

## 6. ELUTRIATION OF PARTICLES FROM FLUIDIZED BEDS

Elutriation is the process in which fine particles are carried out of a fluidized bed due to the fluid flow rate passing through the bed. Typically, fine particles are elutriated out of a bed when the superficial velocity through the bed exceeds the terminal velocity of the fines in the bed. However, elutriation can also occur at slower velocities.

Fine particles are present in fluidized beds from several sources:

- Feed streams
- Mechanical attrition or breakage of larger particles
- Temperature stress cracking
- Size reduction due to chemical reactions, shrinkage, etc.

When fines elutriation is a significant problem and modifications to the bed design cannot aid in reducing the problem, fines can often be recovered such as with cyclones or hydrocyclones.

Leva (*Chem. Engr. Prog.*, **47**, 39, 1951) measured the rate of elutriation (total mass per time) from a bed of particles with a bimodal size distribution. He found that

- (1) When the column height above the bed is small, the elutriation rate is high. But if the height exceeds a certain minimum size then the rate is a constant minimum value (Figure 6-1).

This occurs because small particles that are expelled from the top of the bed have high velocities and they require greater distance to slow down and turn around to return to the bed.

- (2) The elutriation process causes a decrease in particle concentration. The concentrations may be empirically modeled by an Arrhenius type expression as

$$C = C_0 e^{-Mt} \quad (6-1)$$

where  $C$  = concentration at time,  $t$ ;  $C_0$  is the initial concentration; and  $M$  is an empirical constant.

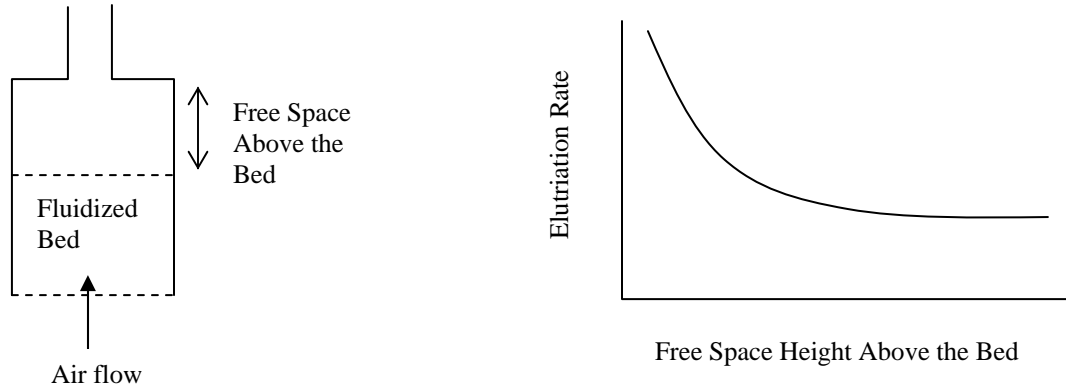


Figure 6-1. Elutriation Rate (total mass/time) vs the free space height above the bed. A fluidized bed behaves similar to a mixture of liquids with different volatilities. In the liquid-liquid mixture, the more volatile material leaves the mixture at the lower boiling temperature.

By analogy with boiling of liquid mixtures, finer particles have a lower boiling temperature than larger particles. The boiling temperature is analogous to the fluidization velocity. The higher the velocity, the greater the rate at which the low boilers will leave the bed. The free space height above the bed serves as a condenser, to cool and slow down the elutriated particles and return them to the mixture. The greater the boiling rate, the greater capacity that is needed of the condenser, hence the greater free space height.

Not all elutriation bad. Sometimes elutriation can be helpful. For example, elutriation may be used to remove dusts or very fine particles from coarser particles.

### 6.1 Definition of Terms

Lets define some terms that we can use to describe the elutriation process.

The flux of solids carried out of the top of the column is called entrainment,  
 $G_s$  [kg/m<sup>2</sup>/s]

The bulk density of the solids in the exiting gas stream is called the holdup.  
 $\rho^0$  [kg/m<sup>3</sup>]

We note that the entrainment is related to the holdup and the superficial velocity by

$$G_s = \rho^0 V_o \quad (6-2)$$

Free Board Height,  $H_f$ , is defined to be the measure of the free space above the boundary between the dense phase and the lean phase (Figure 6-3).

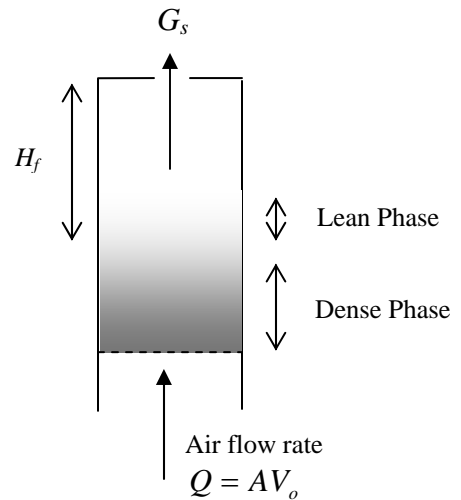


Figure 6-2. Fluidized bed with flux rate  $G_s$ .

For design, we need to know the rate of entrainment and the size distribution of the entrained particles in relation to the size of the particles in the bed. A fluidized bed usually has two regions or phases: dense bubbling phase and lean dispersed phase (Figure 6-2).

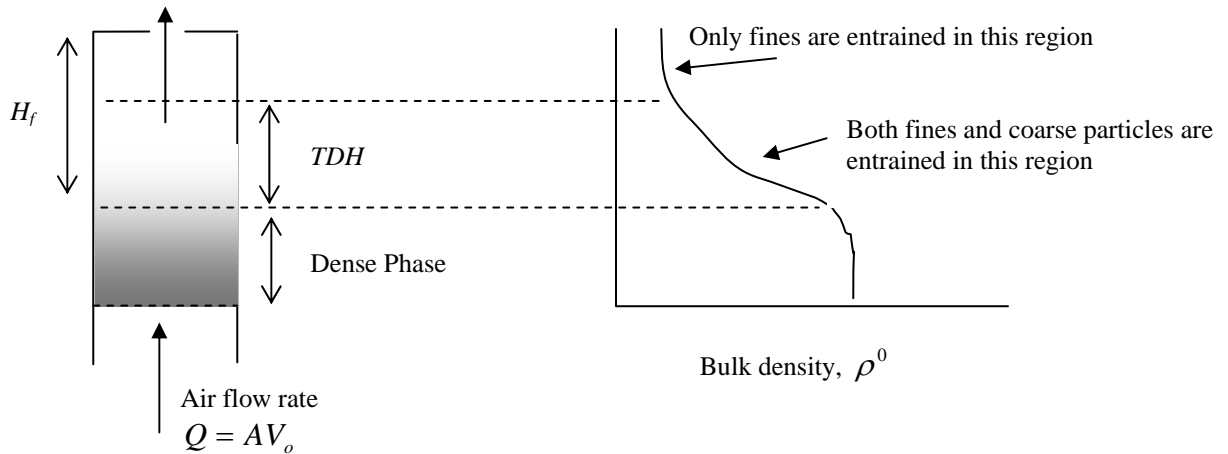


Figure 6-3. Both fines and coarse particle are entrained in the Transport Disengagement Height (TDH) region. Above the TDH only fines are entrained.

The Transport Disengagement Height (TDH) is the height above the dense-phase/lean-phase boundary above which entrainment and bulk density do not change appreciably. *TDH* depends upon the superficial velocity and the particle properties. The *TDH* is the height at which the kinetic energies of particles due to the collisions in the bed has been expended against gravity potential, and the coarse particles whose terminal velocities are greater than the superficial velocity are able to fall back down to the bed. The fine particles, whose terminal velocities are less than the superficial velocity, continue to be entrained out of the column.

When  $H_f > TDH$  then the holdup and entrainment rates are close to their minimums. Usually  $H_f = TDH$  is the most economical design height for the fluidized bed. If  $H_f < TDH$  then coarse particles will be carried out of the column.

## 6.2 Estimation of TDH for Geldart A Particles.

For beds of fine particles (Geldart A classification, see Fluidization notes 5) there are several methods discussed in literature. Kunii and Levenspiel give a good review of this literature. In these notes you are only given a brief introduction.

METHOD 1. Zenz and Weil (*AICHE J.* 4, 472, 1958) proposed a correlation between dimensionless TDH and the vessel diameter. For catalyst pellets in 20 to 150 micron size range, on a log-log plot, the relation between the dimensionless TDH and the vessel diameter are nearly linear (see Kunii and Levenspiel Figure 5 page 173) as indicated in Figure 6-4.

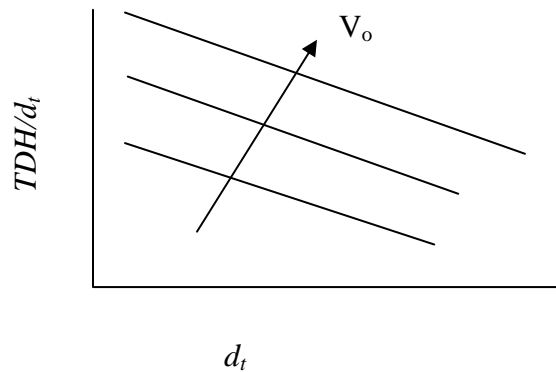


Figure 6-4. Dimensionless TDH/ $d_t$  vs vessel diameter,  $d_t$ .

We can model the data on the chart in the form of

$$\text{Log}(TDH / d_t) = m\text{Log}(d_t) + \text{Log}(b) \quad (6-1)$$

where  $d_t$  is the vessel diameter.

Taking data points from the chart and plotting them we can curve fit to find the parameters  $m$  and  $b$ :

$$m = -0.115V_o - 0.587 \quad (6-2)$$

$$b = 4.64V_o \quad (6-3)$$

Finally, we take the above equations and try to compress the chart by plotting the dimensionless TDH/ $d_t$  versus the Froude Number,  $F_r = V_o^2 / d_t / g$  to get the plot shown in Figure 6-5. (HANDOUT 6.1)

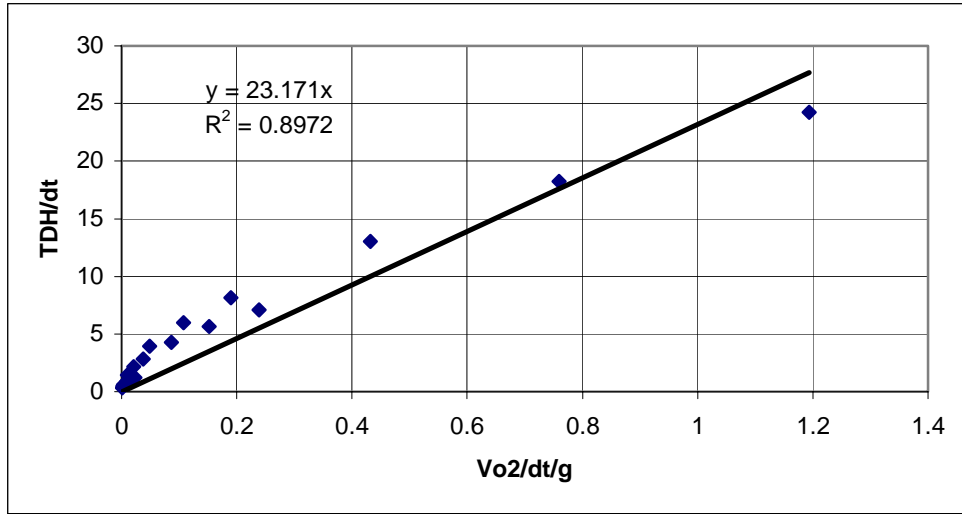


Figure 6-5. Dimensionless  $TDH/d_t$  versus Froude Number.

If we take the linear fit in Figure 6-5 to represent the material behavior, then we can relate

$$\frac{TDH}{d_t} = 23.171 \frac{V_o^2}{d_t g} \quad (6-4)$$

or, upon rearrangement, we get

$$\frac{V_o^2}{TDH g} = \text{constant} = 0.0432 \quad (6-5)$$

The constant in Eq.(6-5) is likely to be material specific. Fournol *et.al.* (*Can. J. Chem. Engr.*, **51**, 401, 1973) independently determined, for a fluidized bed of fine catalyst particles,  $d_p=58$  microns, the TDH for this material to be given by

$$\frac{V_o^2}{TDH g} = 0.001 \quad (6-6)$$

### 6.3 Entrainment Rate from Tall Vessels

There are several methods for estimating entrainment rates. Following the work by Zenz *et.al.* (*AIChE J.*, **4**, 472, 1958; and *Fluidization III*, Grace & Matsen, eds., Plenum, N.Y. 1980) we assume that the flux rate of solid size  $d_{pi}$  is proportional to its mass fraction,  $x_i$ ,

$$G_{si} = x_i G_{si}^* \quad (6-7)$$

where  $G_{si}^*$  is the flux rate from an imaginary bed of all particles of size  $d_{pi}$ . This approach extends the analogy between fluidized beds and boiling of a liquid mixture (discussed in the introduction to Section 6). Raoult's Law for an ideal fluid mixture (R.E. Balzhiser, M.R. Samuels, and J.D. Eliassen, *Chemical Engineering Thermodynamics*, Prentice Hall, Englewood Cliffs, New Jersey, 1972) equates the partial pressure of component  $i$  in the vapor phase to the mole fraction in the liquid phase times the pure fluid vapor pressure.

$$P_i = x_i P_i^* \quad (6-8)$$

hence, the flux rates are analogous to the vapor pressures.

The procedure to determine the flux rate from a bed with known particle size distribution is as follows:

1. Divide the size distribution into narrow intervals and find which intervals have terminal velocities greater than the superficial velocity (these are the particles that are entrained, because  $H_f < TDH$ ).
2. Find  $G_{si}^*$  for each size range.
3. The total entrainment is given by

$$G_s = \sum x_i G_{si}^* \quad (6-9)$$

In terms of a continuous size distribution,  $P(d_p)$ , the total entrainment rate is given by

$$G_s = \int G_{si}^* P(d_p) dd_p \quad (\text{integration over all particles entrained}) \quad (6-10)$$

To apply this procedure, a correlation such as shown in Figure 6-6 is required to find  $G_{si}^*$ .

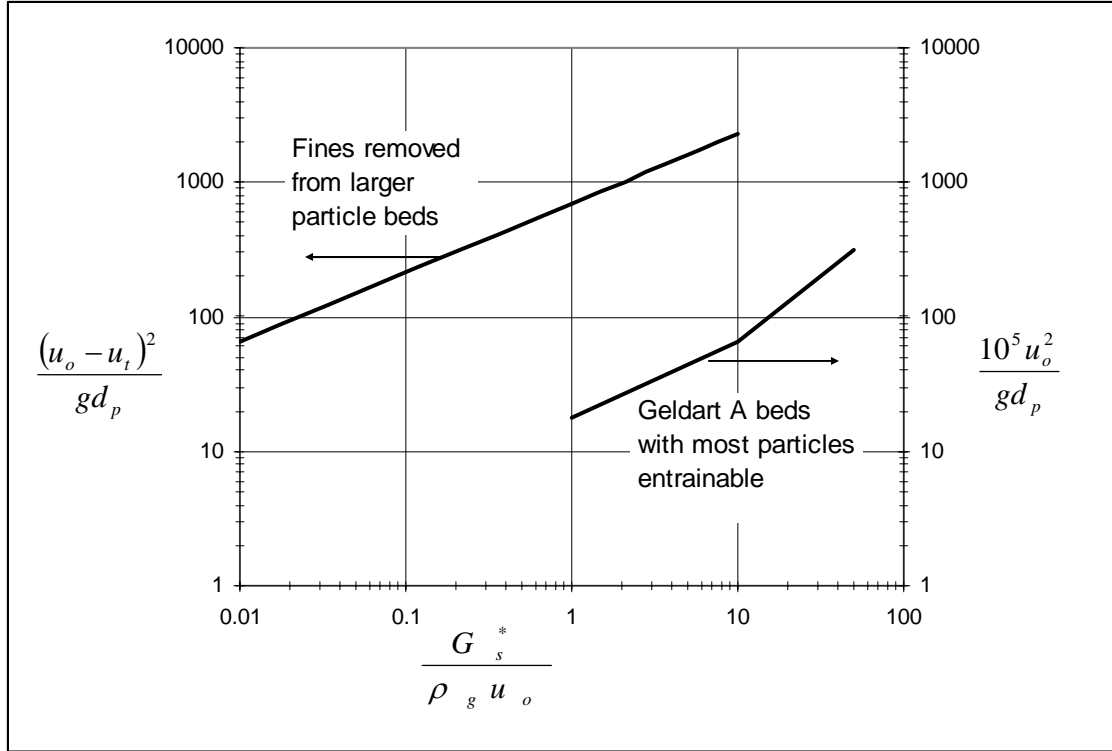


Figure 6-6. Data taken from Kunii & Levenspiel, *Fluidization Engineering*, 2ed, Butterworth, Boston, 1991 (figure 6 page 175). From this plot the value of  $G_s^*$  may be determined for Geldart A particles and for fines removed from larger particle beds.

For Geldart class B, C, or D particles (the larger particles) other predictive models are available. Recommended references:

- Kunii and Levenspiel (*J. Chem. Eng. Japan*, **2**, 84, 1969)
- Lewis *et. al.* (*Chem. Eng. Prog. Symposium Series*, **58** (38), 65, 1962)
- Wen and Chen (*AIChE J.*, **28**, 117, 1982)
- Kunii and Levenspiel (*Fluidization Engineering*, 2ed, Butterworth, Boston, 1991).