How Catalyst Characteristics Affect Circulation

Introduction

Fluidization is of prime importance in catalytic cracking units since all phases of the process (reaction, catalyst stripping, and regeneration) are performed in fluidized beds. In addition the catalyst is transported from one part of the unit to another by using its fluidized form.

The rate at which a catalyst can be circulated has significant effects on the operability of many units. A system which circulates badly is difficult to operate and may be run at lower catalyst to oil ratios than desired, having an adverse effect on yields and product selectivities.

Fluidization Parameters

Minimum Fluidization Velocity
The minimum superficial gas velocity which makes a bed of solids act as though it is a fluid, is said to be the **minimum fluidization velocity**. Below the minimum fluidization velocity the gas will trickle though channels between the particles.

Minimum fluidization velocity can be estimated from the equation by Baeyens (Figure 1, equation A). Note that the average particle size term (dp) should be the mean particle diameter by particle count and not the median by weight fraction (APS) which is commonly reported by catalyst manufacturers. The particle density (ρ_p) is the apparent density of a catalyst particle and is given by equation B in Figure 1.

A low value for Umf is desirable since this makes initial fluidization easier and in particular makes it less likely for the particles to slump in a low velocity area.

Minimum Bubbling Velocity
The two phase theory of gas flow states that once the minimum velocity for fluidization has been reached, any extra gas will not go into the interstitial spaces between the catalyst but will form bubbles which pass through the bed. However, cracking catalyst powders have some capacity to increase the amount of gas in the interstitial space above the volume associated with Umf. Bubbles are seen to form above a higher velocity known as the **minimum bubbling velocity**. This feature is an important one to the ability of a powder to circulate as we shall see later. Abrahamsen, et al., use equation C in Figure 1 to estimate minimum bubbling velocity.

In general a high minimum bubbling velocity is better since bubbling restricts flow in standpipes. However the ratio of Umb to Umf, the Fluidization Index (see below), is a more useful parameter.

Deaeration Rate
Deaeration is the loss of fluidization media which converts the fluidized system back to a packed bed (often called a slumped bed). Deaeration occurs in two stages: first there is a very rapid disengagement of entrained bubbles and then there is a gradual settling of the fluidized catalyst as gas escapes from the void spaces. The Geldart deaeration rate is measured by decreasing the air rate from an initial velocity of 10 cm/sec. The deaeration rate can be estimated from the equations by Abrahamsen and Geldart as shown in Figure 1, equation D.

Since deaeration transforms a fluidized bed into a packed one it follows that low values of Ude are better, though there are unusual circumstances where the opposite is true.

FIGURE 1

(A)

$$\text{Umf} = \frac{9.0\times10^{-4}\ \bar{d}_p^{\ 1.8}\left[\left(\rho_p - \rho_g\right)g\right]^{0.934}}{\rho_g^{\ 0.066}\ \mu_g^{\ 0.87}}$$

(B)

$$\rho_p = \frac{1}{x + \frac{1}{\rho_{ABS}}}$$

(C)

$$\text{Umb} = \frac{2.07\,\bar{d}_p\ \rho_g^{\ 0.06}\ \exp\left[0.176F_{45}\right]}{\mu_g^{\ 0.347}}$$

(D)

$$\text{Ude} = \frac{0.314\rho_g^{\ 0.023}\left(\rho_p - \rho_g\right)^{0.271}\ \bar{d}_p^{\ 1.232}\ \exp\left[0.508F_{45}\right]}{\mu_g^{\ 0.5}\,h^{0.244}}$$

Significant Fluidization Parameters

The terms for minimum fluidization velocity, minimum bubbling velocity and deaeration rate are significant in themselves; however, two other parameters are also used to characterize the circulating ability of a catalyst. These are described below:

Fluidization Index
This is the ratio of minimum bubbling velocity to minimum fluidization velocity. Dividing the Abrahamsen equation by the Baeyens equation gives equation E in Figure 2. This can be simplified to a fluidization index as shown by equation F in Figure 2.

The higher the ratio the more gas a catalyst can hold between its minimum fluidization and bubbling points. This means that for a correct initial aeration rate between these two values the catalyst will be less likely to form bubbles for a small increase in velocity (from additional aeration gas for example) and less likely to deaerate due to a reduction in velocity (due to pressure build up in a standpipe for example).

In a sense a high fluidization index implies that the catalyst has a certain "plasticity" and can be expanded, contracted and bent around corners without problem. A low fluidization index implies a "brittle" fluidization state where a small change could cause a break from the uniformly fluidized catalyst to a bubbling regime or a packed bed. This is particularly a problem in standpipes where the reduction in velocity due to pressure build up causes defluidization, but addition of too much aeration gas causes bubbles to form which impede catalyst flow. A catalyst with a higher fluidization index prevents this.

F-PROP
F-PROP (Figure 2, equation G) is a correlation originally used by Gulf to track the fluidization characteristics in certain units. Studies on these units indicated that low slide valve differentials were due to poor pressure build up in the standpipes. The pressure profiles were uniform but the design density of 545 kg/m^3 (341b/ft^3) was not achieved. This was thought to be due to inadequate defluidization in the regenerated catalyst hopper. Since nearly all the aeration media entering with the catalyst stays engaged and travels down the standpipe, the volumes moved are too large for the pipe diameter and circulation problems follow. In this case a catalyst system which deaerates faster improves circulation because of the resulting higher standpipe densities. F-PROP measures the capability of a catalyst to deaerate in a hopper or standpipe entrance. F-PROP is an alternative form of the Abrahamsen and Geldart equations for deaeration rate divided by minimum fluidization velocity.

Note that both F-PROP and the fluidization index use the mean particle diameter and not the APS. The APS reported by catalyst manufacturers' laboratories is the median particle size by weight distribution. If APS is substituted for dp then errors will arise if the shape of the particle size distribution curve changes.

Catalyst 0-40 micron Fines Content
An increased number of fine catalyst particles having diameters less than 40 microns will improve circulation in most units. Terms reflecting 0-40 fines appear in the fluidization factor and in F-PROP, both directly and via the average particle diameter. It was said before that cracking catalysts exhibit a minimum bubbling velocity at a rate higher than the minimum fluidization rate, and the higher the ratios of the two terms the more gas flows interstitially. The amount of gas flowing interstitially is a function of the catalyst 0-40 micron fines content (Figure 3). The effect of the higher fines content is therefore to give a higher fluidization index. In a sense the fines give the system a greater safety margin between going above Umb and bubbling or going below Umf and slumping.

Correlations can be Misleading

Correlated values for F-PROP and the fluidization index are useful for monitoring a unit on a given catalyst and can be used to interpret trends which might result in fluidization problems. However correlations are not always meaningful when comparing different catalysts; laboratory measurements are then required.

Table 1 shows three catalysts from different suppliers with the calculated and measured F-PROP and fluidization indices. Catalyst A has the best values because of its high fines content, but note that while catalyst B has better calculated values than C its measured values are far worse, particularly for Ude. The measured values reflected the refiner's perceptions of how these catalysts circulated. F-PROP was used here since the circulation limit was due to deaeration problems in a spent standpipe hopper.

One reason for the differences in calculated and measured values is thought to be due to particle shape and its effects on drag and minimum fluidizing velocity. Another may be due to using APS in place of dp when the bell curves for particle size distribution were known to change.

FIGURE 2

(E)

$$\frac{\text{Umb}}{\text{Umf}} = \frac{2300\rho_g^{\,0.126}\mu_g^{\,0.523}\exp\left[0.176F_{45}\right]}{\bar{d}_p^{\,0.8}g^{0.934}\left[\rho_p-\rho_g\right]^{0.934}}$$

(F)

$$\frac{\text{Umb}}{\text{Umf}} = \frac{\exp\left[0.176F_{45}\right]}{\bar{d}_p^{\,0.8}\times ABD^{0.934}}$$

(G)

$$F-\mathrm{Pr}op = \frac{\exp\left[0.508F_{45}\right]}{\bar{d}_p^{\,0.568}ABD^{0.663}}$$

FIGURE 3
INTERSTITIAL GAS FLOW INCREASES WITH HIGHER CATALYST FINES CONTENT

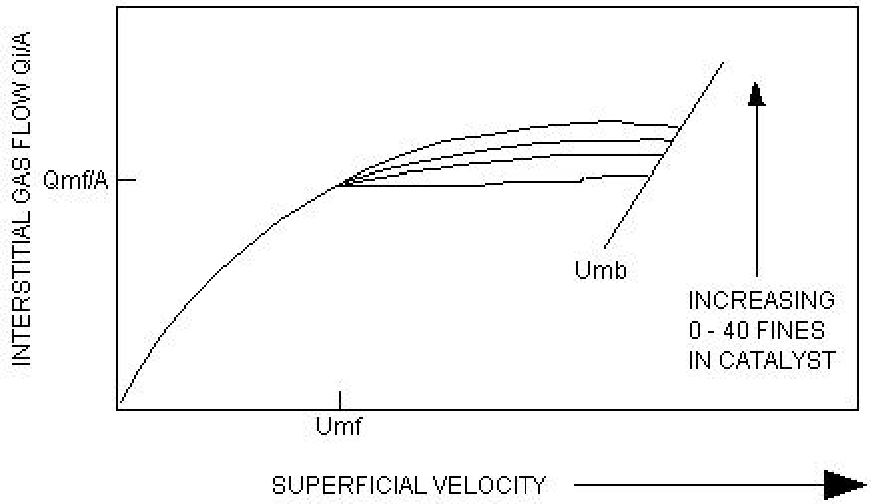


FIGURE 4
FLOW REGIMES AND PRESSURE PROFILES IN STANDPIPES

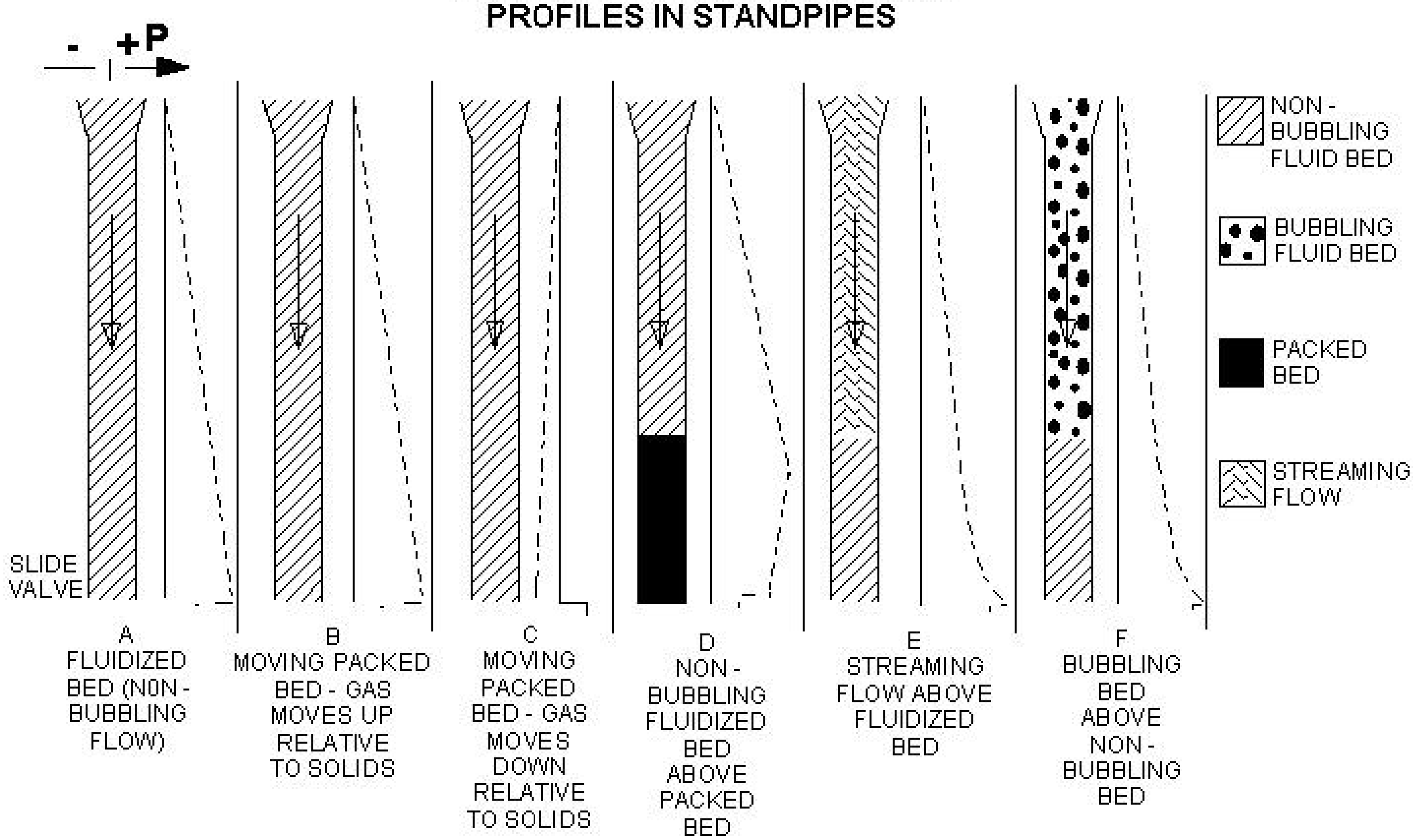


FIGURE 5

EFFECT OF GAS COMPRESSION ON FLOW REGIME IN STAND PIPES

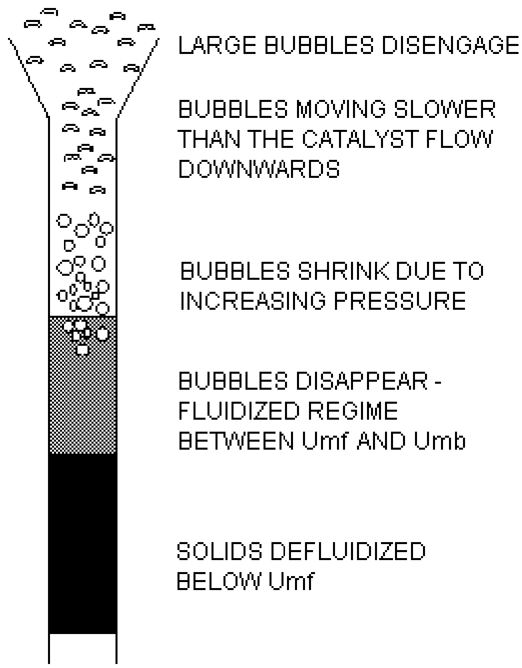
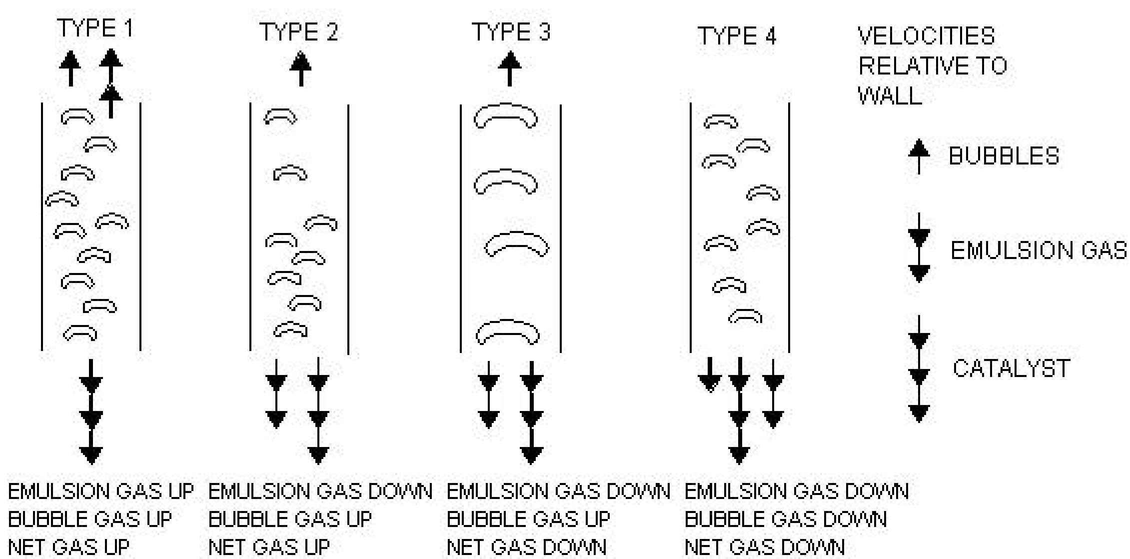


FIGURE 6

TYPES OF BUBBLING FLUIDIZED FLOW IN STAND PIPES



Standpipes are used to build pressure differentials through the use of static head of a fluidized particle system. The pressure above a slide valve is given by:

$$P = \rho_B gh$$

Catalyst flow down a standpipe can be in four different phases: streaming (essentially free fall), bubbling mode, fluidized (non-bubbling mode) and packed bed. The presence of a packed bed in a standpipe can result in a pressure drop profile reversal. Pressure drop profiles are shown in Figure 4. Although the catalyst always flows downwards the emulsion or bubble phases may travel upwards or downwards depending on the catalyst circulation rate, the amount of aeration gas, and the type of solids. It is usual for the gas to be flowing down a standpipe though a slow-moving catalyst in bubbling mode can result in an upward movement of gas relative to both the catalyst and walls.

The point to note from Figure 4 is that a packed bed may have a negative pressure gradient down the standpipe. The pressure build up itself can reduce gas volumes until velocities go below Umf and the bed deaerates. The parameters which help prevent this condition are a low Umf and a high fluidization index. F-PROP does not relate to this condition.

The effect of gas compression on flow regime in a standpipe is shown in Figure 5. As compression takes place, it is often necessary to add aeration gas to prevent defluidization. It is important not to add too much gas since this could cause the formation of bubbles.

Streaming flow is commonly seen in cyclone diplegs. A dipleg is essentially a special form of standpipe which relies on the fluidized bed to form a seal between the regenerator and flue gas system.

Knowlton characterizes bubbling flow into 4 regimes (Figure 6). If the standpipe operates in type 1 or type 2 flow, then the bubbles will rise and grow by coalescence. The rising bubbles will hinder the downward flow of solids. The larger the bubbles, the greater the cross sectional area they will take and the worse their hindrance will be. The effect is less for type 3 flow, but flow will still be hindered since catalyst falls at a greater rate than bubbles and must flow around them. In type 4 flow the bubbles will not greatly affect catalyst flow, but they will reduce the apparent density and hence the pressure build up in the standpipe.

The catalyst characteristics which help avoid bubbling flow are a high fluidization index (to contain the maximum amount of gas in the interstitial spaces) and for some systems a high F-PROP (to avoid entraining too much gas into the standpipe in the first place).

A pressure profile which slowly increases may be due to the presence of bubbles; reducing the amount of aeration may improve the profile. One which shows a pressure gradient reversal is slumping and needs more aeration at the lower end of the standpipe. In both cases the best catalyst characteristics are ones which increase Umb/Umf to allow the best chance to operate in a fluidized regime without forming bubbles or deaerating.

Conclusions

The ideal conditions for operation of a standpipe are obtained when the relative velocity between the gas and catalyst particles lies between Umf and Umb. As the pressure head builds up down the standpipe, compression effects drive the catalyst towards minimum fluidization and possibly defluidization. To avoid this aeration gas must be injected, but if this is judged incorrectly large bubbles may form which will hinder flow. A stable operation therefore requires a catalyst with the largest range of non-bubbling fluidized flow. This is one with a large ratio of Umb/Umf.

It is better to measure Umb and Umf than to rely on correlations. However, if properly carried out, the collapse test gives a useful indirect indication of the fluidization index.

TABLE 1
FLUIDIZATION CORRELATIONS CAN BE MISLEADING

CATALYST	A	B	C
MEASURED VALUES			
0-40 microns, wt%	22	14	11
APS, microns	58	65	73
ABD, kg/m3	950	860	930
Umf, mm/s	2.4	2.6	2.2
Umb, mm/s	7.2	5.4	5.6
Ude. mm/s	2.4	0.85	1.90
F-PROP	1.0	0.33	0.86
Umb/Umf	1.0	0.69	0.85
CALCULATED VALUES			
F-PROP	1.0	0.96	0.84
Umb/Umf	1.0	0.79	0.72

Note: F-PROP and Umb/Umf normalized versus catalyst A as a base case.

NOMENCLATURE

Umf	minimum fluidization velocity m/s
Umb	minimum bubbling velocity m/s
F45	fraction of catalyst below 45 microns
dp	average particle diameter m
g	acceleration due to gravity m/s2
ABD	bulk density of gently settled catalyst kg/m3
ρ_P	particle density kg/m3
ρ_{ABS}	absolute density of catalyst particle kg/m3
ρ_B	aerated density of catalyst in standpipe kg/m3
ρ_g	gas density kg/m3
μ_g	gas viscosity kg/ms
h	height of catalyst bed m
Qi	interstitial gas flow m3/s
A	standpipe cross sectional area m2
x	pore volume of catalyst m3/kg

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