PACKED AND FLUIDIZED BEDS

Skill Outcomes:
In completing this particular experiment, the student should develop or improve mastery of the following skills:

- Ability to safely operate the fluidized bed apparatus located in 116 Jarvis
- Knowledge of the applications of packed and fluidized beds in the chemical process industry
- Definition of bed friction factor
- Definition of minimum fluidization velocity
- Ability to apply the basic notions of flow past solids to packed and fluidized beds to determine pressure drops and the transition from packed to fluidized bed

Objectives:

1. Determine experimental values for minimum fluidization velocity for two beds located in 116 Jarvis. Compare these values to theoretically predicted values of minimum fluidization velocity.
2. Determine the relationship between the bed friction factor, $f_p$, and the particle Reynolds number, $N_{Re,p}$, Compare the relationship obtained experimentally to empirical relationships described in the Theory section.

System:

In this experiment you will investigate the flow of air through a bed of solid particles. The equipment includes two transparent beds, rotameters, an inclined manometer, a source of low pressure air and appropriate valves and fittings. The physical parameters of the solid particles to be studied are displayed on the bed.

Theory:

The theory for this experiment is covered in Chapter 7 of the 6th Edition of McCabe, Smith, and Harriott (M,S,&H). The following material is a condensation of that chapter as it relates to the experiment at hand. As an aid to you, some specific equations in M,S,&H are referred to. There are two areas of the text which are pertinent to this assignment: 1) Relationship between the pressure drop and the flow rate and 2) Minimum fluidization velocity.

(1) Relationship between pressure drop and flow rate

The flow of a fluid, either liquid or gas, through a static packed bed can be described in a quantitative manner by defining a bed friction factor, $f_p$, and a particle Reynolds number, $N_{Re,p}$, as follows:
\[ f_p \equiv \frac{\Delta p \phi_s D_p \varepsilon^3}{\rho \overline{V}_o^2 L (1 - \varepsilon)} \]  
Similar to 7.19 in M,S,&H \hspace{1cm} (1)

(Note that the friction factor defined in this case is different than that for flow through a circular conduit.)

\[ N_{Re,p} = \frac{\rho \overline{V}_o D_p}{\mu} \]  
where
\[ \Delta P = \text{pressure drop across the bed} \]
\[ L = \text{bed depth or length} \]
\[ \sigma = \text{conversion constant (=unity if SI units are used)} \]
\[ D_p = \text{particle diameter} \]
\[ \rho = \text{fluid density} \]
\[ \varepsilon = \text{bed porosity or void fraction} \]
\[ \overline{V}_o = \text{superficial fluid velocity} \]
\[ \mu = \text{fluid viscosity} \]
\[ \Phi_s = \text{sphericity} \]

The friction factor and the Reynolds number are dimensionless. Some typical sphericity factors are given in McCabe, Smith and Harriott (p.158 Table 7.1).

For laminar flow, where only viscous drag forces come into play, \( N_{Re,p} < 20 \), experimental data may be correlated by means of the Kozeny-Carman equation:

\[ f_p = \frac{150(1 - \varepsilon)}{N_{Re,p}^{0.4}\Phi_s} \]  
Similar to 7.17 MS & H \hspace{1cm} (3).

For highly turbulent flow where inertial forces predominate, \( N_{Re,p} > 1000 \), experimental results may instead be correlated in terms of the Blake-Plummer equation:

\[ f_p = 1.75 \]  
Similar to 7.20 MS & H \hspace{1cm} (4)

While both equations (3) and (4) have a sound theoretical basis, Ergun empirically found that the friction factor could be described for all values of the Reynolds number by simply adding the right-hand sides of equations (3) and (4). Thus:

\[ f_p = \left( \frac{150(1 - \varepsilon)}{N_{Re,p}^{0.4}\Phi_s} + 1.75 \right) \]  
Similar to (7 - 22) MS & H \hspace{1cm} (5)

(2) Minimum fluidization velocity

At a sufficiently high flow rate, the total drag force on the solid particles constituting the bed becomes equal to the net gravitational force and the bed becomes fluidized. For this situation a force balance yields:
\[
(-\Delta p)A = LA(1 - \varepsilon_M)(\rho_p - \rho) \frac{g}{g_c} = M \frac{(\rho_p - \rho)}{\rho_p} \frac{g}{g_c}
\]

where
- \(\varepsilon_M\) = void fraction at the minimum fluidization velocity
- \(A\) = cross-sectional area of the bed
- \(\rho_p\) = particle density
- \(g\) = gravitational acceleration
- \(M\) = total mass of packing.

This is Eq. 7.48, 7.49 MS&H. The superficial fluid velocity at which the fluidization of the bed commences is called the incipient or minimum fluidization velocity, \(V_{0M}\). The incipient fluidization velocity may be determined by combining equations (1), (3), and (6) with the following result [Eq. (7.52) MS&H] for the case of small particles and consequent, \(N_{Re} < 1\):

\[
V_{0M} = \frac{g(\rho_p - \rho)\varepsilon_M^3 \phi_s^2 D_p^2}{150 \mu (1 - \varepsilon_M)}
\]

This equation is the basis for some empirical equations found in the literature. The terms can be grouped as follows:

\[
V_{0M} = \frac{\varepsilon_M^3 \phi_s^2 D_p^2}{150(1 - \varepsilon_M)} \cdot \frac{g(\rho_p - \rho)D_p^2}{\mu}
\]

The first factor contains the sphericity of the particles and the bed porosity at the point of incipient fluidization. Neither of these factors is usually known with a high degree of accuracy. If spheres are assumed \(\phi_s = 1\) and a reasonable value of voidage, say \(\varepsilon_M = 0.4\), then the first factor is 0.00071. The factor is quite sensitive to \(\varepsilon_M\). For example, if \(\varepsilon_M = 0.413\), then the factor is 0.0008.

**Comments and Things to Consider**

1. Calibration curves for the rotameters will be provided.
2. Increase the flow rate of air in small steps (especially initially) noting the rotameter and manometer readings until the bed is fluidized and the pressure drop does not change appreciably. Continue the measurements until the bed is appreciably fluidized. Obtain at least fifteen readings in the packed-bed region and ten readings in the fluidized-bed region.
3. Be sure to take extra readings in the area of minimum fluidization velocity.
4. Decrease the flow rate, noting the flow rate and pressure drop values.
5. Produce at least three curves (both increasing and decreasing flow) for each bed.
6. For each bed, plot the measured pressure drop (in cm of H2O) versus the volumetric flow rate in liters/min. (Note that the manometer is at an angle of 19°) There will likely be a “hysteresis effect” in that the pressure drop curve for increasing flow rate will differ from that for decreasing flow rate. Therefore, use different symbols for increasing and decreasing flow rates. Explain the likely cause of this effect.

7. For each bed, calculate the friction factor and corresponding particle Reynolds number for each data point using Equations (1) and (2). Then prepare a single plot of $f_p$ versus $N_{re, p}$ which combines the results for the two beds. Use a different symbol for each bed and show symbols only (no lines). On this plot, also show the predicted values from Equations (3), (4), and (5). Show these as solid or dashed lines, and do not show the points used for determining these plots.

8. From your plots in Part 6 above, determine the pressure drop at the point where fluidization begins in cm H2O. Using Equation (6), calculate the predicted value of the pressure drop at this point in cm H2O. Assume that $\varepsilon_M$ is approximately equal to the porosity given for the bed material. Comment on your findings.

9. From your plots in Part 6 above, estimate $V_{0M}$ in m/s and ft/s for each of your runs and beds. Compare your experimental value to that predicted by Equation (7).

10. As you increase the flow rate of air, observe what the bed looks like at various stages. Do your observations help explain some discrepancies between measured and theoretical values.

**References**