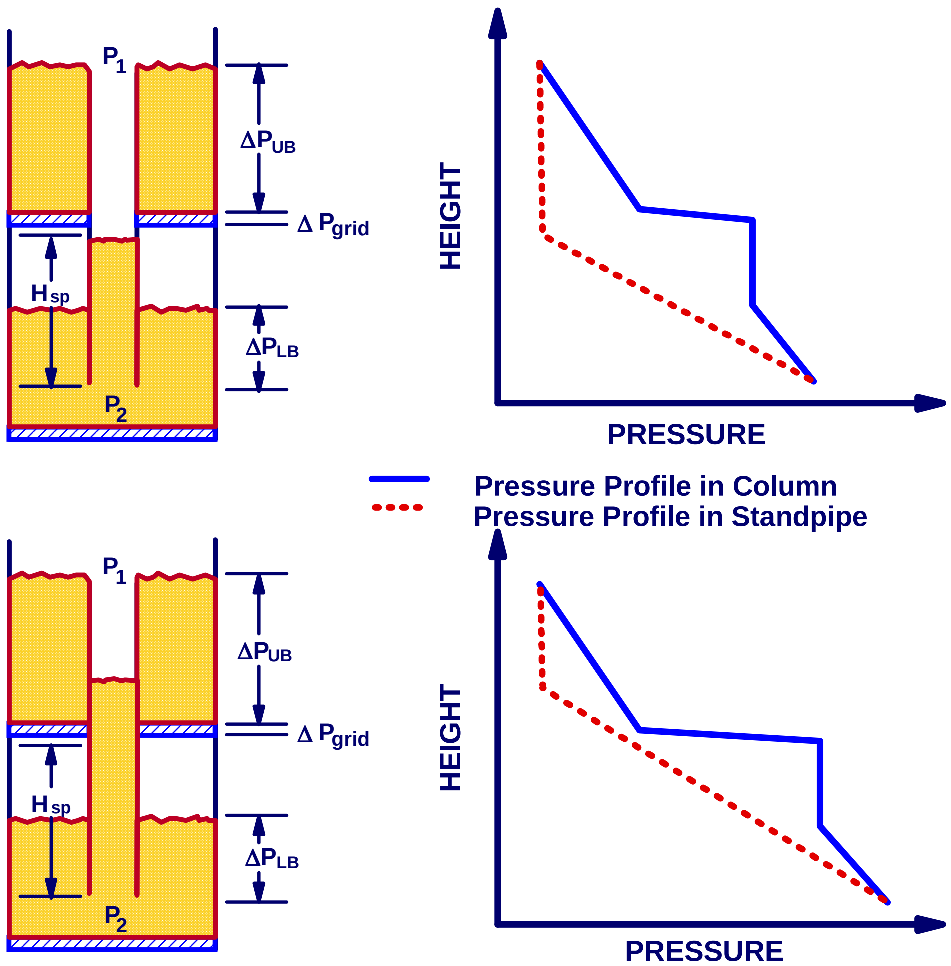

Figure 6. Fluidized Overflow Standpipes Operation

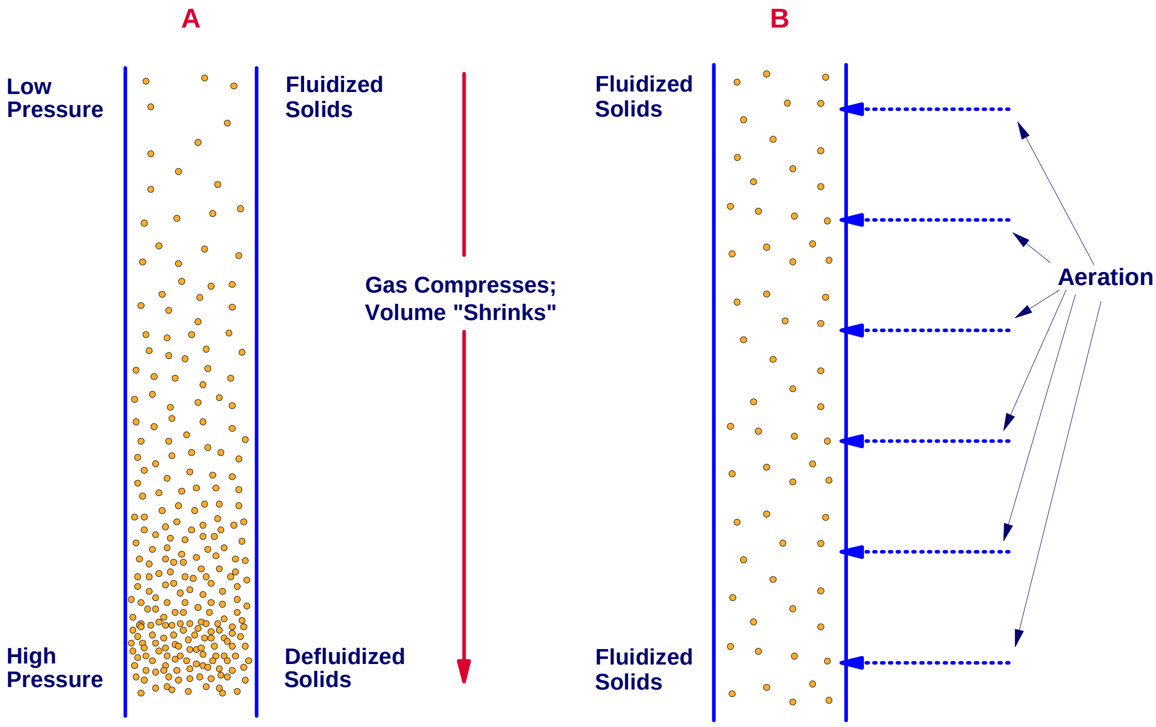

Figure 7. Adding Aeration to a Standpipe Prevents Defluidization

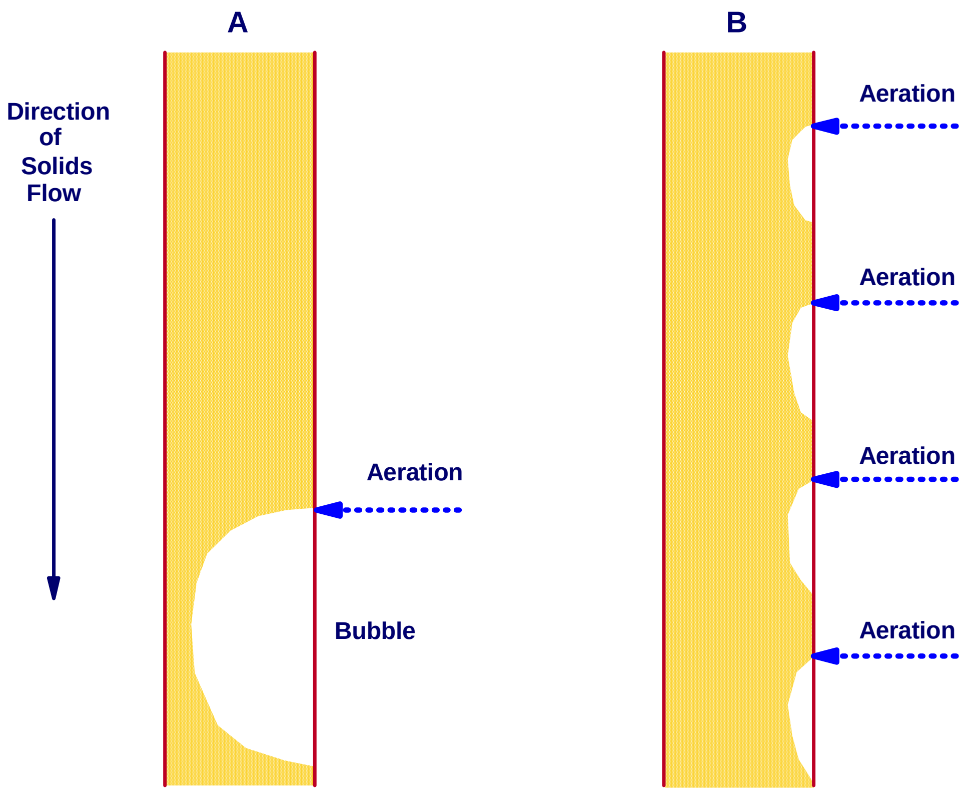

Figure 8. The Effect of Single and Multiple Aeration Points on Standpipe Aeration

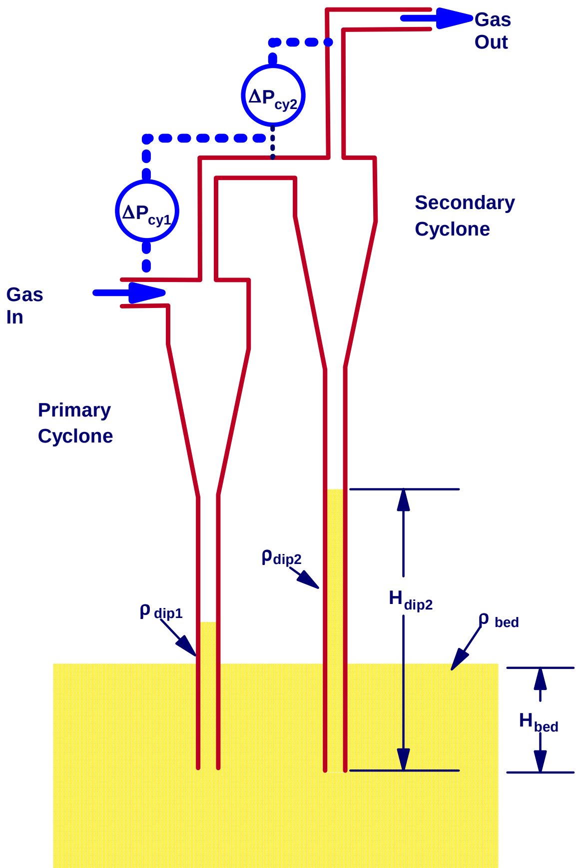

Figure 9. Primary and Secondary Cyclone Recirculation System

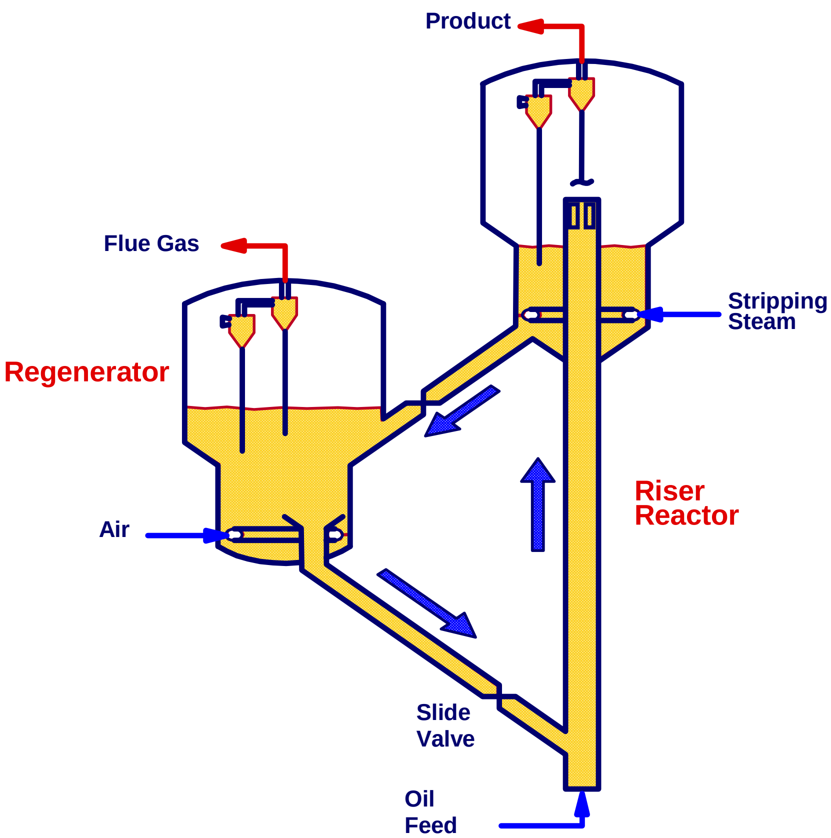

Figure 10. UOP Side-by-Side FCC Unit

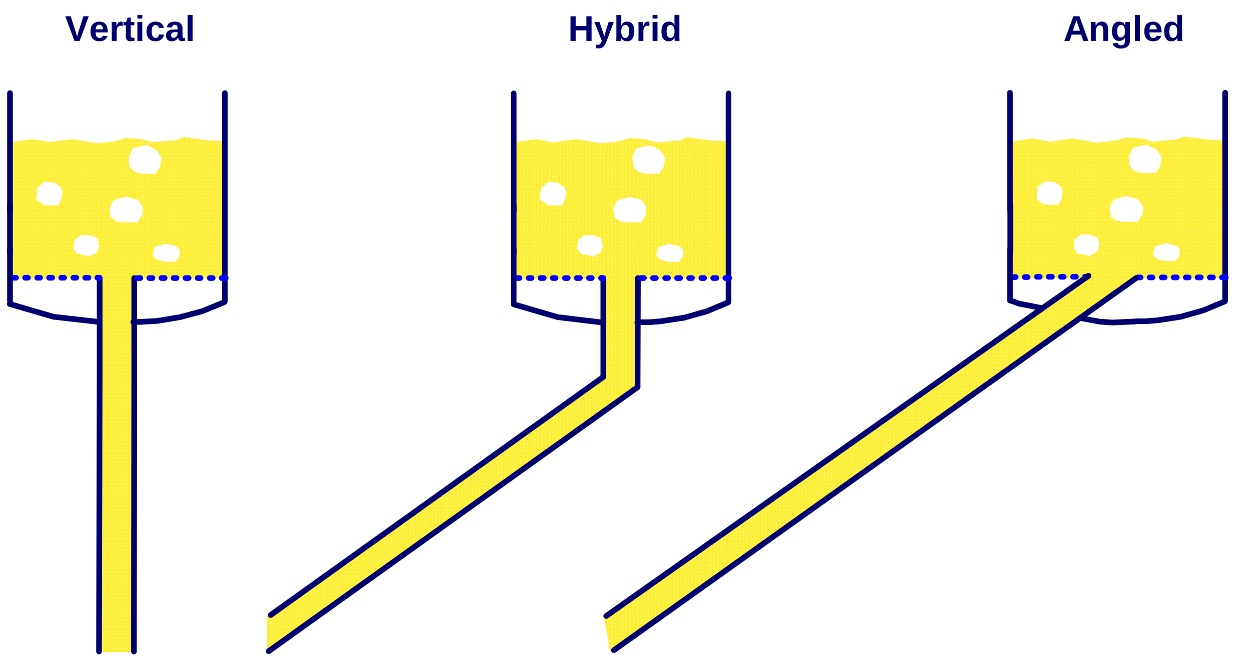

Figure 11. Vertical, Angled and Hybrid Standpipes

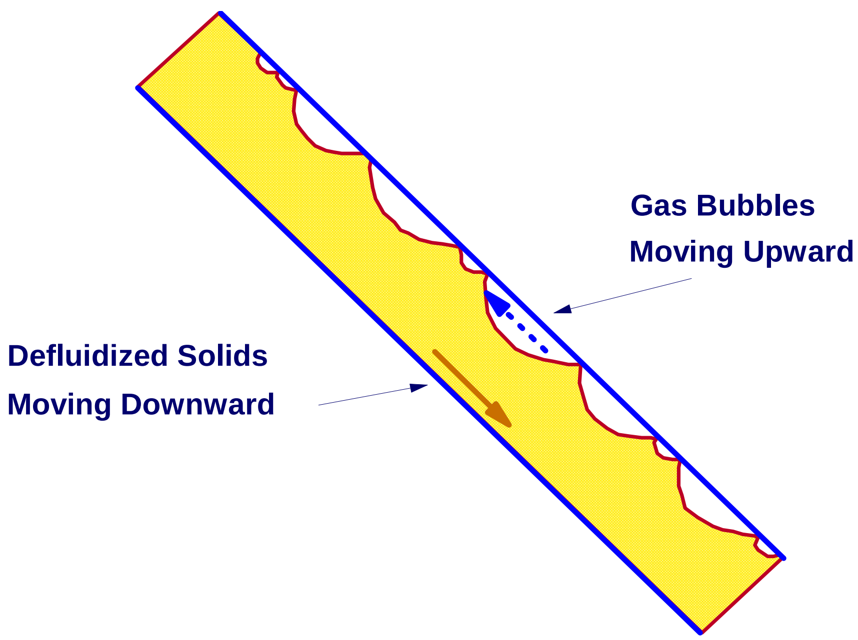

Figure 12. Gas and Solids Flow in an Angled Standpipe

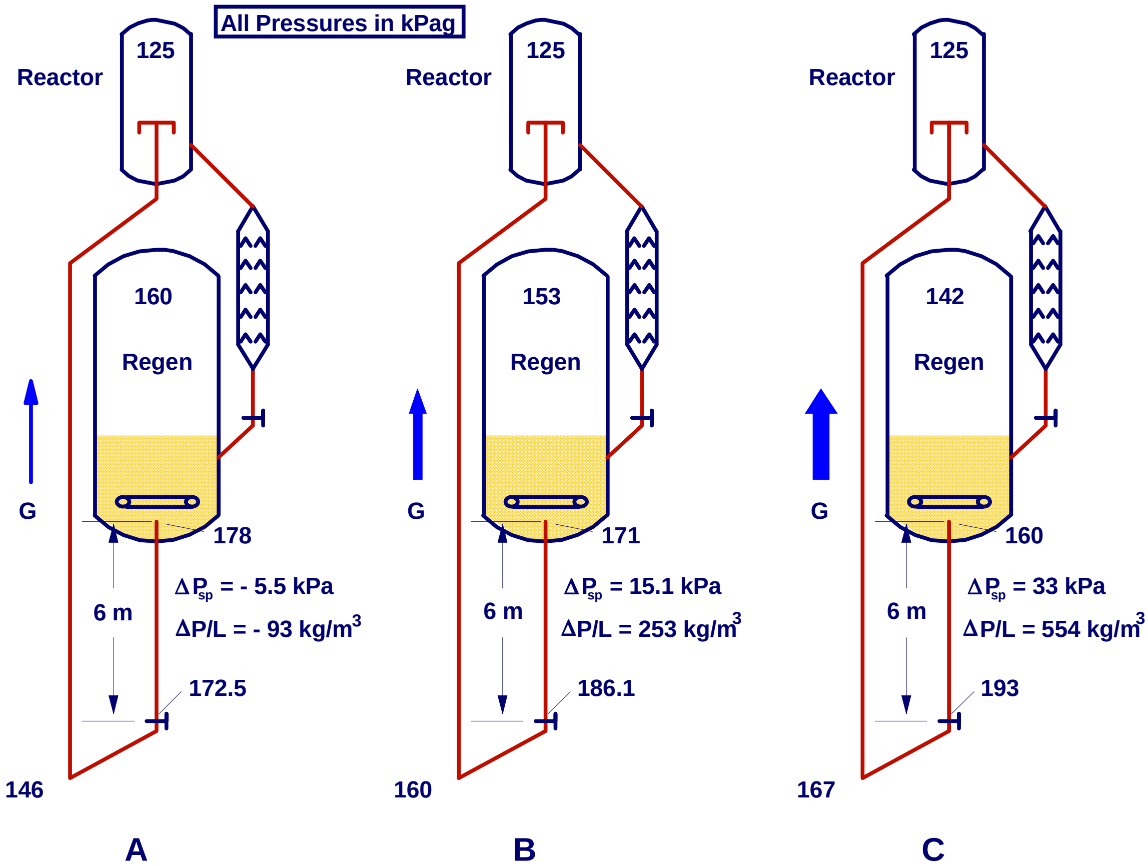

Figure 13. Standpipes Adjust to Balance the Pressure Drop Loop

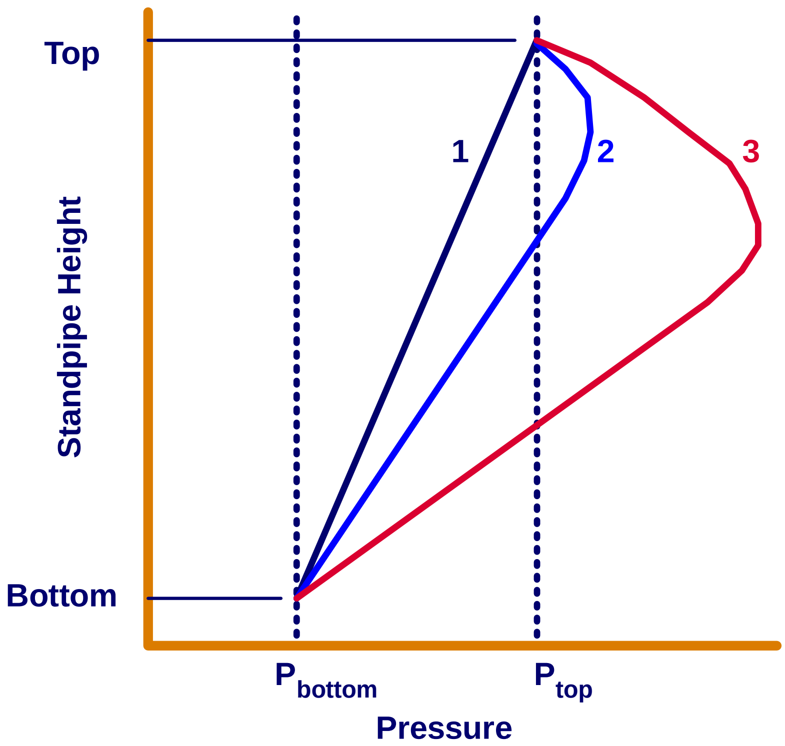

Figure 14. Possible Pressure Profiles in a Standpipe Dissipating Pressure

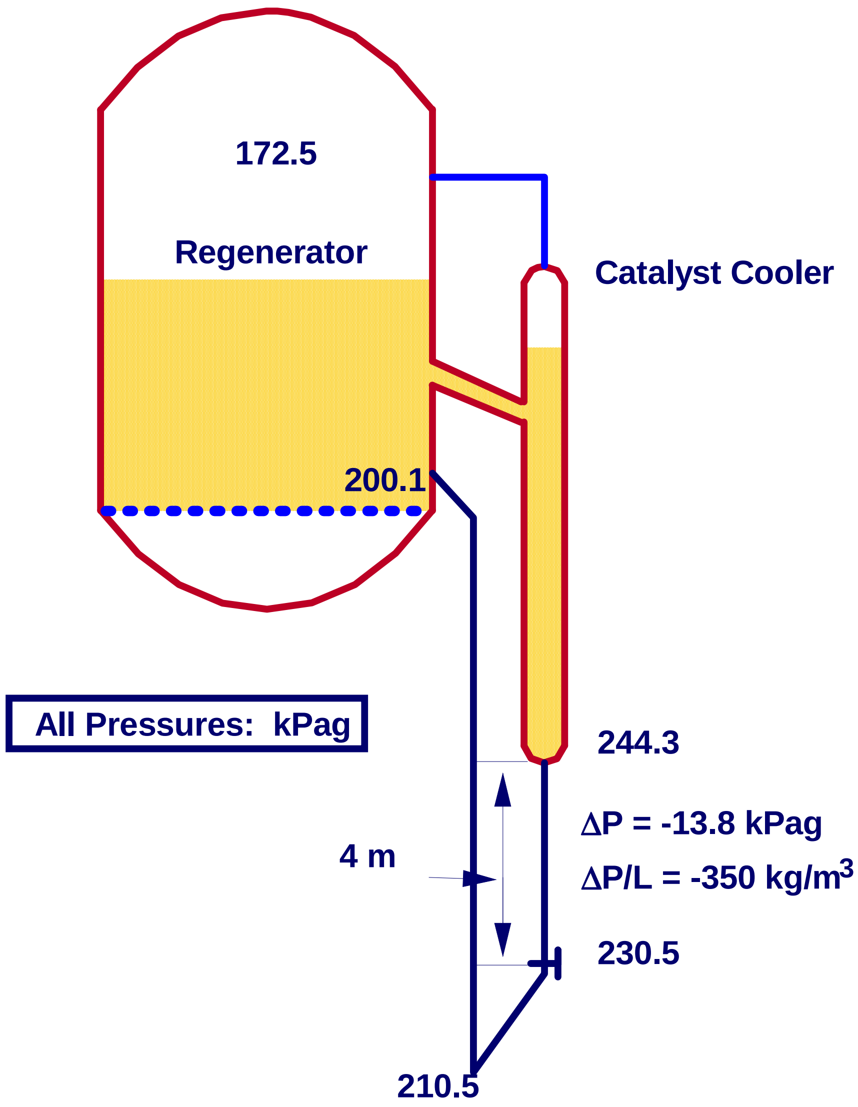

Figure 15. Catalyst Cooler Standpipe Dissipating Pressure