Department of Chemical and Biomolecular Engineering
University of California, Irvine

CBE 140A: Packed Beds and Particle Drag

1 Introduction

Packed beds are unit operations where a fluid, either a gas or liquid, is forced through a bed of solid particulate matter; typical industrial applications utilize a heterogeneous catalyst as a solid with the fluid-phase reactant being flown through the catalytic bed. This technology is used in fluidized catalytic crackers (FCCs), the production of acrylonitrile and polyethylene, Fischer-Tropsch synthesis, and more. [1, 17-17]. The behavior of fluid flow through a solid, from a mechanistic perspective, is closely connected to the phenomenon of particle drag. This experiment will provide opportunity to characterize the behavior of packed beds as well as the drag force acted on particles falling through liquids.

2 Objective

This apparatus consists of two cylindrical beds which can be loaded with one of two varieties of solid packing material. Each bed is equipped to flow water or air through the packed bed. The changes height and pressure drop across the bed, as well as the point of fluidization, will be observed while controlling the type of fluid, flow rate, type of packing, and amount of packing. Particle drag will be investigated by dropping objects of various shapes, sizes, and materials in static columns of water and glycerol and observing their terminal velocities.

3 Theory

Packed beds can be separated into two regimes, based on their behavior under flow: as a fixed or fluidized bed. At low flow rates, the fluid will be able to follow tortuous paths around the solid particles with minimal forces exerted and no movement of the solids. Beyond a critical flow rate, the bed will begin to churn and fluidize, the gas or liquid forming bubbles as it moves through the particulate matter. Continuing the flow rate further still, the fluid would have the ability to entrain the solids, resulting in pneumatic transport. An illustration of these flow regimes can be found in Figure 17-4 of [1].

A well-known empirical method for determining the pressure drop in a fluid flow across a fixed bed is known as the Ergun Equation:

$$\frac{\Delta P}{L} = \frac{150\mu(1-\varepsilon)^2 V}{D_p^2 \varepsilon^3} + \frac{1.75(1-\varepsilon)\rho_{\text{fluid}} V^2}{D_p \varepsilon^3} \tag{1}$$

where ΔP = pressure drop as a result of flow through a fixed bed,
L = the length or, for this experiment, height of the fixed bed,
ε = the bed void fraction,
μ = fluid viscosity,
V = fluid superficial velocity,
D_p = average particle diameter, and
ρ_{fluid} = fluid density.

The definition for a solid void fraction is the ratio of empty volume between the solid particles to the total volume of the bed. Conversely, $1 - \varepsilon$ is the ratio of volume occupied by solids to total bed volume. The superficial velocity is defined as the ratio of the fluid volumetric flow rate to the total cross sectional area of the bed. Equation 1 can be simplified to the first term at low flow rates, often referred to as the Kozeny-Carman equation, or to only the second term at high flow rates, often referred to as the Burke-Plummer equation. An entirely separate empirical model for pressure drop in fixed beds is the Leva equation, given in [1] as Equation 6-166.

As the force exerted on the bed increases (calculated as the pressure drop multiplied by the bed's cross-sectional area), eventually this will exceed the total weight of the bed. Since the particles can independently move, further increase in fluid flow results in bed fluidization, which can be thought of as spatial and temporal fluctuations in the void fraction. As bubbles of fluid form in the solid, the local void fraction increases, decreasing the local pressure drop. The end result is a bed that, upon fluidizing, will increase its average porosity (and equivalently, its height) at a constant pressure drop with further increase in fluid flow. The equation describing pressure drop in fluidized beds depends on whether flow is laminar or turbulent. Air beds are likely laminar, resulting in the following equation,

$$\Delta P = gL(1-\varepsilon)(\rho_{\text{particles}} - \rho_{\text{fluid}}) = \frac{150\mu(1-\varepsilon)^2 VL}{D_p^2 \varepsilon^3} \tag{2}$$

whereas fully turbulent flow in a fluidized bed, as is likely the case with water, instead results in the following relation.

$$\Delta P = gL(1-\varepsilon)(\rho_{\text{particles}} - \rho_{\text{fluid}}) = \frac{1.75(1-\varepsilon)\rho_{\text{fluid}} V^2 L}{D_p \varepsilon^3} \tag{3}$$

Variables introduced in these equations include g, gravitational acceleration, and $\rho_{\text{particles}}$, the density of the solid particles. Note that for fluidized beds pressure drop, the left-hand side of the equation, is constant. For the terms on the right-hand side to remain constant, variations in the bed height, void fraction, and superficial velocity must negate each other. More specifically, as the velocity increases, the bed height will increase and the void fraction will also increase in a nonlinear fashion. More detail is available in chapter 11 of [2].

The other phenomenon at play in this experiment is particle drag. Described further in the laboratory protocol, the terminal velocity of a dense solid falling through a liquid will provide a basis for characterizing particle drag. To begin, terminal velocity implies an unchanging velocity, therefore no acceleration, therefore no net force. Summing all forces acting on a falling particle, we include gravity, buoyancy, and drag:

$$\sum F = 0 = F_g + F_b + F_D \tag{4}$$

Note that here I am summing forces as vectors; for our system, gravity acts downward while the other two forces act upward—be careful with your signs!

Substituting the relevant equations in, we can find the following:

$$0 = m_p g - \frac{m_p g \rho_l}{\rho_p} - \frac{C_D \rho_l A_p V^2}{2} \tag{5}$$

Where new variables consist of ρ_l, the fluid density, the particle mass m_p, the (dimensionless) drag coefficient, C_D, and A_p, the projected area of the particle in the plane perpendicular to the direction of particle movement. For a sphere, this area is simply $0.25\pi D_p^2$.

From the force balance, the drag coefficient can be determined from empirical data. Solving for this term results in:

$$C_D = \frac{2m_p g(\rho_p - \rho_l)}{\rho_p \rho_l A_p V^2} \tag{6}$$

The question, then, is whether the drag coefficient can be predicted, and what it could be dependent upon. Luckily enough, this is a well-explored field of study. For rigid spherical particles, at low Reynolds numbers (identical to the usual definition with the particle diameter used as the characteristic length-scale), Stokes' law concludes:

$$C_D = \frac{24}{Re} \quad \text{for} \quad Re < 0.1. \tag{7}$$

For intermediate turbulence, the following equation can estimate the drag coefficient:

$$C_D = \left(\frac{24}{Re}\right)\left(1 + 0.14 Re^{0.70}\right) \quad \text{for} \quad 0.1 < Re < 1{,}000. \tag{8}$$

Beyond this regime, Newton's law predicts a relatively constant $C_D = 0.445$ up to a Reynolds number of 350,000. Beyond this regime, weird stuff happens which is more relevant to aerodynamics courses—for our purposes, we'll leave that material for another time. These predictions are summarized in Figure 6-57 of [1].

4 Experimental Apparatus

Figure 1 illustrates the equipment used to study packed beds and particle drag. From left to right, there is a water packed bed (5), an air packed bed (11), a column of glycerol (18), and a column of water (19).

The liquid packed bed has a reservoir of water (1) connected to a pump (2) which, when plugged in, introduces flow through the system. Flow rate is metered (4) and controlled with a valve (3) before flowing through the bed (5), eventually returning to the reservoir through an overflow opening at (6). A digital manometer (7) can measure the pressure differential between the top and bottom of the column. Ensure both points are submerged in water and fixed in place to increase the accuracy of your measurements.

The gas packed bed introduces air into the system with a compressor (8) which can be powered on with a switch (not shown). Air flow is controlled with the valve (9) and metered with the flow meter (10) before passing through the bed (11) and eventually reentering the room (12). A fluid manometer (13) allows measurement of the pressure differential across the bed. Two types of packing material are available for study: fine and coarse ballotini, spherical particles with average diameters of 267 and 485 micrometers, respectively.

Both particle drag columns are identical except that one is filled with glycerol (18) and the other contains water (19). A motorized bucket (15) can be filled with the particle to be studied. Its position can be manipulated with its control switch, (14), allowing the particle to be dropped into

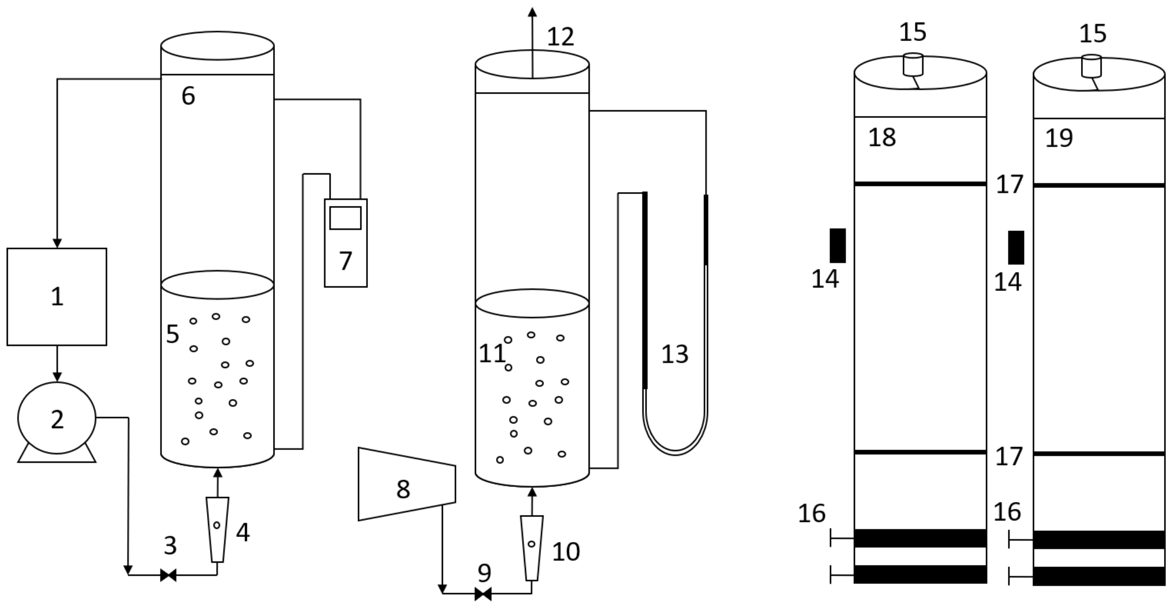

Figure 1: Experiment 9: packed beds and particle drag apparatus.

the fluid. Tape markings on the columns (17) are one meter apart. Measuring the time elapsed as the particle drops from the higher to lower marking allows estimation of velocity. At the bottom of each column is two large gate valve; they should normally all be closed. When retrieving a dropped particle, open, then close the top gate, and subsequently open, then close the lower gate. This double-gate system permits retrieval without emptying the entire column. Ensure a bucket is placed under the gate to catch the particle and fluid. Not pictured is a large assortment of spherical and streamlined beads of various materials and sizes.

A mass balance is available for measuring particle weights. Graduated cylinders are supplied for measurement of volume. A caliper is available for precise measurement of particle sizes.

5 Safety

The major hazards associated with this experiment are the following: The pump and compressor, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the power cord is not wetted or touched when in operation. Through accumulation of biological contaminants in the water, there is also a risk of infection. Contact the instructional staff if you believe the tubing needs cleaned or replaced. If water splashes out of the apparatus, there are risks to clothing damage, slips, and falls. Avoid this by carefully considering the impact of opening or closing of valves prior to acting, and clean spills immediately if they do occur. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

6 Experimental Procedure

Prior to beginning the experiment, the liquid flow meter will need to be calibrated. This can be done by measuring the volume of water expelled by the pump with a graduated cylinder over a recorded duration of time for several settings on the flow meter.

To study the behavior of the liquid packed bed, begin by filling the column and bed with the water. Note the type of packing in the bed and the diameter of the column. After this is accomplished, fully close the flow control valve while keeping the pump or compressor on. Zero the water column's manometer and record the initial bed height (300 mm is recommended as a first trial but not necessary). Open the valve by a small increment and allow the system to reach steady state. Record the flow rate on the flow meter, the pressure differential displayed on the manometer, and the height and state of the bed. Continue collecting data points across the range of flow rates which can be measured by the flow meter. Repeat the process starting at the maximum flow rate and decreasing by small increments. Take clear notes to delineate data recorded when the flow rate was increasing and when it was decreasing.

Analysis of the air packed bed is identical to the liquid system, except that the column does not need to be filled prior to used and the manometer need not be zeroed.

For both beds, additional trials can be conducted by varying the type of packing used and its initial height.

Note: the void fraction must be experimentally determined for packing materials used. We will leave it as an exercise for the experimentalist to determine the best approach for its measurement.

To study particle drag, start with small ceramic beads and the glycerol column. Record the diameter and mass of the bead. Place one bead into the bucket, oriented upright, from the step ladder. When back on the floor, ready a stopwatch for use. Turn the bucket switch to dump the bead into the glycerol. When the particle reaches the top tape mark, start the timer, and when it passes the lower tape marking, stop the timer. Repeat this process for a large variety of bead shapes, sizes, and materials into glycerol and water. After many particles accumulate in the column, use the double-gate to retrieve them. Refill columns with the appropriate fluid as needed. The volume of particles with arbitrary shape can be determined by submerging the particle in a known volume of water in a graduated cylinder. Repeating identical trials might be worth considering, particularly for high velocity, fast-falling particles (denser, larger particles in water will travel fastest).

7 Data Analysis

Characterize the packed bed behavior for each trial conducted by: plotting the pressure drop and bed height as a function of volumetric fluid flow. Calculate the pressure drop and superficial velocity at the point of fluidization. Compare these charts and values to their expected shapes and values—if there is disagreement, what might be the cause, and is there evidence for it?

Based on the data you were able to collect, investigate the effect of packing type, initial bed height, and type of fluid with the multiple trials conducted by comparing the relationships between pressure drop vs. flow rate and bed height vs. flow rate, as well as the pressure drop and superficial velocity at the point of fluidization. Note this is combinatorial, allowing several methods of analysis. Comment on significant results. Do they agree with the predicted relationships between these parameters? If not, what might be the cause, and is there evidence for it?

Characterize the results from particle drag by calculating an experimental drag coefficient for each particle. How they compare to predicted results? Investigate the relationship between the drag coefficient and particle size, material, shape, and type of fluid. How does the data look relative to the expected trends? If there is disagreement, what might be the cause, and is there evidence for it?

Comment on the commonalities between packed bed and particle drag phenomena. How are these concepts related? Can results from one experiment inform how the other might behave?

References

[1] Don W. Green, editor. *Perry's chemical engineers' handbook.* McGraw-Hill, eighth edition, 2008.

[2] Noel de Nevers. *Fluid mechanics for chemical engineers.* McGraw-Hill, third edition, 10 2004.