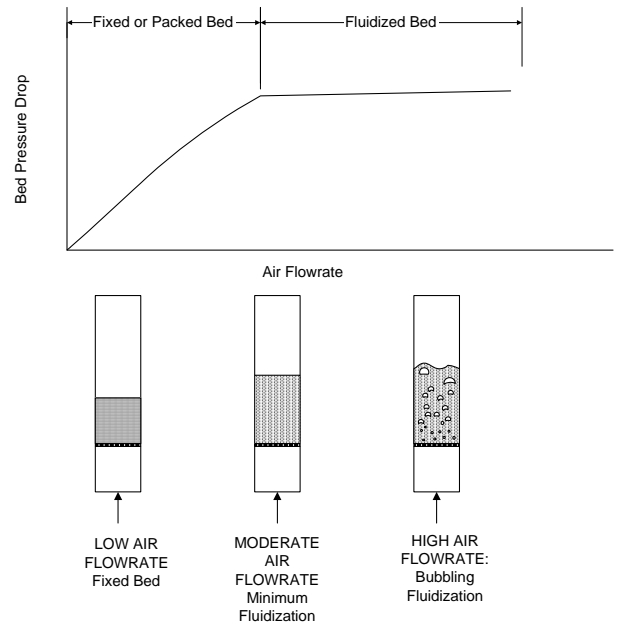# Fluidization
by
by Robert P. Hesketh[1]

Prepared for the Process Fluid Transport

Objectives
1) Examine the flow regimes of a fluidized bed.
2) Measure pressure as a function of flowrate through a bed of particles that are not constrained.
3) Determine minimum fluidization from experimental data and compare this with theoretical predictions.

Fluidization Fundamentals

In fluidization, a gas or liquid is passed through a bed of solid particles which is supported on a perforated or porous plate. In the case of fluidized bed coating, air is passed through a bed of polymer particles. When the frictional force acting on the particles, or pressure drop, of the flowing air through the bed equals or exceeds the weight of the bed, the powder particles become suspended and the bed exhibits liquid-like behavior. As shown in the figure below, at gas flowrates less than the fluidization velocity, the bed is a fixed bed and there is no movement of particles. At flowrates above minimum fluidization the bed expands and bubbles appear.

Figure 1: Overview of Fluidization

The air velocity corresponding to a pressure drop that just equals the weight of the bed is referred to as the minimum fluidization velocity. At this air velocity or flowrate all of the bed particles are completely suspended by the air stream. For a given system, minimum fluidization velocity can be determined from a pressure drop vs. air velocity diagram.

As air flow is increased above the minimum fluidization velocity, the bed may exhibit behaviors ranging from smooth fluidization to bubbling fluidization to dilute fluidization in which powder can be transported by the air stream. Smooth fluidization is desirable for optimal performance in the powder coating process.

The liquid-like nature of the fluidized powder bed allows for high heat and mass transfer rates between the gas phase and the solid phase. As a result many applications for fluidization are utilized as given in Table 1.

Table 1: Industrial Applications of Fluidized Beds

Polymeric Materials	- gas phase polymerization of polyethylene - production of silicon for the semi-conductor industry
Biochemical	- cultivation of microorganisms for the food and pharmaceutical industries
Chemical Synthesis	- phthalic anhydride - Fischer-Tropsch synthesis of hydrocarbons - acrylonitrile, maleic anhydride, activated carbon, calcination, roasting of sulfide ores, chlorination, reduction,
Petroleum Processing	- fluid catalytic cracking (FCC) for production of gasoline from oil - coal gasification - thermal cracking of naphtha petroleum fractions to produce ethylene and propylene - fluid coking
Combustion	- coal combustion - solid waste incineration - steam raising
Physical Operations	- coating metal objects - drying of solids - adsorption of solvents

Fluidization regimes

Geldart[2] classified the fluidization of particles into four groups which are used extensively in the industry. The following are the major groups:

Group A Small particle size or density less than 1.4 g/cm^3. Easily fluidized with smooth fluidization at low gas velocities and controlled bubbling with small bubbles at higher gas velocities. When fluidized by air at ambient conditions, result in a region of non-bubbling fluidization beginning at U_{mf} , followed by bubbling fluidization as fluidizing velocity increases. Gas bubbles rise faster than the rest of the gas. Major example is the FCC catalyst.

Group B are sand like powders which result in vigorous bubbling fluidization under these conditions. Bubbles form as soon as the gas velocity exceeds the minimum fluidization velocity. Majority of gas-solid reactions occur in this regime based on particle size of raw materials.

Figure 2: Spouted Bed

Group C cohesive, or very fine powders. Normal fluidization is difficult for these solids because of interparticle forces that are greater than those resulting from the action of the gas on the particles. In small diameter beds these particles form a plug of solids that rises upward. powders - very fine, cohesive powders which are incapable of fluidization in the strict sense. Examples: Face powder, flour, and starch.

Group D spoutable, large and/or dense particles as shown in Figure 2. Examples include drying grains, peas, roasting coffee beans, gasifying coals and roasting of metal ores.
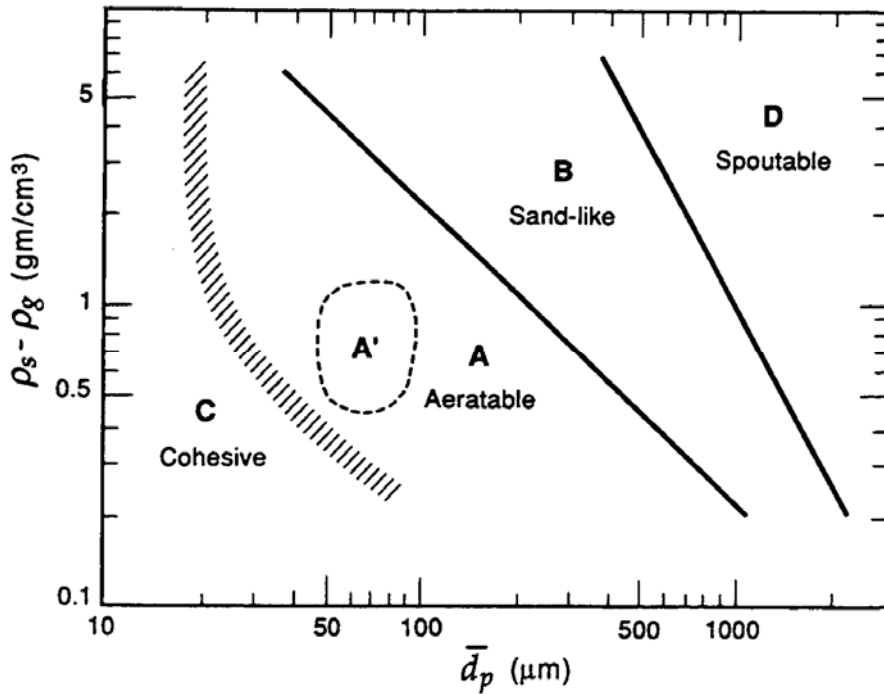
Figure 3: Geldart Classification of Particles for air at ambient conditions[3] Region A' is a range of properties for well-behaved Fluidized Catalytic Cracking (FCC) catalyst

The minimum fluidization velocity can be predicted by relating the weight of the bed of solids to the force created by the pressure acting over the cross-sectional area of the bed.

$$\Delta P A_c = W = A_c L_{mf}(1 - \varepsilon_{mf})(\rho_s - \rho_g)g$$

The difficulty in using this equation is that the minimum fluidization void fraction, ε_{mf}, is a complex function of the diameter of the particles, shape and type of particles. A good equation that can be used to predict the minimum fluidization velocity from Wen and Yu[4] is

$$Re_{p,mf} = [(33.7)^2 + 0.0408Ar]^{0.5} - 33.7$$

Where

$$Re_{p,mf} = \frac{D_p v_{mf} \rho_g}{\mu}$$

And the Archimdes or Galileo Number is the ratio of the force of gravity to the viscous force

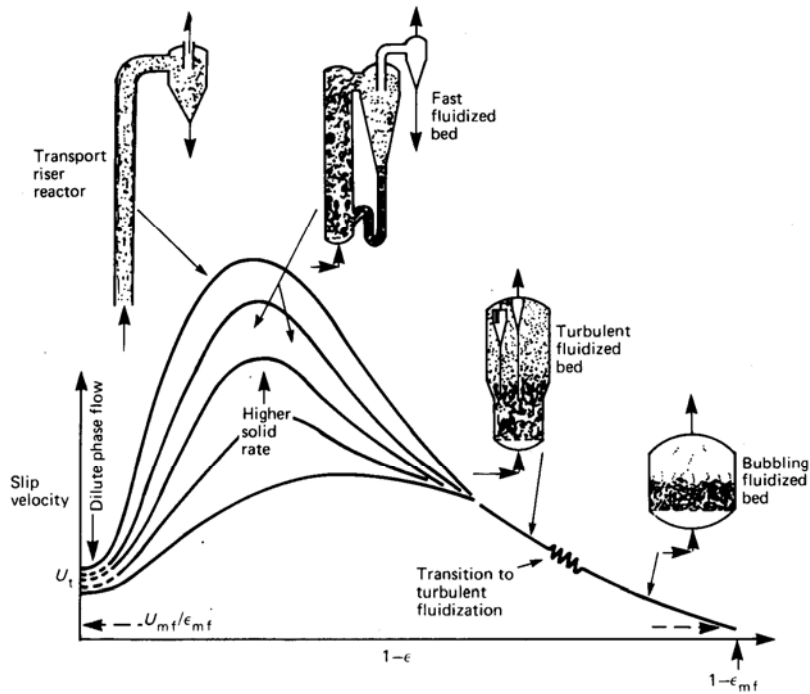$$Ar_{p,mf} = \frac{D_p^3 \rho_g (\rho_s - \rho_g)g}{\mu^2}$$

3

Figure 4: Depiction of Fluidization Regimes and corresponding Reactor Types. The slip velocity on the y-axis is defined as $u_{slip} = u_o/\varepsilon - u_{particle}$ [3]
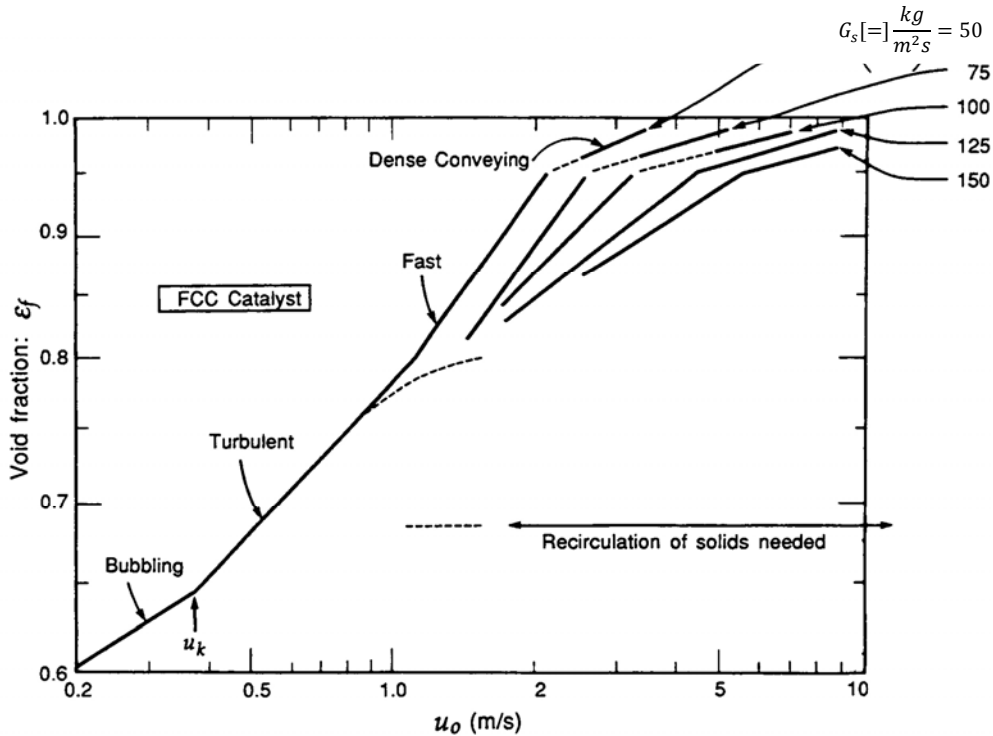

Figure 5: A mapping of the fluidization regimes for a FCC Catalyst. This graph shows that the void fraction increases with increasing superficial velocity. The gas superficial velocity is u_o and ε_f is the gas voidage. [5]

In this experiment you will see that at low superficial velocities the bed will remain as a packed bed. With increasing velocity the bed will expand and then bubbles will appear as shown in Figure 6 from Rowe[6]. The value of u_k is the superficial gas velocity at the turbulent regime. At higher velocities a regime labeled fast fluidization occurs. In this regime particles are recirulated from the top of the column back into the bottom of the column. This is a typical operating regime for a fluidized catalytic cracker riser tube. In the riser tube the hydrocarbon is cracked with the aid of the catalyst, but quickly becomes deactivated as a result of carbon deposits on and within the catalyst. The catalyst is regenerated by burning off the carbon in an air fluidized bubbling bed.
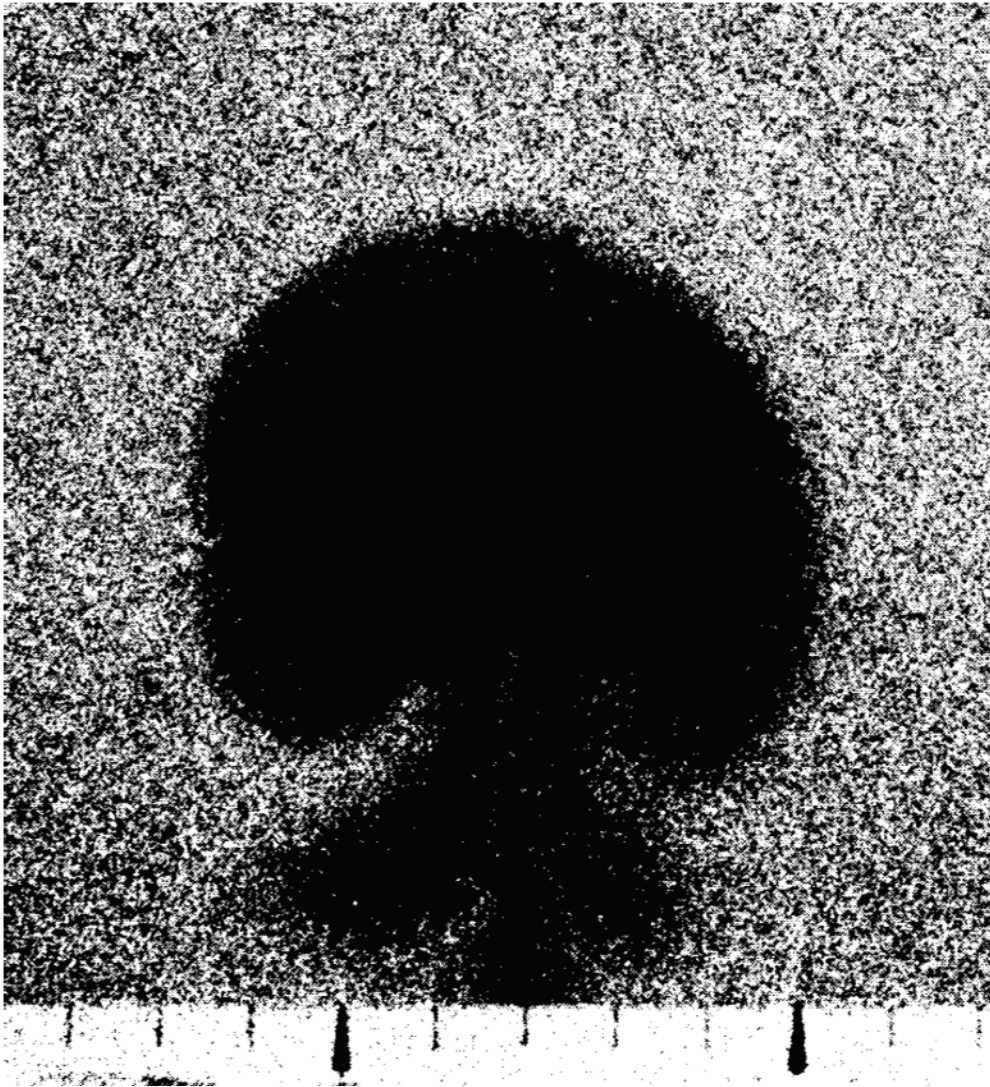
Figure 6: A 2-dimensional bubble from Rowe[6]

The dimensionless numbers shown in Figure 7 are defined as:

$$d_p^* = \left(Ar_{p,mf}\right)^{1/3} = D_p \left(\frac{\rho_g(\rho_s - \rho_g)g}{\mu^2}\right)^{1/3}$$

$$u^* = u\left(\frac{\rho_g^2}{\mu(\rho_s - \rho_g)g}\right)^{1/3} = \frac{Re_p}{\left(Ar_{p,mf}\right)^{1/3}}$$

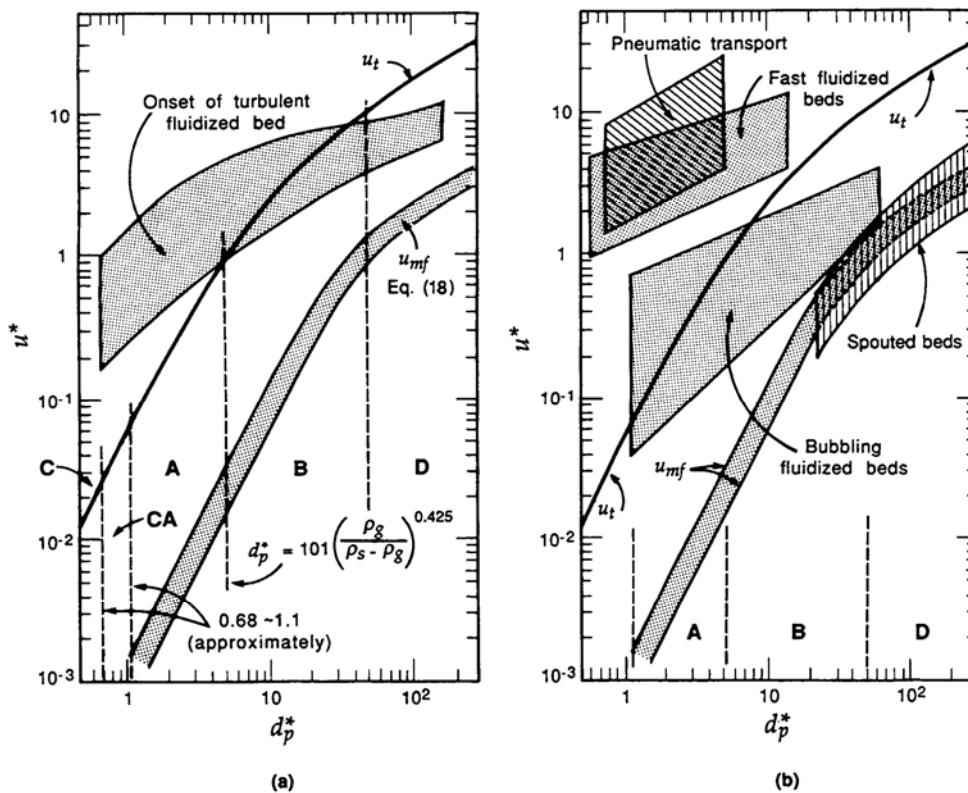$$Re_p = \frac{D_p u_o \rho_g}{\mu}$$

Figure 7: General Flow regime diagram originally developed by Grace using coordinates first presented by Zenz and Othmer. The letters C, A, B and D refer to the Geldart classification given in Figure 3.[5]
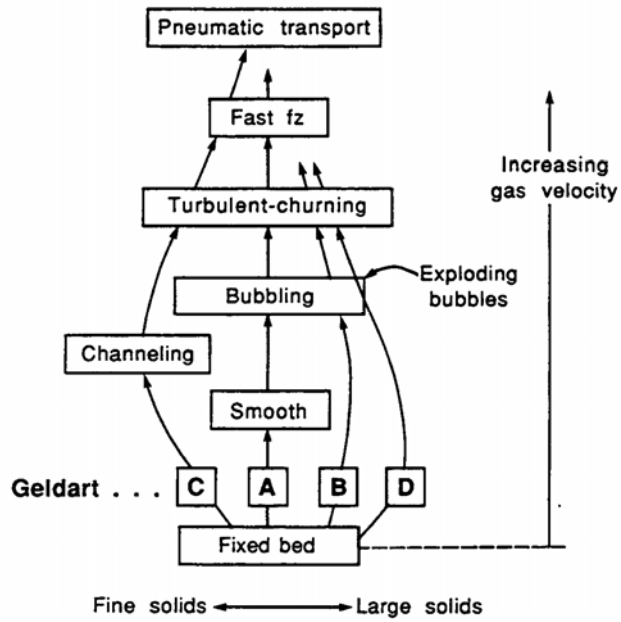
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Figure 8: Flow chart of the progression between flow regimes for the Geldart classification of particles.[3]
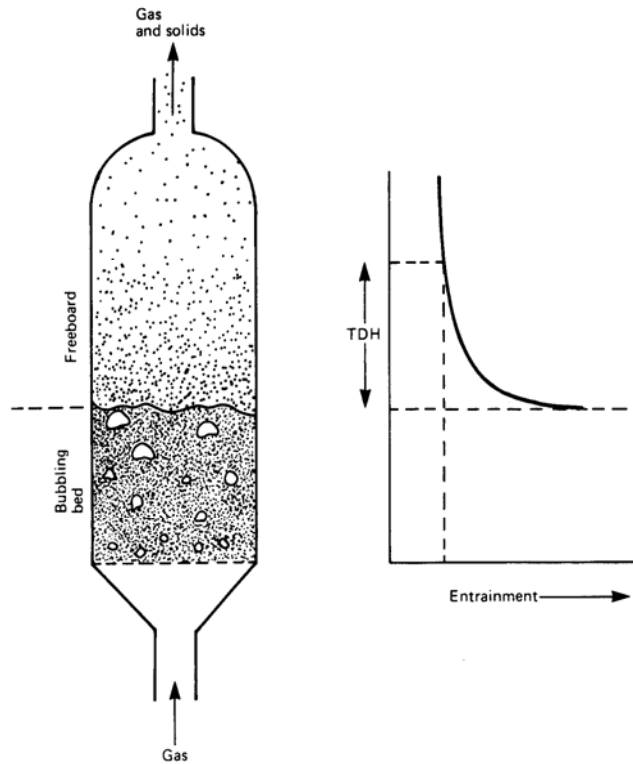

Figure 9: Bubbling Fluidized Bed with entrained particles in the freeboard region above the dense bubbling bed. Transport disengaging height (TDH) is the zone required for particles with terminal velocities less than the gas velocity to fall back to the bubbling bed.[3]

Figure 8 gives a flowchart of the progression through regimes for each of the Geldart classified powders. This chart is an excellent summary of the possible paths through particulate regimes as the velocity of the fluidizing gas is increased within the bed.

One of the great advantages of a fluidized bed is the high heat and mass transfer rates that are generated compared to that in a gas only or packed bed. In Figure 10 it is demonstrated that the rate of heat transfer can be increased at least 12 times higher than that of a packed bed. This is a great advantage for chemical processing as well as heating of fluids.
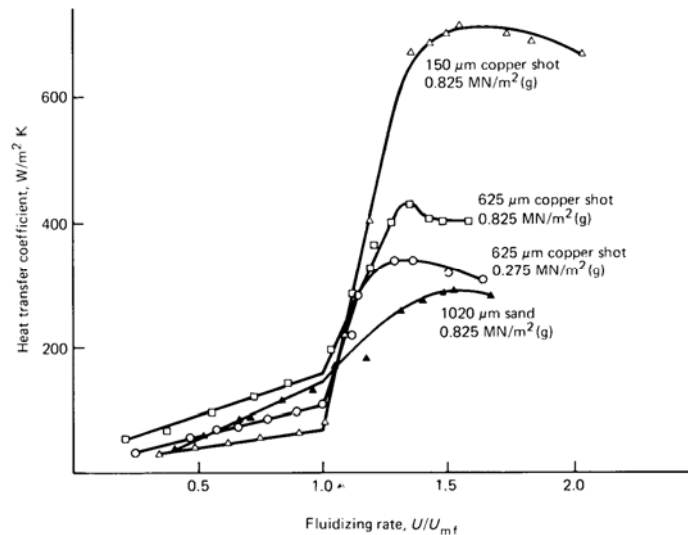
**Figure 10: This figure shows how the heat transfer coefficient between a bed of particles and a solid surface such as a boiler tube increases with increasing gas velocity.[3]**
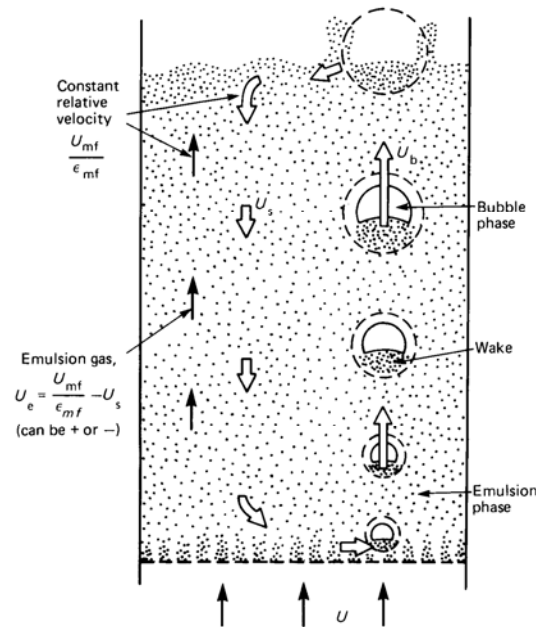
Figure 11: Fluid Flow Pattern within a bubbling bed. The rising bubbles move both gas and particles upward as well as a corresponding flow of particles downward. This movement within the bed creates an intensive mixing of the particulate phase.[3]
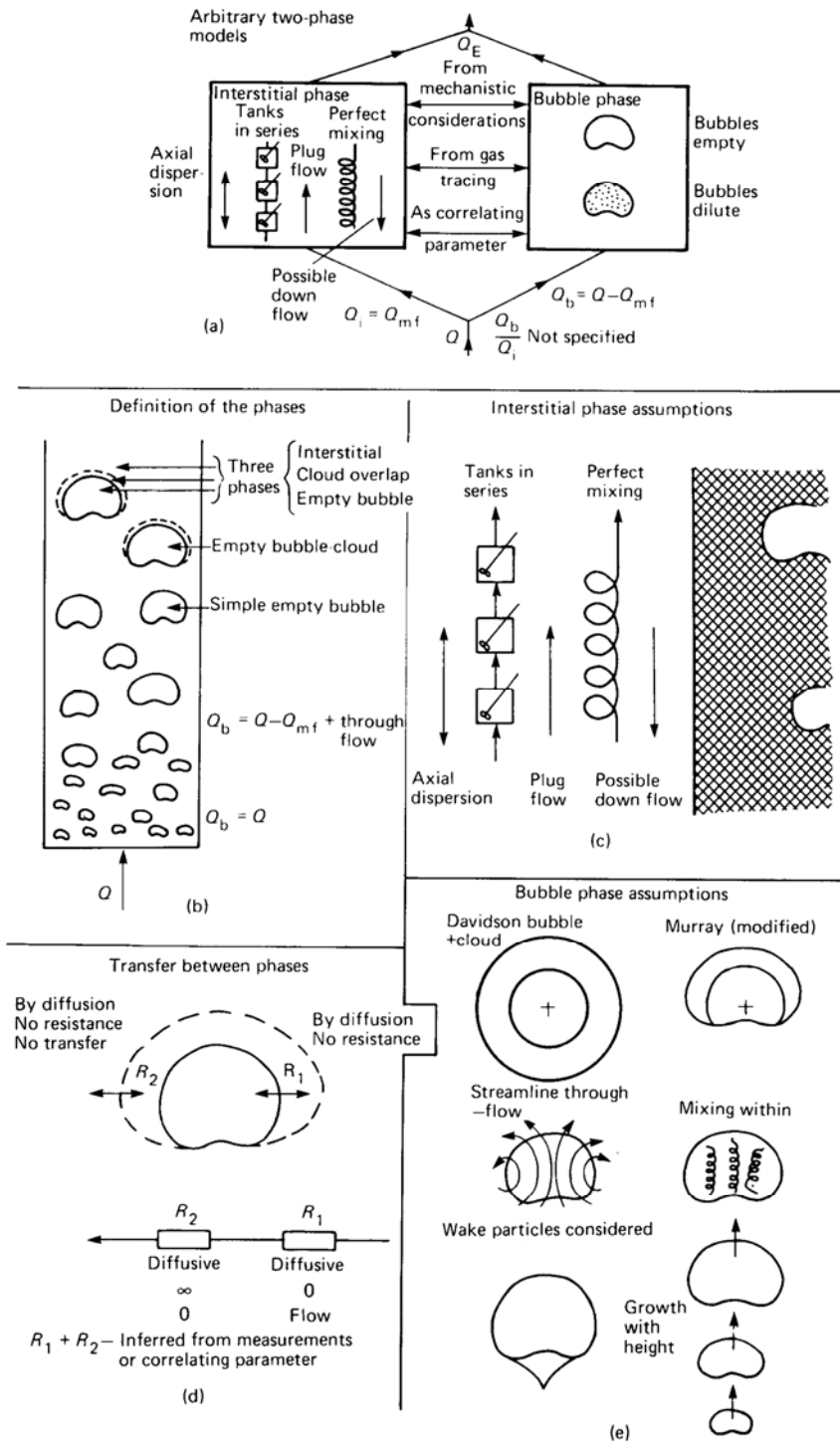
Figure 12: Summary of essential concepts of the reactor models for fluidized beds[3]

Figure 12 shows the basic fundamentals of fluidized bed models. The simplest model of a bubbling fluidized bed will be employed in your chemical reaction engineering course in which you will assume that the bubbling bed is a well-mixed reactor. This is a reasonable approximation of a fluidized bed, but there are many more complicated models that can be seen in the above figure.

Experiment - Safety

1. Safety goggles or glasses are required since there is a possibility of fine powder and line breakages entering the eyes of the participants.
2. The polymer powder used in the coating process is very fine and will produce dust. Loading of the fluid bed column should be done in a hood. A paper towel should be secured over the top of the column when operating at high air flow rates where entrainment of the powder can occur.
3. Observe normal laboratory safety practices.

Relevant Data
Coating Material: Functionalized polyethylene copolymer based powder
Polymer Density = $\rho = 0.934$ g/cm^3
Polymer Melting Point = 221°F or 105°C

Required Equipment:

Fluidized Bed Unit with Polyethylene Porous Distributor and drop mechanism
Rotameter connected to air supply
Polyarmor Powder - PFS Thermoplastic Powder Coatings (functionalized polyethylene copolymer-based powder coating)
Stopwatch
U-Tube Manometer

Familiarization with equipment:
1) Observe the fluidized bed set-up and identify the following components: (use the adjacent figure as a guide).
    a) Air pressure regulator
    b) Pressure gauge
    c) Air supply valve
    d) Air flowmeter (rotameter) and valve
    e) Air plenum of fluidized bed (empty chamber below distributor plate)
    f) Air distributor plate
    g) Polymer particles
    h) Manometer for differential pressure readings. Identify the connection points of the clear plastic tubing with the fluidized bed.
    i) Before proceeding check your identification of components with the graduate assistant or professor.
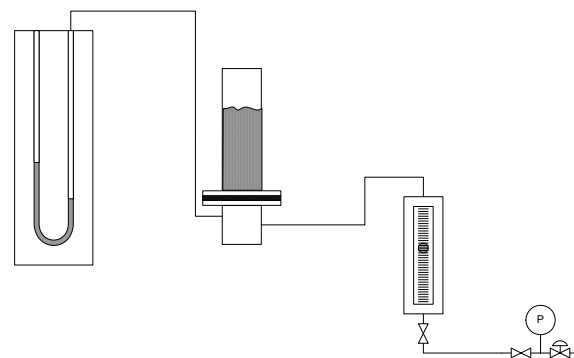

Figure 13: Fluid Bed Apparatus

2) Reproduce the data table shown on the last page. See the first page for instructions on placing information in the laboratory notebook.
3) Secure a Kim Wipe (paper tissue for chemical laboratories) with a rubber band over the top of the column to prevent any of the Polyarmor powder from blowing out of the column during the following exercise.

4) Adjust the pressure regulator (pull out yellow ring and turn to adjust, push in to lock) to read 20 psig on the pressure gauge and open the air supply valve (Turn the valve until it is all the way on, then twist it back once).

5) **Investigate Fluidization**: Slowly turn on the air using the rotameter valve and observe the fluidization regimes shown in Figure 1 given above. Write down your general observations in your laboratory notebook. Make sure that you have observed the bubbling fluidization regime. You may need to gently rock the bed to free the static forces between particles. Slump the bed by turning the air flow off. Temporarily remove the Kim Wipe from the top of the bed. Holding a ruler in the bed feel the difference between unfluidized and fluidized particles. Replace the Kim Wipe on the top of the column. Record your observations.

6) **Fluidization Curve**: Obtain a pressure drop data for a fluidization curve by measuring the pressure at flowrates that cover the range shown in Figure 1. At each flowrate measure and record the height of the bed

7) **Plot a fluidization curve**. From your data you will need to subtract the pressure drop across the porous polypropylene distributor plate to obtain the pressure drop across only the bed of particles. Using the corrected pressure drop data construct a plot as shown in Figure 1. On this curve you will superimpose two lines. One line will fit the data for flow through a packed bed. The second line will be a fit of the data for a fully fluidized bed which is a nearly horizontal line. The intersection of these two curves is the minimum fluidization velocity.

8) **Calculate** an average particle size using the measured fluidization velocity and the equation for minimum fluidization.

9) **Make a plot of bed height as a function of flowrate.** Make an additional comparison plot showing both the pressure drop and the bed height as a function of flowrate.

To be submitted Next week. (One per group)
1. Observations of the fluidization of polyethylene particles. At the minimum, comment on the height of the bed, the bubbles that are formed and the overall motion of the solid particles.
2. Plot of fluidization curve with the identification of the minimum fluidization velocity. Second plot showing both the pressure drop and the height of the bed as a function of flowrate.
3. Calculation of the average particle size.
4. Calculate the terminal velocity of these particles using the equations given in section 6.13 of de Nevers. Show all of your work. Give the particle Reynolds number, the drag forc coefficient and the equation that was used. You should use Figure 6.26 as a guide, but back up your terminal velocity using the appropriate equations.
5. Make a determination of the Geldart Particle regime for the particles in your fluidized bed based on Figure 3 and your observations.
6. Comment on the superficial velocity that would be required to operate a bed filled with these particles in the turbulent, fast and transport fluidized regimes.

Table 2: Data Table for Experiment

Flowmeter Reading (scale reading)	Distributor Plate + Bed Pressure Drop (in H_2O)	Bed Expansion (from zero air flow) (inches)
0		
5		
10		
15		
20		
30		
40		
50		
60		
70		
80		
90		
100		
110		
120		
130		
140		

Notes:

[1] Students that contributed to this project since its inception are Michael Carney, Robert Schwenck and Abby Post

[2] Geldart, D., Powder Tech., **7** 285 (1973)

[3] Yates, J. G. Fundamentals of fluidized-bed Chemical Processes, Butterworths, London, 1983.

[4] Wen, C.Y. and Y.H. Yu, AIChEJ, **12** 610 (1966).

[5] Kunii, D. and Levenspiel, O.: *Fluidization Engineering*, 2nd Ed., Butterworth-Heinemann, Boston, 1991

[6] Rowe, P. N.Chem Eng Prog 60(3)75 (1964)