

A SIMPLE BUT EFFECTIVE FLUIDIZED-BED EXPERIMENT

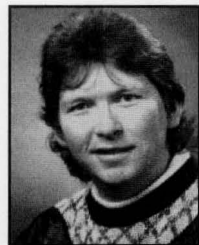
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Fluidization is an aspect of chemical engineering not usually covered in depth at the undergraduate level, but engineers are as likely to meet with fluidization during their careers as they are some other, more extensively taught, unit operations. It has applications ranging from chromatography and fermentation through filtration, drying, and catalysis and is likely to be encountered by non-engineering professionals such as chemists and biologists.

The laboratory experiment described in this paper was designed as part of a course in process technology for chemistry and biology majors. Often, such courses (intended to introduce "engineering principles" to science students) are given toward the end of the student's schooling, and it is difficult to pitch material at an appropriate level to students who are senior but who have little background in engineering. For obvious reasons, the mathematical demands of this practical session are low, but it still demonstrates basic engineering principles well and provides an effective, interactive learning experience for the student. The session is loosely structured, giving students an opportunity to test out their investigative skills—but not so loose as to allow them to wander off-track. This approach avoids boring senior students without demanding an unreasonably high level of engineering knowledge.

The laboratory would suit first- or second-year chemical engineering students and may be easily modified to include more sophisticated concepts for advanced engineering students.



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EXPERIMENTAL PREPARATION

Students are given a brief introduction to the concept of fluidization and its use as a processing tool, including reasons why one would want to contact a fluid with a solid in the first place. This section includes a qualitative description of the desirability on the one hand of using small particles that have a high surface-area-to-volume ratio, and, on the other hand, the need to keep the pressure drop through such a bed of particles low.

A comparison with a packed bed is made to highlight some advantages of the fluidized bed in terms of lower pressure drops, uniformity of temperature, a greater tolerance for solids in the feedstream, etc. The concepts of frictional drag around a sphere and terminal settling velocities are also qualitatively outlined, together with the notion that bed washout can be avoided. (The students have, by this stage, had several lectures on fluid dynamics, so the concepts of boundary layers and viscous drag are not new to them.)

The students are given only the following four hypotheses to test, with the task of describing and explaining observed bed behavior, especially noting any differences between the two beds provided.

Hypothesis 1: That at flowrates equal to and above the point of minimum (incipient) fluidization the bed behaves as a "liquid" with a density between the fluid and the solid densities.

Hypothesis 2: That the pressure drop in the bed is a function of the superficial velocity, u_s (m s^{-1}), of the bed, where

$$u_s = \frac{Q}{A_c} \quad (1)$$

where Q is the volumetric flowrate of the fluidizing medium ($\text{m}^3 \text{s}^{-1}$) and A_c is the cross-sectional area of the column (m^2).

Hypothesis 3: That at the point of minimum fluidization the frictional losses over the entire bed height will equal the

total weight of the particles in the bed. That is, at the onset of fluidization

$$\text{Drag force by Upward Moving Fluid} = \text{Weight of Particles}$$

$$\left(\begin{array}{c} \text{pressure} \\ \text{drop} \\ \text{across bed} \end{array} \right) \left(\begin{array}{c} \text{cross-} \\ \text{sectional area} \\ \text{of column} \end{array} \right) = \left(\begin{array}{c} \text{volume} \\ \text{of} \\ \text{bed} \end{array} \right) \left(\begin{array}{c} \text{fraction} \\ \text{of} \\ \text{solids} \end{array} \right) \left(\begin{array}{c} \text{specific} \\ \text{weight} \\ \text{of solids} \end{array} \right)$$

$$\Delta P A_c = W = (A_c L_{mf})(1 - \epsilon_{mf})(\rho_s - \rho_f)g \quad (2)$$

where

- ΔP pressure drop in the bed (Pa)
- W weight of particles (N)
- L_{mf} height of the bed at the point of minimum fluidization (m)
- ϵ_{mf} voidage at the point of minimum fluidization (-)
- ρ_s solid density (kg m^{-3})
- ρ_f the fluid density (kg m^{-3})
- g gravity (m s^{-2})

Hypothesis 4: That above the point of minimum fluidization the bed will expand (*i.e.*, its height will increase) with increasing fluid velocity.

The amount of assistance given to the students regarding methodology can easily be adjusted. Some will need little, if any, help, while others will require a little more prompting. For instance, some students can figure out on their own how to measure ϵ_{mf} ; others might only need the hint to use a displacement method using a measuring cylinder, while some may need the methodology spelled out for them in greater detail. Engineering students ought to cope with developing the force balance expression given under Hypothesis 3 by themselves.

APPARATUS

Students are provided with two plexiglass columns (see Figure 1). The columns can be any size, but I wanted them to be large enough for students to be able to see what was going on internally. The columns should be large enough to allow the students to float or sink a few objects (such as a block of wood) in the (fluidized) bed. The columns used in my class are 0.45 m in height, with an inside diameter of 0.074 m.

The first column, fluidized by air, contains 0.163-mm diameter glass beads to a height of 0.38 m (at rest), while the second column, fluidized by water, contains 1-mm glass beads to a height of 0.26 m. Each column has a plexiglass support plate with 44 holes (3-mm diameter) and a fluid distributor plate, used also to retain the bed particles, made from 85- μm and 750- μm aperture sieve material for the air- and water-fluidized beds respectively. Each column has a valve and rotameter for setting and measuring volumetric flowrates and a manometer that allows measurement of the pressure drop between two pressure probes (Pitot tubes)

located at different heights within each bed. The height of each probe within the bed is adjustable. Bed particles are prevented from entering the Pitot tubes by pieces of brass sieve material held in place over the ends of the Pitot tubes with screw-on collars. This arrangement is necessary because the sieves can block over time and it is best to replace them regularly. Also provided is a small block of wood which can be introduced to the air-fluidized bed via the top of the column. Water exits the water column via a drain tube located on the side of the column, above the bed. Air is vented directly from the top of the air column.

Adequate flowrate ranges are 0 to $2.5 \times 10^{-4} \text{ m}^3 \text{ s}^{-1}$ for the air-fluidized bed, and 0 to $5 \times 10^{-5} \text{ m}^3 \text{ s}^{-1}$ for the water-fluidized bed. The cost of the apparatus was less than NZ\$2000 (US\$1000).

RESULTS

The students were enthusiastic, and they all remarked positively on the fluidization laboratory when they were asked in course appraisals to recall their most enjoyable practical session.

The apparatus lends itself well to demonstration. It is simple to operate, repeatable results are easy to obtain, and there is no setting-up time required before each session. There is no deadtime or time spent waiting for steady state, and measurements can be repeated literally in seconds. Also, even the most hapless students would find it difficult to harm either themselves or the equipment.

The magical moment when the block of wood floats in a bed of solids never fails to fascinate the students. Even the "coolest" student in the class cannot repress a childish amusement and the urge to repeatedly push the block of wood into the bed and watch it bob back to the surface and float around. If the columns are mounted so they can be tilted, the liquid-like flow properties of the fluidized particles can be easily shown.

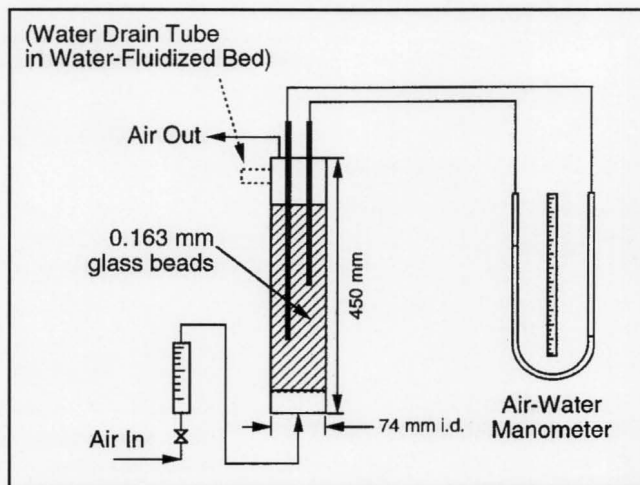


Figure 1. The air-fluidized bed apparatus. A similar column is used for water-fluidization

The following experimental results for the air-fluidized system are typical. Those for the water-fluidized column are qualitatively similar.

For Hypothesis 1, the more mathematically literate students can derive an expression for the effective density of the bed at minimum fluidization with little difficulty. Less quantitatively inclined students are satisfied with demonstrating that a block of wood with a density between that of air and glass floats in the fluidized bed.

A plot (Figure 2) of total bed-pressure drop versus superficial velocity is sufficient to show the existence of a relationship, as predicted by Hypothesis 2. The pressure drop in an equivalent packed bed can be calculated using the well-known Ergun equation^[1]

$$\frac{\Delta P}{L} = \frac{150(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu u_s}{(\phi d_p)^2} + \frac{1.75(1-\varepsilon)}{\varepsilon^3} \frac{\rho_f u_s^2}{\phi d_p} \quad (3)$$

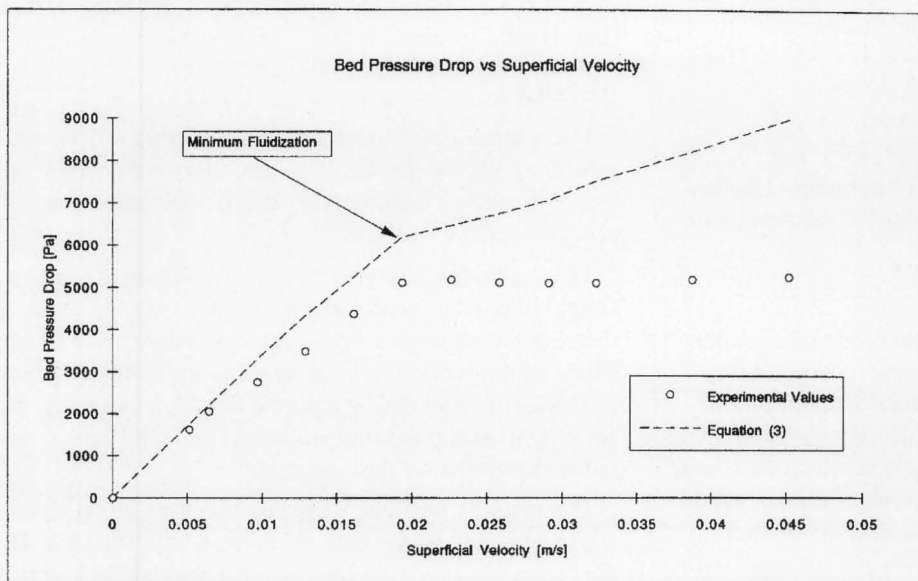


Figure 2. Total bed pressure drop versus superficial velocity in the air-fluidized bed.

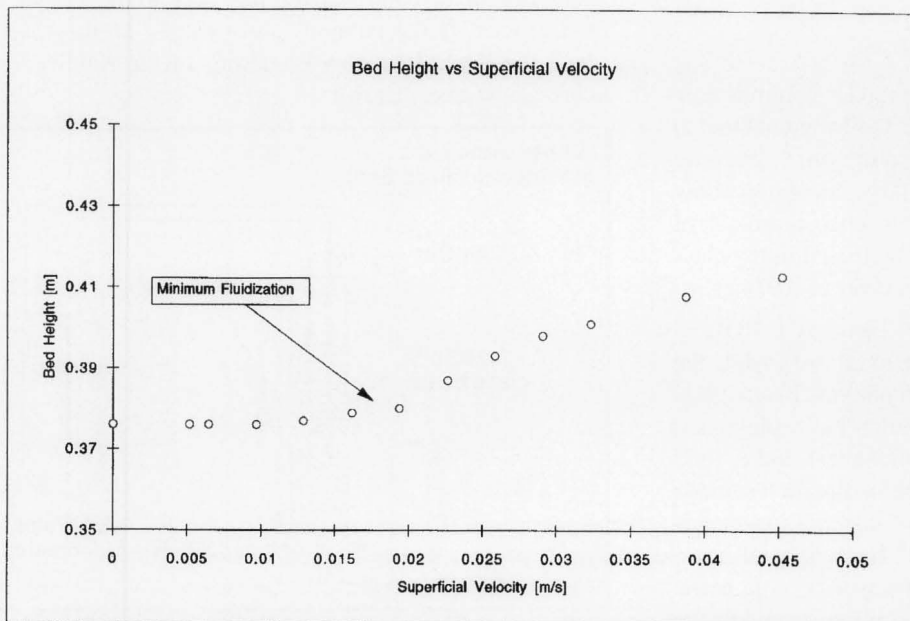


Figure 3. Bed height versus superficial velocity in the air-fluidized bed.

where ε is the bed voidage and ϕ is the sphericity of the particles. The increase in bed voidage due to the expansion of the bed with increasing superficial velocity above minimum fluidization can be calculated from measurements of bed height. If this is taken into account, Eq. (3) predicts pressure-drop values which initially are close to the experimental values, but which become higher than the experimental values as superficial velocity is increased, as might be expected for unrestrained particles. The slope of the pressure drop versus superficial velocity predicted by Eq. (3) changes at the point of minimum fluidization.

Figure 2 also illustrates that once the particles are fluidized, the frictional losses do not increase significantly with increased superficial velocities, in contrast to the behaviour of packed beds. This is explained partly by the increased bed voidage and also by the fact that the excess air flow (above that required for fluidization) moves through the bed largely as bubbles, as can be seen through the column walls. The bubbles bypass the solids and therefore do not contribute significantly to the frictional losses, similar to the case of air bubbling through water in which the pressure required for air injection depends mainly on the static pressure head and not on the flowrate.

To test Hypothesis 3, ε_{mf} must be known. The void fraction for non-fluidized beads, measured by water displacement, is about 0.35 for both columns. At minimum fluidization, bed expansion over the rest state is negligible, so ε_{mf} is also 0.35. The density of the glass is given by the supplier as 2.09 g cm^{-3} . The pressure drop at minimum fluidization is 5120 Pa,

giving a value for the left-hand side of Eq. (2) of

$$(5120 \text{ Pa})(0.0043 \text{ m}^2) = 22.0 \text{ N}$$

compared to a right-hand side value of

$$(0.0043 \text{ m}^2)(0.380 \text{ m})(1 - 0.36)(2090 \text{ kg m}^{-3} - 1.2 \text{ kg m}^{-3})(9.81 \text{ m s}^{-2}) = 21.4 \text{ N}$$

The resultant force balance of within 3% is pretty good!

Hypothesis 4 is easily tested, as shown in Figure 3—but it requires some conceptual thought by the students to explain the observed behavior, as follows. The frictional drag on a particle is a function of the relative velocity between the particle and the fluid moving through the void space surrounding it. At minimum fluidization the drag is just sufficient to support the weight of the particles, as proposed in Hypothesis 3. As the flowrate is increased above minimum fluidization, the particles in the bed begin to lift due to the extra drag force generated by the greater fluid velocity in the available void space. But the void space correspondingly increases until the fluid velocity, relative to the particle, reduces to the level at which the drag force again just balances the particle's weight. Hence the bed expands, but the particles are not washed out with the fluid, and the explanation for this is consistent with the observation that the pressure drop (frictional loss) in the bed is relatively constant above minimum fluidization (at least within the limits of this experiment).

The superficial velocity at the point of minimum fluidization, u_{mf} , can be determined from either Figure 2 or 3, and in this case it is about 0.02 m s^{-1} . The experimentally determined value of u_{mf} can then be compared to that calculated from packed bed considerations by combining Eqs. (2) and (3), equating u_s with u_{mf} , and using the voidage and bed height at minimum fluidization.^[2] The following quadratic in u_{mf} is obtained:

$$\left(\frac{1.75(1 - \epsilon_{mf})\rho_f}{\epsilon_{mf}^3 \phi d_p} \right) u_{mf}^2 + \left(\frac{150(1 - \epsilon_{mf})^2 \mu}{\epsilon_{mf}^3 (\phi d_p)^2} \right) u_{mf} - (1 - \epsilon_{mf})(\rho_s - \rho_f)g = 0 \quad (4)$$

Solving Eq. (4) for u_{mf} , using the data from the air-fluidized bed, yields a value for u_{mf} of 0.02 m s^{-1} . Given that Eq. (3) is expected to represent data only to within $\pm 25\%$, this result is in surprisingly good agreement with the values found from Figures 2 and 3.

There are numerous points for discussion and they can be stimulated by perusing any standard fluidization text, such as the one by Kunii and Levenspiel.^[2] A few possibilities are:

- *Comparisons between the gas- and liquid-fluidized beds, such as bubbling and slugging in the former, can be highlighted and the consequences for scale-up pointed out.*
- *How does bubbling affect fluid-solid contact?*
- *Why are particles not washed out of the bed at superficial velocities immediately above minimum fluidization, and does this have anything to do with bed expansion?*
- *Why not place the pitot tubes at the very bottom or top of the bed?*
- *Would the fluid distributor at the base affect fluidization?*
- *What would heat transfer be like in the bed?*

CONCLUSIONS

We have developed a low-cost fluidized bed laboratory experiment, using apparatus that is safe and simple to operate and which requires no running costs. The level of experimental or theoretical complexity of the laboratory session can easily be adjusted to suit the backgrounds and capabilities of the students involved.

The experimental results can be presented and analyzed in both quantitative and

qualitative fashion. Students have found the session interesting and enjoyable, and they relate well to the engineering principles involved, such as fluid-solid contacting, pressure drop and frictional losses, etc. In particular, the session is designed to stimulate and hold the interest of relatively senior undergraduate students from outside of engineering, whose limited quantitative backgrounds often constrain their engineering practical sessions to more mundane topics.

NOMENCLATURE

A_c	cross-sectional area of bed, m^2
d_p	particle diameter, m
g	acceleration due to gravity, m s^{-2}
L	bed height, m
L_{mf}	bed height at minimum fluidization, m
ΔP	axial pressure drop in bed, Pa
Q	volumetric flowrate, $\text{m}^3 \text{s}^{-1}$
u_s	superficial velocity, m s^{-1}
u_{mf}	superficial velocity at minimum fluidization, m s^{-1}
W	weight of bed material, N

Greek Symbols

ϵ	bed voidage
ϵ_{mf}	bed voidage at minimum fluidization
ϕ	particle sphericity
μ	fluid viscosity, $\text{kg m}^{-1} \text{s}^{-1}$
ρ_s	density of solid particles, kg m^{-3}
ρ_f	density of fluid, kg m^{-3}

ACKNOWLEDGMENTS

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REFERENCES

1. Ergun, *Chem. Eng. Prog.*, **48**, 89 (1952)
2. Kunii, D., and O. Levenspiel, *Fluidization Engineering*, 2nd ed., Butterworth-Heinemann, Boston, MA (1991) □