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### Revision Memo

**12/02** Corrections and minor updates.



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## SCOPE

This section covers other fluid solids design items such as gas distributors and heat exchangers used to extract heat from fluidized beds. Distributor types, stability criteria, pressure drop and jet penetration are included. Heat exchanger design and heat transfer between gas and particles are described.

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## GAS DISTRIBUTORS

### DISTRIBUTOR TYPE

Selection of a gas distributor type is often dependent on specific process characteristics. Several types are shown in [Figure 1](#).

The perforated plate grid ([Figure 1a](#)) is probably the most widely used in hExxon commercial scale equipment. It is relatively cheap and simple to fabricate and maintain, and it should always receive consideration.

For use at very high temperatures, an insulated grid ([Figure 1b](#)) may be used. The insulated grid requires that cool gases be passed up through the grid in order to keep temperatures of structural metal in the plenum at acceptable levels. Grid metal temperature differentials and stresses are much lower than in unlined grid plates. Three or four in. (75 to 100 mm) of refractory are placed on the top of the grid. Grid holes are on the order of 3/8 to 1/2 in. (9.5 to 12.5 mm). The grid holes are surrounded by metal shrouds (pipe stubs) whose length equals the refractory thickness. The diameter of the shrouds is small enough to contain the expanding gas jet issuing from the grid holes. This is necessary to prevent erosion of the refractory near the gas outlets and also minimize solids attrition at those points. Erosion and attrition are caused by clockwise recirculating eddies detaching from the expanding jet, which pull in bed solids and scour the top surface of the grid near the gas outlet holes. The diameter of the shrouds is calculated from:

$$\frac{H}{D - d_o} \geq 5.2 \quad \text{Eq. (1)}$$

where: H = The height of the shroud  
D = The inside diameter of the shroud  
d<sub>o</sub> = The diameter of the grid holes

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H/D ratios of 4:1 are usually used.

Shrouds can also be used to prevent grid erosion and solids attrition in those cases where refractory lining is not required. Design details are given in Reference (1) and in the FCCU Maintenance Guide.

Dished perforated plates (Figures 1c and 1d) may be used where strength is needed, although present practice is to use flat grids with a separate support, if possible. Dished plates, especially the upward dished, have an inherent tendency for uneven gas distribution. This can result in increased pressure drop, grid hole erosion, and solids attrition. This effect can be counteracted by installing riser pipes so that all gas discharges are at the same elevation (Figure 1e). The grid may be refractory coated on the bottom to protect against incoming hot gas. The top section may also filled with an insulating refractory. Gas is discharged through orifices in the caps mounted on the riser pipes.

Bubble cap or tuyere distributors (Figure 1f) are especially useful when it is necessary to prevent backflow of bed particles through the grid at conditions of low or interrupted flow of fluidizing gas. They are also useful when grid gas jets must enter downwards into the bed for reasons of fouling.

A pipe grid (Figure 1g) consists of an array of pipes with upward- or downward-facing nozzles. For large diameter vessels, pipe grids may permit some saving in vessel height when compared to a plate grid with grid plenum beneath. Under certain conditions mechanical design may be simpler and cheaper, and there is some indication that with downwards-facing nozzles a lower grid pressure drop is required than for other grid configurations. Pipe grids are especially useful when bed solids are to be withdrawn downwards through the grid level, as occurs for instance at the bottom of strippers. Gas outlet holes are usually 1/2 to 1 in. diameter (13 to 25 mm) and outlet gas velocity is usually 100 to 150 ft/s (30 to 45 m/s). The holes are shrouded by 2 in. (50 mm) diameter nipples with a 1:1 to 4:1 length to diameter ratio to minimize solids attrition. Two sets of outlet holes are used, each angled at approximately 45° from the vertical. A large number of hMobil units use pipe grid distributors and relevant design information can be obtained from EE.31E.2002.

## GRID STABILITY

A grid is said to be stable when gas is passing upward through all grid holes and solids are not sifting down through any grid holes. When this condition occurs, all parts of the bed above the grid will be fluidized, and the bed is also said to be stable. An unstable bed has slumped or unfluidized zones. Therefore, an important consideration in the design of a large grid is to ensure sufficient grid pressure drop for good gas distribution and stable bed operation. One approach to calculating grid pressure drop necessary for stability is shown in Figure 2. The pressure drop through a grid hole will increase with gas velocity. However, pressure drop through the bed immediately above that hole will decrease as gas preferentially channels through the hole, because the density of the bed decreases as gas flow increases. Therefore, local grid and bed conditions will move to the minimum in the total pressure drop curve in Figure 2 by stopping gas flow through some of the holes. In order for the grid to be stable, total pressure drop through a grid hole plus the bed above the hole must increase as gas flow starts to channel preferentially. This will halt the channeling by forcing gas to flow through other grid holes as well. A simplified case is instructive.

Assuming that the bed is bubbling freely, pressure drop through the bed is given by:

$$\Delta P_b = \frac{\rho H}{144} \frac{g}{g_c} = \frac{\rho_{mf} H}{144} \frac{g}{g_c} \left( \text{psi} \right) \quad \text{Eq. (2c)}$$

$$1 + \frac{U - U_{mf}}{U_B}$$

$$\Delta P_b = 10^{-3} g H \rho = \frac{10^{-3} g \rho_{mf} H}{1 + \frac{U - U_{mf}}{U_B}} \quad (\text{kPa}) \quad \text{Eq. (2m)}$$

**where:**  $\Delta P_b$  = The pressure drop through the bed (psi), (kPa)  
 $\rho$  = The fluidized bed density (lb/ft<sup>3</sup>), (kg/m<sup>3</sup>)  
 $H$  = The fluidized bed height (ft), (m)  
 $\rho_{mf}$  = The minimum fluidized bed density (lbs/ft<sup>3</sup>), (kg/m<sup>3</sup>)  
 $U$  = The gas velocity (ft/s), (m/s)  
 $U_{mf}$  = The minimum fluidization velocity (ft/s), (m/s)  
 $U_B$  = The bubble rise velocity (ft/s), (m/s)  
 $g$  = The acceleration due to gravity (32.2 ft/s<sup>2</sup>) (9.81 m/s<sup>2</sup>)  
 $g_c$  = The gravitational conversion factor [(32.2 ft/s<sup>2</sup>) (lb mass/lb force)]

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and grid pressure drop is:

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

**where:**  $\Delta P_g$  = The pressure drop through the grid (psi), (kPa)

$C$  = The grid hole coefficient  $(\text{s}/\text{in} \sqrt{\text{ft} \cdot \text{lb}_f/\text{lb}_m})$ ,  $(\text{s} \sqrt{\text{m} \cdot \text{kPa}}/\text{kg})$

$Q$  = The gas flow rate through the grid ( $\text{ft}^3/\text{s}$ ), ( $\text{m}^3/\text{s}$ )

$A$  = The grid hole area ( $\text{ft}^2$ ), ( $\text{m}^2$ )

$\rho_a$  = The density of the mixture flowing through the grid ( $\text{lb}/\text{ft}^3$ ), ( $\text{kg}/\text{m}^3$ )

Solving for the stability condition that  $d(\Delta P_g + \Delta P_b) / dU > 0$  gives the criterion:

$$\frac{\Delta P_g}{\Delta P_b} > \frac{U}{2(U + U_B - U_{mf})} \quad \text{Eq. (4)}$$

for stable grid operation. A grid operated at too low a pressure drop will redistribute the gas flow so that some of the holes are inoperative and the remainder satisfy the criterion. Exxon practice is to maintain grid pressure drops of 25% to 40% of bed pressure drop to keep all holes active.

Unstable bed conditions are most likely to occur during turndown and certain startup operations when flow rates and grid  $\Delta P$  are low. If this occurs, it is usually seen as high temperatures below the grid due to solids sifting, uneven  $\Delta P$  measurements, and possibly high solids losses through internal cyclones. The high losses occur if cyclone diplegs terminate in slumped bed zones. If this happens, the solids in the diplegs back up into the cyclone and make it inoperative. Grid chimneys can be placed on a small fraction of grid holes to assure that those holes will remain active during low flow conditions. Those holes will remain active since the bed  $\Delta P$  above the chimneys is less than that above the remaining grid holes. To prevent cyclone dipleg flooding, it is recommended that chimneys be placed over half of the grid holes in the vicinity of each dipleg termination. The holes with chimneys should be alternated with plain holes to minimize re-start problems in the event of loss of fluidizing gas. Chimney ID should be the same as grid hole ID with a 6:1 chimney length/ID ratio. Chimneys are particularly recommended for grids through which both gas and solids flow. Startup problems are more likely since only gas is passed through the grid during startup and the pressure drop is therefore very low. Chimneys can also be used for gas flow only grids, but the need is less than for the gas plus solids flow design.

### GRID PRESSURE DROP

Grid pressure drop is calculated by [Equation \(3\)](#). The grid hole coefficient used in [Equation \(3\)](#) is 0.0135 (conventional units) for gas flow through a flat grid plate. For grids lined with 4 in. (100 mm) refractory, the coefficient is lower due to pressure recovery in the 4 in. (100 mm) long grid holes through the refractory section. A coefficient of 0.0115 (conventional units) should be used for gas flow through refractory lined grids but calculations should be made to test the sensitivity of the grid design, e.g., grid  $\Delta P$ , to an assumed coefficient of 0.010 (conventional units). For the case of solids flow through a grid, the coefficient decreases with hole velocity and solids loading. See [Figure 2, Section VI-A](#) for FCC catalyst and gas flow through a grid.

Measurements of grid pressure drop must be corrected for the static head of solids between the upper DP tap and the top of the grid. Actual flow through the grid must also be used by correcting for any flows which bypass the grid.

### GRID JET PENETRATION

Gas entering a fluid bed from an orifice usually seems to form a jet, with jet penetration distances being determined by hole velocity and diameter. These jets allow gas to bypass the bed and so should not penetrate to the bed surface or occupy an inordinate fraction of bed height. Jet impingement can also cause severe erosion of surfaces within the bed and such submerged surface as heat transfer tubes and cyclone diplegs should be located away from any jet penetration zones. An empirical formula for jet penetration is given by Merry (2):

|                                                  |                                                                                                                       |                |             |
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$$L/d_o = 5.2 \left( \frac{\rho_g d_o}{\rho_p d_p} \right)^{0.3} \left[ 1.3 \left( \frac{V_o^2}{g d_o} \right)^{0.2} - 1 \right] \quad \text{Eq. (5)}$$

**where:** L = The jet penetration length (ft), (m)  
 $d_o$  = The diameter of a grid hole (ft), (m)  
 $\rho_g$  = The density of the fluidizing gas (lbs/ft<sup>3</sup>), (kg/m<sup>3</sup>)  
 $\rho_p$  = The solids particle density (lbs/ft<sup>3</sup>), (kg/m<sup>3</sup>)  
 $d_p$  = The average particle diameter (ft), (m)  
 $V_o$  = The grid hole gas velocity (ft/s), (m/s)  
 $g$  = The acceleration due to gravity (32.2 ft/s<sup>2</sup>), (9.81 m/s<sup>2</sup>)

Having selected a grid hole velocity and pressure drop sufficient for good gas distribution, significantly higher velocities should be avoided. Attrition of bed particles increases rapidly as grid hole velocity increases, and erosion of bed internals in the vicinity of the grid jet can also become serious. However, the effect of grid hole velocity on attrition and erosion can be mitigated by using grid hole shrouds described previously. High grid pressure drop also wastes compressor power. In some multi-bed processes, high grid pressure drop adversely affects the pressure balance necessary for solids circulation.

In some cases, grid holes near bed internals may be blanked to prevent jet impingement and erosion of the internals. Since fluidization in the vicinity of diplegs can affect cyclone performance, the choice of blanking holes to prevent erosion, maintaining holes, or placing chimneys on holes to promote localized fluidization should be made after considering all issues including those related to the process.

FCC regenerator grid holes, through which both gas and catalyst pass, have plugged in some units after catalyst changes. Preliminary findings indicate the plugging is due to the formation of very fine particles resulting from attrition of newer catalysts, coupled with fluid dynamic effects which tend to cause the fine particles to accumulate near the grid hole wall, and thermal effects which increase the temperature of these particles to the softening point. Plugging may be mitigated by using tapered grid holes. Consult Process Engineering Department for further information.

Penetration from downward flowing jets (e.g., in strippers) is considerably less. An empirical formula for downward jet penetration is given by Zenz (3):

$$L / d_o = 21.6 \log V_o \sqrt{\rho g} - 31.5 \quad \text{Eq. (6c)}$$

$$L / d_o = 21.6 \log V_o \sqrt{\rho g} - 33.4 \quad \text{Eq. (6m)}$$

### HEAT EXCHANGER DESIGN

#### INTRODUCTION

In some fluids solids processes, heat must be extracted from a fluidized bed to maintain temperature of the bed within certain limits or to recover energy from the bed. Examples are in fluidized bed combustion or in FCC regenerators operating under conditions of high coke yield. Heat exchange was also used in the past in Fluid Hydroforming regenerators. Heat can be removed by tubular heat exchangers immersed in the fluidized beds or by circulating the solids between the process vessel and another vessel containing the heat exchanger. The immersed heat exchanger is discussed in this section. It has been used in Exxon installations in the past, is reliable, but has the disadvantage of not being able to vary the rate of heat removal from the bed. External heat exchange systems can control the rate of heat removal by controlling the circulation rate. Consult Engineering Equipment and Environmental Department for further information.

Heat exchanger design technology for fluid solid systems is also available from vendors. UOP has licensed a number of external dense phase coolers which are reported to be operating satisfactorily. Similar systems are available from Air Products/HRI. Other vendor systems are also available, but less is known about operating experience and reliability. These include a dilute phase cooler from Kellogg and a flow through system from UOP. Consult Process Engineering Department if vendor designs are to be considered.

Immersed heat exchangers are usually cooled by a forced circulation water system. Parallel cooling circuits are used in the event of tube failure. Other systems which have been used are steam/atomized water and a natural convection circulation system. The forced circulation system is generally recommended.

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## HEAT EXCHANGER DESIGN (Cont)

### HEAT TRANSFER BUNDLES

The heat transfer surface can consist of horizontally or vertically oriented tubes usually containing water and steam as the heat transfer medium. Other liquids or gases can also be used as the heat transfer medium. However, attention must be given to the effect of the high heat fluxes associated with heat transfer from a fluidized bed on the heat transfer medium, e.g., coking, vapor blanketing, etc.

Horizontal tube orientation is generally recommended since design parameters are better defined and vertically oriented tube bundles were known to be susceptible to vapor locking when used in the past by Exxon in Fluid Hydroformers. Equipment and Environmental Engineering Department should be consulted if vertical tube orientation is being considered.

Basic design parameters are discussed below. Also see References (4), (5).

**Heat Transfer Coefficients.** Heat transfer coefficient correlations are available, based on studies published in the literature, for convective heat transfer to fully immersed horizontal (6) and vertical tube bundles, and for additional radiant heat transfer at higher temperatures (7). The total heat transfer coefficient,  $h_t$ , is the sum of the convective,  $h_c$ , and radiant,  $h_r$ , coefficients. Some information is available on heat transfer in the freeboard area, heat transfer to fully immersed extended surface exchangers (finned tubes) and the variation in local heat transfer coefficients with position on tube surfaces (8). The final point is important for temperature sensitive heat transfer fluids and is also used to determine maximum tube metal temperatures. These correlations cover a range of operating variables and can be used for preliminary screening studies. For recommended correlations to be used in critical designs, consult the Equipment and Environmental Engineering Department.

- **Horizontal Tubes.** Convective heat transfer coefficients from the fluidized bed to fully immersed horizontal tubes can be obtained from the Vreedenberg correlations (6).

For fine, light particles, i.e., for  $\frac{Gd_p \rho_p}{\rho_g \mu_g} < 2050$  :

$$\left[ \frac{h_c d_{to}}{k_g} \right] \left[ \frac{3600 C_p \mu_g}{k_g} \right]^{-0.3} = 0.66 \left[ \frac{G d_{to} \rho_p (1 - \varepsilon)}{\rho_g \mu_g \varepsilon} \right]^{0.44} \quad \text{Eq. (7c)}$$

$$\left[ \frac{h_c d_{to}}{k_g} \right] \left[ \frac{C_p \mu_g}{k_g} \right]^{-0.3} = 0.66 \left[ \frac{G d_{to} \rho_p (1 - \varepsilon)}{\rho_g \mu_g \varepsilon} \right]^{0.44} \quad \text{Eq. (7m)}$$

**where:**  $h_c$  = The bed side convective heat transfer coefficient (Btu/hr ft<sup>2</sup> °F), (W/m<sup>2</sup>K)  
 $d_{to}$  = The tube outside diameter (ft), (m)  
 $K_g$  = The thermal conductivity of the gas (Btu/hr ft °F), (W/mK)  
 $C_p$  = The heat capacity of the solids (Btu/lb °F), (J/kgK)  
 $G$  = The gas superficial mass flux (lbs/ft<sup>2</sup>s), (kg/m<sup>2</sup>s)  
 $\mu_g$  = The gas viscosity (lbs/ft s), (kg/ms)  
 $\varepsilon$  = The bed voidage fraction  
 $\rho_g$  = The gas density (lb/ft<sup>3</sup>), (kg/m<sup>3</sup>)  
 $\rho_p$  = The solids particle density (lb/ft<sup>3</sup>), (kg/m<sup>3</sup>)

This equation is claimed to correlate data to within  $\pm 40\%$ .

For coarser and heavier particles, i.e.,  $\frac{Gd_p \rho_p}{\rho_g \mu_g} > 2550$  :

$$\left[ \frac{h_c d_{to}}{k_g} \right] \left[ \frac{3600 C_p \mu_g}{k_g} \right]^{-0.3} = 420 \left[ \frac{G d_{to} \rho_p}{\rho_g \mu_g} \times \frac{\mu_g^2}{d_p^3 \rho_p^2 g} \right]^{0.3} \quad \text{Eq. (8c)}$$

$$\left[ \frac{h_c d_{to}}{k_g} \right] \left[ \frac{C_p \mu_g}{k_g} \right]^{-0.3} = 420 \left[ \frac{G d_{to} \rho_p}{\rho_g \mu_g} \times \frac{\mu_g^2}{d_p^3 \rho_p^2 g} \right]^{0.3} \quad \text{Eq. (8m)}$$