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Revision Memo

12/02 Corrections and minor updates. Added a new riser slip factor correlation



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SCOPE

This section deals with the circulation of solids between process vessels. It includes the pressure balance around vessels between which solids are being continuously circulated, vessel layout, transfer line design, and aeration requirements.

EXXON commercial processes (fluid catalytic cracking and Fluid/FLEXICOKING) have process-specific design notes ⁽¹⁾ ⁽²⁾, which should be consulted in conjunction with work involving those processes.

REFERENCES

1. Baker, C. L. et. al., *Fluid Coker Design Notes* (Rev. 1), 83 HOP 51, March 14, 1983.
2. Luckenbach, E. C., *Design Notes, Catalytic Cracking*, 2002FLPD1-531
3. Smith, J. S., *Validation of GTO Hydrodynamic Correlations with Heritage Mobil Commercial FCC Data*, 2001BCRUT2024, 2001

DEFINITIONS

Transfer Lines - Transfer lines make up the system used to move solids between the vessels of a fluid solids unit. Transfer lines consist of various combinations of standpipes, angle and vertical risers, J-bends, U-bends and slide valves.

Standpipe - The standpipe is the vertical pipe at the bottom of a fluidized bed in which the fluidized solids build up a static head high enough to transfer solids to another vessel or location (see [Figure 1](#)). The solids are aerated to maintain a fluidized state, but at a relatively high density.

Riser - The riser is the portion of the transfer line connecting the bend at the bottom of the standpipe to the second vessel. In [Figure 1A](#), a J-bend is shown connecting to an angle riser. Angle risers provide horizontal movement of the solids to vertical risers, which lift the solids into the opposite vessels. In other units, the standpipe is connected to the vertical riser through a U-bend ([Figure 1B](#)) and there is no angle riser. Risers are aerated to maintain the solids in a fluidized state and adjust density of the flowing mixture. Aeration rates in the vertical riser are high to maintain a low density in the riser. Risers can operate in the dilute phase downstream of points where feed or large amounts of gas are injected.

Slide Valve - Slide valves are used to control or shut off solids flow in transfer lines. Slide valves are shown in [Figure 1](#).

PRESSURE BALANCE

[Figure 1](#) shows typical two vessel process configurations. The sketches are shown only to illustrate the concepts of pressure balance and transfer line design. They are derived from Fluid Catalytic Cracking designs but are not exact copies of any particular process configuration and cannot be used as such.

Continuous circulation of solids between two vessels, such as those shown in [Figure 1](#), will occur if the combination of vessel pressures, fluidized solids static heads, and other pressure differentials due to friction, acceleration, bends, valves, etc., in the transfer lines connecting the vessels are properly set. The static heads are set by choosing the proper transfer line lengths and vessel elevations and adjusting the density of the solids in the transfer lines by the flow of aeration gas. For example, the density in the standpipe of vessel A2 ([Figure 1](#)) is maintained at fairly high level by a minimum flow of aeration gas. The density in the vertical riser entering vessel A1 is low due to a high feed flow rate. The static head developed at the bottom of the standpipe by the high-density aerated solids is sufficient to cause flow of solids into the riser where the static head is lower due to the lower density. Solids flow in reverse direction from vessel 1 to vessel 2 either due to a favorable pressure gradient caused by vessel elevations and pressures (System A) or the use of a standpipe and riser combination (System B).

The procedure used to set the standpipe and riser elevations and vessel pressures is the calculation of a pressure balance. The pressure balance is calculated by starting with the pressure at the top of a vessel as specified in the DBS, or as assumed, then calculating pressure differentials through the vessels, transfer lines and through slide valves and grids due to static or slide valve ΔP required to close the pressure balance is calculated by difference as the final step in the pressure balance. The pressure in one of the vessels, e.g., vessel 2, is adjusted until a reasonable combination of vessel pressures and elevations, transfer line heights, slide valve pressure drops and aeration gas rates results.

The pressure balance is usually a trial and error procedure and is finally established only after other design considerations such as vessel sizes, vertical height requirements of slide valves and expansion joints, vessel and transfer line spacing, and injection systems are finalized.

It is also suggested that representative pressure balances based on operating data be calculated for existing units to confirm the calculation methods. The verified pressure balances can then be used for operating guidance.

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PRESSURE BALANCE (Cont)

CALCULATION PROCEDURES

The equations used to calculate pressure differentials are given below.

The pressure differential along a transfer line due to the static head is given as:

$$\Delta P_{sh} = \frac{\rho_m H}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (1c)}$$

$$\Delta P_{sh} = 10^{-3} \rho_m H \quad (\text{kPa}) \quad \text{Eq. (1m)}$$

where: ΔP_{sh} = The pressure differential due to the static head (psi), (kPa)
 ρ_m = The density of the mixture in the transfer line (lb/ft³), (kg/m³)
 H = The height of the transfer line (ft), (m)
 g = The acceleration due to gravity 32.2 ft/s² (9.81 m/s²)
 g_c = The gravitational conversion factor [(32.2 ft/s²) (lb mass/lb force)]

Transfer line densities are discussed in a subsequent section.

Frictional effects in lines such as standpipes where the velocity is low can be included in this term by choosing a value of the density somewhat different than ρ_m , e. g., lower than ρ_m for standpipes.

Frictional losses in lines such as risers where the velocity is higher are calculated using friction factors.

$$\Delta P_f = \frac{f \rho_a U^2 L}{2 g_c (144) D} \quad (\text{psi}) \quad \text{Eq. (2c)}$$

$$\Delta P_f = \frac{10^{-3} f \rho_a U^2 L}{2 D} \quad (\text{kPa}) \quad \text{Eq. (2m)}$$

where: ΔP_f = The pressure differential due to friction (psi), (kPa)
 f = A friction factor based on operating data
 g_c = The gravitational conversion factor [(32.2 ft/s²) (lb mass/lb force)]
 L = The length of the transfer line (ft), (m)
 D = The diameter of the transfer line (ft), (m)
 U = The superficial gas velocity (ft/s), (m/s)
 ρ_a = The apparent flowing density of the mixture calculated for the flow rate of gas and solids, assuming no slip (lb/ft³), (kg/m³)

Grid and slide valve pressure differentials can be calculated from orifice equations. The equation for grid loss is:

$$\Delta P_g = \rho_a C^2 \left(\frac{Q}{A} \right)^2 \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (3)}$$

where: ΔP_g = The pressure differential across the grid (psi), (kPa)
 C = The grid (orifice) coefficient ($\text{s} \sqrt{\text{ft lb}_f / \text{lb}_m / \text{in.}}$), ($\text{s} \sqrt{\text{kPa m} / \text{kg}}$)
 Q = The gas flow rate through the grid (ft³/s), (m³/s)
 A = The total open area of the grid (ft²), (m²)

C is related to the conventional orifice discharge coefficient C_o by the equation:

$$C = 1 / C_o \sqrt{144 \times 2 g_c} \quad (\text{s} \sqrt{\text{ft lb}_f / \text{lb}_m / \text{in.}}) \quad \text{Eq. (4c)}$$

$$C = 1 / C_o \sqrt{2 \times 1000} \quad (\text{s} \sqrt{\text{kPa m} / \text{kg}}) \quad \text{Eq. (4m)}$$



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PRESSURE BALANCE (Cont)

Values of C_o are given in Figure 2 for gas and solids flow through a grid. Curves are shown for conventional cylindrical holes and converging holes used in some grids to prevent plugging. Gas-only flow conditions are represented by the low density portion of the curves. The values of C_o in Figure 2 include some pressure recovery due to discharge into a fluidized bed downstream of the orifices. Particles passing through the grid are not fully accelerated to gas velocity, hence the dependence of C_o on velocity and flowing density. Figure 2 is for FCC catalyst. Use Figure 2 for other solids if specific data are not available.

Slide valve pressure drop is calculated from the equation:

$$\Delta P = \left(\frac{49.84W}{AC_o} \right)^2 \frac{1}{\rho_{mf}} \quad (\text{psi}) \quad \text{Eq. (5c)}$$

$$\Delta P = 5 \times 10^{-4} \left(\frac{W}{AC_o} \right)^2 \frac{1}{\rho_{mf}} \quad (\text{kPa}) \quad \text{Eq. (5m)}$$

where: W = The solids circulation rate (tons per minute), (kg/s)
 A = The slide valve open area (in.²), (m²)
 C_o = A conventional orifice discharge coefficient ⁽¹⁾
 ρ_{mf} = The minimum fluidization density (lb/ft³), (kg/m³)⁽²⁾
 ΔP = The pressure drop (psi), (kPa)

The equation is dimensional with the constants correcting for the units used.

Pressure differentials due to velocity changes of the flowing mixture (acceleration losses) are given by:

$$\Delta P_a = \frac{G^2}{144 g_c} \left(\frac{1}{\rho_{m2}} - \frac{1}{\rho_{m1}} \right) \quad (\text{psi}) \quad \text{Eq. (6c)}$$

$$\Delta P_a = 10^{-3} G^2 \left(\frac{1}{\rho_{m2}} - \frac{1}{\rho_{m1}} \right) \quad (\text{kPa}) \quad \text{Eq. (6m)}$$

where: ΔP_a = The pressure differential due to acceleration (psi), (kPa)
 ρ_m = The density of flowing mixture at Points 1 and 2 in the line (lb/ft³), (kg/m³)
 G = The solids mass flux (lb/ft²s), (kg/m²s)

Flow through cones, bends, at transfer line exits and vessel inlets involve pressure differentials due to a combination of velocity changes, friction, entrance and exit effects. These effects are usually accounted for by expressing them as a fraction or multiple of the loss due to a "velocity head."

$$\Delta P_{vh} = \frac{n \rho_m U_g^2}{2 g_c (144)} \quad (\text{psi}) \quad \text{Eq. (7c)}$$

$$\Delta P_{vh} = 10^{-3} \frac{n}{2} \rho_m U_g^2 \quad (\text{kPa}) \quad \text{Eq. (7m)}$$

where: ΔP_{vh} = The velocity head pressure differential (psi), (kPa)
 n = The fraction or multiple of a velocity head associated with pressure loss due to acceleration, entrance/exit effects, bends, etc.
 U_g = The gas phase superficial velocity (ft/s), (m/s)

Notes:

- (1) Use 0.75 for FCC catalyst. The value for other solids may be less. See process documents.
- (2) Use ρ_{mf} = 90% of loose bulk density if data are not available.

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PRESSURE BALANCE (Cont)

Values of n are based on experience. Typical values are given below.

Effect	n
Acceleration	1.0
Entrance or exit	1.0
Bend	1.0 - 1.25

Specific examples of pressure balance equations and procedures are given below. These are included only to illustrate the manner in which pressure balances can be calculated. See [Figure 1](#) for vessel identification.

Vessel A1 to Vessel A2 (A1 Riser Circuit)

- Obtain the first approximation of vessel 1 (V1) pressure at the top of the dilute phase. This is usually given in the DBS.
- Calculate V1 dilute phase ΔP

$$\Delta P_{dp} = \frac{W_{dp}}{A_{dp}} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (8c)}$$

$$\Delta P_{dp} = 10^{-3} g \frac{W_{dp}}{A_{dp}} \quad (\text{kPa}) \quad \text{Eq. (8m)}$$

where: ΔP_{dp} = The dilute phase pressure differential (psi), (kPa)
 W_{dp} = The dilute phase holdup (lb), (kg)
 A_{dp} = The vessel cross sectional area in the dilute phase region (in.²), (m²)
 g = The acceleration due to gravity (32.2 ft/s²) (9.81 m/s²)
 g_c = The gravitational conversion factor (32.2 ft lb mass/s² lb force)

The dilute phase holdup can be obtained from the PEGASYS cyclone module. It is described in **Section VI-C**, Appendix A. Vessel 1 dilute phase ΔP is usually small.

- Calculate V1 dense bed ΔP

$$\Delta P_{db} = \frac{H_{db} \rho_{db}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (9c)}$$

$$\Delta P_{db} = 10^{-3} g H_{db} \rho_{db} \quad (\text{kPa}) \quad \text{Eq. (9m)}$$

where: ΔP_{db} = The dense bed pressure differential (psi), (kPa)
 H_{db} = The dense bed height (ft), (m)
 ρ_{db} = The dense bed density [Equation (18), Section VI-E] (lb/ft³), (kg/m³)

- Calculate V1 grid ΔP

$$\Delta P_g = \frac{\rho_a}{2(144) g_c} \left(\frac{Q}{C_o A} \right)^2 \quad (\text{psi}) \quad \text{Eq. (10c)}$$

$$\Delta P_g = \frac{\rho_a}{2 \times 1000} \left(\frac{Q}{C_o A} \right)^2 \quad (\text{kPa}) \quad \text{Eq. (10m)}$$

where: ΔP_g = The grid pressure differential (psi), (kPa)
 ρ_a = The apparent flowing density of the solids, gas mixture passing through the grid assuming no slip (lb/ft³), (kg/m³)
 C_o = The grid hole coefficient ([Figure 2](#))
 Q = The gas flow rate through the grid⁽¹⁾ (ft³/s), (m³/s)
 A = The total grid hole area (ft²), (m²)

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PRESSURE BALANCE (Cont)

5. Calculate V1 inlet conical section ΔP

$$\Delta P_c = \frac{0.70 H_c \rho_{db}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (11c)}$$

$$\Delta P_c = 0.7 \times 10^{-3} g H_c \rho_{db} \quad (\text{kPa}) \quad \text{Eq. (11m)}$$

where: ΔP_c = The cone section pressure differential (psi), (kPa)

H_c = The cone height (ft), (m)

This term includes pressure drop due to the deflector baffle.

6. Calculate the vertical riser ΔP

$$\Delta P_{vr} = \Delta P_{vrsh} + \Delta P_{vrff} + \Delta P_{vrV} \quad (\text{psi}), (\text{kPa}) \quad \text{Eq. (12)}$$

where: ΔP_{vr} = The vertical riser pressure differential (psi), (kPa)

ΔP_{vrsh} = The vertical riser static head (psi), (kPa)

ΔP_{vrff} = The vertical riser frictional pressure differential (psi), (kPa)

ΔP_{vrV} = The vertical riser velocity head pressure differential (psi), (kPa)

$$\Delta P_{vrsh} = \frac{\bar{\rho}_{vr} H_{vr}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (13c)}$$

$$\Delta P_{vrsh} = 10^{-3} \bar{\rho}_{vr} H_{vr} \quad (\text{kPa}) \quad \text{Eq. (13m)}$$

where: $\bar{\rho}_{vr}$ = The average density in the vertical riser (lb/ft³), (kg/m³)⁽¹⁾

H_{vr} = The vertical riser height from the feed injection point to the bottom of the cone (ft), (m)

$$\Delta P_{vrff} = \frac{(2.0 \text{ E} - 5) \bar{\rho}_{vr} \bar{U}_{vr}^2 H_{vr}}{D_{vr}} \quad (\text{psi}) \quad \text{Eq. (14c)}$$

$$\Delta P_{vrff} = \frac{(7.6 \text{ E} - 6) \bar{\rho}_{vr} \bar{U}_{vr}^2 H_{vr}}{D_{vr}} \quad (\text{kPa}) \quad \text{Eq. (14m)}$$

where: $\bar{U}_{vr}$ = The average velocity in the vertical riser (ft/s), (m/s)⁽¹⁾

D_{vr} = The vertical riser inside diameter (in.), (m)

$$\Delta P_{vrV} = \frac{n G^2}{2 g_c \rho_{vro} (144)} \quad (\text{psi}) \quad \text{Eq. (15c)}$$

$$\Delta P_{vrV} = 10^{-3} \frac{n G^2}{2 \rho_{vro}} \quad (\text{kPa}) \quad \text{Eq. (15m)}$$

where: n = The number of velocity heads⁽²⁾

= 1.0 for acceleration

= 1.25 for each 30° bend

ρ_{vro} = The vertical riser outlet density (lb/ft³), (kg/m³)

G = The solids mass flux (lb/ft²s), (kg/m²s)

Notes:

(1) Obtained from process correlations.

(2) The pressure drop due to vessel entrance effects is offset by the pressure gain due to deceleration of the flow in the cone.

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PRESSURE BALANCE (Cont)

7. Calculate the angle riser ΔP

$$\Delta P_{ar} = \frac{0.8 \rho_{mf} H_{ar}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (16c)}$$

$$\Delta P_{ar} = 0.8 \times 10^{-3} g \rho_{mf} H_{ar} \quad (\text{kPa}) \quad \text{Eq. (16m)}$$

where: ΔP_{ar} = The angle riser pressure differential including static head and frictional loss (psi), (kPa)
 ρ_{mf} = The bed density at minimum fluidization (lb/ft³), (kg/m³)
 H_{ar} = The vertical height of the angle riser from the centerline of the J-bend to the feed injectors (ft), (m)
 g = The acceleration due to gravity (32.2 ft/s²) (9.81 m/s²)
 g_c = The gravitational conversion factor, (32.2 ft lb mass/s² lb force)

8. Calculate V2 dilute phase pressure differential, ΔP_{dp} based on the dilute phase holdup [Eq. (8)].

9. Obtain or assume V2 dilute phase pressure.

10. Calculate V2 standpipe ΔP

$$\Delta P_{st} = P_{v1} + \Delta P_{dp} + P_{db} + \Delta P_g + \Delta P_c + \Delta P_{vr} + \Delta P_{ar} - (P + \Delta P_{dp})_{v2} \quad (\text{psi}), (\text{kPa}) \quad \text{Eq. (17)}$$

11. Calculate the height of solids in the overflow well of V2 standpipe

$$H_{st} = \frac{144 \Delta P_{st}}{0.8 \rho_{mf}} \frac{g_c}{g} \quad (\text{ft}) \quad \text{Eq. (18c)}$$

$$H_{st} = \frac{10^3}{0.8 g} \frac{\Delta P_{st}}{\rho_{mf}} \quad (\text{m}) \quad \text{Eq. (18m)}$$

The solids level in V2 standpipe must be checked for a ± 5 psi (± 35 kPa) change in V2 dilute phase pressure to assure that the solids level in the standpipe is above the J-Bend and below V2 overflow well inlet. For design purposes, the solids level in the standpipe is set at V2 grid level. The sensitivity to a V2 pressure change is calculated from:

$$\Delta H_{st} = \frac{144 (\pm 5 \text{ psi})}{0.8 \rho_{mf}} \frac{g_c}{g} \quad (\text{ft}) \quad \text{Eq. (19c)}$$

$$\Delta H_{st} = \frac{10^3}{0.8} \frac{(\pm 35 \text{ kPa})}{g \rho_{mf}} \quad (\text{m}) \quad \text{Eq. (19m)}$$

Vessel A1 to Vessel A2 (A1 Standpipe Circuit)

This pressure balance is calculated to assure that the slide valve ΔP is greater than 5 psi (35 kPa) to assure operating flexibility and less than 10 psi (70 kPa) to limit valve erosion.

- Obtain V1 dilute phase pressure, P_{v1}
- Calculate V1 dilute phase pressure ΔP [Eq. (8)]
- Calculate V1 dense bed ΔP [Eq. (9)]
- Calculate V1 transition cone ΔP

$$\Delta P_c = \Delta P_{csh} - \Delta P_{ca} \quad (\text{psi}), (\text{kPa}) \quad \text{Eq. (20)}$$

where: ΔP_c = The V1 transition cone pressure differential (psi), (kPa)
 ΔP_{csh} = The static head through the cone (psi), (kPa)
 ΔP_{ca} = The acceleration loss through the cone (psi), (kPa)

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PRESSURE BALANCE (Cont)

$$\Delta P_{\text{csh}} = \frac{0.7 H_c \rho_{\text{mf}}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (21c)}$$

$$\Delta P_{\text{csh}} = 0.7 \times 10^{-3} g H_c \rho_{\text{mf}} \quad (\text{kPa}) \quad \text{Eq. (21m)}$$

$$\Delta P_{\text{ca}} = \frac{0.7 \rho_{\text{mf}} (U_{\text{sc}}^2 - U_{\text{sb}}^2)}{2 g_c (144)} \quad (\text{psi}) \quad \text{Eq. (22c)}$$

$$\Delta P_{\text{ca}} = \frac{0.7}{2} \times 10^{-3} \rho_{\text{mf}} (U_{\text{sc}}^2 - U_{\text{sb}}^2) \quad (\text{kPa}) \quad \text{Eq. (22m)}$$

where: U_{sb} = The solids velocity in the bed (ft/s), (m/s)
 U_{sc} = The solids velocity at the cone outlet (ft/s), (m/s)

Since the solids velocities are low, the acceleration loss term may be negligible.

5. Calculate the stripper ΔP

$$\Delta P_s = \frac{0.7 \rho_{\text{mf}} H_s}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (23c)}$$

$$\Delta P_s = 0.7 \times 10^{-3} g \rho_{\text{mf}} H_s \quad (\text{kPa}) \quad \text{Eq. (23m)}$$

where: ΔP_s = The stripper pressure differential (psi), (kPa)
 H_s = The stripper height (ft), (m)
 g = The acceleration due to gravity (32.2 ft/s²), (9.81 m/s²)

6. Calculate the stripper transition cone ΔP , ΔP_{sc} , using a modified form of **Eq. (20)** where the velocity and height terms refer to conditions in the stripper cone. Use $0.7 \rho_{\text{mf}}$ as the density term.
7. Calculate the standpipe ΔP

$$\Delta P_{\text{st}} = \frac{0.8 \rho_{\text{mf}} H_{\text{st}}}{144} \frac{g}{g_c} \quad (\text{psi}) \quad \text{Eq. (24c)}$$

$$\Delta P_{\text{st}} = 0.8 \times 10^{-3} g \rho_{\text{mf}} H_{\text{st}} \quad (\text{kPa}) \quad \text{Eq. (24m)}$$

where: ΔP_{st} = The standpipe pressure differential (psi), (kPa)
 H_{st} = The standpipe height (ft), (m)

8. Calculate the pressure above the slide valve, P_{sv}

$$P_{\text{sv}} = P_{\text{v1}} + \Delta P_{\text{dp}} + P_{\text{db}} + \Delta P_{\text{c}} + \Delta P_{\text{s}} + \Delta P_{\text{sc}} + \Delta P_{\text{st}} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (25)}$$

9. Calculate the pressure at the spent solids inlet to V2.

$$P_{\text{si}} = (P_{\text{dp}} + \Delta P_{\text{dp}} + \Delta P_{\text{db}})_{\text{v2}} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (26)}$$

The pressure differential through the angled transfer line between the slide valve and the inlet to V2 is kept at a low level by the injection of a fairly small amount of steam into the line. Gas velocity in the line is about 0.5 ft/s (0.15 m/s). This results in a loss of fluidization in the transfer line, no pressure buildup, and therefore decreases the required pressure drop across the slide valve by an amount equal to the static head which would have built up through the line if the solids had been fluidized. Therefore, the pressure at the slide valve outlet is essentially equal to the pressure at the spent solids inlet to V2, P_{si} .

10. Calculate the pressure drop across the slide valve.

$$\Delta P_{\text{sv}} = P_{\text{sv}} - P_{\text{si}} \quad (\text{psi}), \quad (\text{kPa}) \quad \text{Eq. (27)}$$

Note:

- (1) Density in this equation is for illustrative purposes only. Actual densities and ΔP will depend on gas and solids rates.