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Tools and Techniques for Diagnosing and Solving Operating Problems in Fluidized Bed Systems

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Résumé — Outils et techniques pour diagnostiquer et résoudre les problèmes des réacteurs en lit fluidisé — Les procédés de réaction à deux phases, gaz-solide, sont extrêmement difficiles à exploiter. Les systèmes de réacteur et de recyclage à lit fluidisé comptent parmi les systèmes à deux phases les plus complexes, et offrent de ce fait un défi spécifique si l'on veut en obtenir une exploitation correcte et les maintenir en exploitation continue. Une étude a montré que les unités traitant des solides ne fonctionnent qu'à 64 % de leur capacité nominale dans leur première année d'exploitation, alors que la norme industrielle, pour les unités qui n'en traitent pas, est d'environ 90 à 95 %.

Durant les deux dernières décennies, divers outils et techniques ont été développés pour aider à minimiser les problèmes posés au démarrage et à l'exploitation des unités où entrent en jeu une réaction et/ou un transport de solides. Ces méthodes, utilisées d'une manière adaptée, constituent des outils très utiles pour trouver une solution aux problèmes posés. La perte financière produite par un arrêt d'unité, perte qui peut atteindre plusieurs millions de dollars, montre l'importance que représente la résolution (et la prévention) de ces problèmes de maintien des unités en exploitation.

Parmi ces outils, l'on peut utiliser les maquettes froides et les unités pilotes pour diagnostiquer et rechercher les problèmes rencontrés dans l'exploitation des unités industrielles à chaud. On peut dans de nombreux cas se servir des maquettes froides (fonctionnant dans des conditions de température et de pression ambiantes) pour simuler et résoudre des problèmes survenant dans l'unité à chaud. Ces maquettes sont appréciées car elles peuvent être construites en plastique transparent, permettant ainsi d'observer le régime d'écoulement. Toutefois, elles sont relativement coûteuses et assez longues à construire.

Il est également possible d'utiliser les unités pilotes du procédé, surtout dans le cas où les problèmes rencontrés sont de nature chimique, ou bien s'il est nécessaire de simuler les conditions exactes du procédé. Une utilisation judicieuse des unités pilotes peut apporter de nettes améliorations à l'exploitation du procédé.

Des exemples décrivant la manière dont ces outils peuvent être utilisés pour simuler et résoudre ces problèmes sont ici décrits et explicités.

Mots-clés : maquette froide, diagnostic, fluidisation, écoulement de solides, extrapolation, remèdes.

Abstract — Tools and Techniques for Diagnosing and Solving Operating Problems in Fluidized Bed Systems — *Two-phase, gas-solid processes are extremely difficult to operate. Fluidized-bed reactor systems and fluidized-solids recycle systems are two of the more complex two-phase systems and, therefore, offer special challenges in getting them to operate well and keeping them operating. A study* *has shown that plants processing solids operate at only about 68% of design capacity in the first year of operation, whereas the industry standard for plants that do not process solids is about 90 to 95%.*

During the past two decades, various tools and techniques have been developed to assist in minimizing startup and operating problems in plants that react and/or transport solids. These are very helpful tools, and if applied correctly can be used with much success to solve problems. When plant downtime can mean a multi-million dollar loss, solving (and preventing) problems in order to keep the units operating becomes extremely important.

Two of the tools that can be used to diagnose and troubleshoot problems in commercial, hot units are cold models and pilot plants. Cold models (models operated at ambient temperature) can often be used to simulate and solve problems occurring in the hot unit. They are popular because they can be constructed of clear plastic to allow visual observation of the flow system. They are also relatively inexpensive and can be constructed in a relatively short time.

Pilot plants that were used for scaling up a process can also be used for solving problems. This is more the case if the problems are of a chemical nature or if operation at exact process conditions is required. Using pilot plants judiciously can lead to significant improvements in the operation of the process.

Keywords: cold models, diagnosis, troubleshooting, fluidization, solids flow, scaling.

NOMENCLATURE

D_t tube diameter (m)
g gravitation constant, 9.81 m/s^2
L pipe length (m)
U_g superficial gas velocity (m/s)
U_{mf} superficial minimum fluidization velocity (m/s)
ΔP_{fg} pressure drop due to gas friction in pipe (kg/m^2)
μ gas viscosity (kg/m·s)
ρ_g gas density (kg/m^3)
ρ_p particle density (kg/m^3)

INTRODUCTION

Processes that involve the reaction of gases and solids are extremely difficult to operate. Processes incorporating a fluidized-bed reactor and/or a solids recycle transport system are among the more complex of these. This is especially true both in starting up the plants and keeping them operating.

The difficulty of operating solids processing plants has been shown in a paper by Merrow [1] that was a joint study conducted by the US Department of Energy and the Rand Corporation. The study found that the majority of performance problems in solids processing plants was caused by solids flow difficulties—not process chemistry problems. It also concluded that government and industrial research and development expenditures neglected this important solids handling area.

The study used as a database, 37 solids processing plants operating in the US and Canada. Merrow found that, on average, solids processing plants operated at only 64% of design capacity in the first year of operation. The industry average for non-solids operating plants was 90 to 95%.

To analyze the data from the plants, Merrow defined a performance problem as anything that caused a plant to be off-line for a period of one week or more. He found that 94% of the plants in the study experienced such a performance problem. He organized the plant performance problems into two categories: chemical and non-chemical problems. He then listed those problems experienced by the greatest percentage of the plants in each category. In the non-chemical problem category, the most common problems were:

– solids transfer failures (experienced by 52% of the plants);
– failures of mechanical equipment (48%);
– plugging of reactors by solids (45%);
– handling of fines and dust (23%).

In the chemical problem category, the most common problem was corrosion and erosion of equipment (29%) while other process chemistry failures accounted for only 6% of the performance problems. This information is summarized in Table 1.

TABLE 1

Performance problems in solids operating plants

	(%) of sample
Plants with performance problems*	94
Non-chemical problems	
Solid transfer failures	52
Failure of mechanical equipment	48
Plugging of reactor by solids	45
Handling of fines and dust	23
Chemical problems	
Corrosion/erosion	29
Other process chemistry failures	6

* A performance problem was defined to be anything that caused a plant to be inoperable for one week or more.

In a second paper, Merrow [2] also reported that solids processing plants take a much longer time to start up than plants using no solids. He compared the planned startup *versus* the actual startup time for plants processing liquid and gas, refined solids, and raw solids. All of the plants took longer to actually start up than predicted. However, there was a marked contrast in the planned *versus* actual startup times for the solids processing plants. As shown in Figure 1, the planned and actual startup times for the liquid/gas plants were about 2 and 2.5 months, respectively. For the refined solids processing plants these values were 3.5 and 9 months, respectively. For the raw solids processing plants, the values for the planned and actual startup times were 5 and 18 months, respectively. Thus, the actual startup times for the solids processing plants were over two to three times the planned startup times.

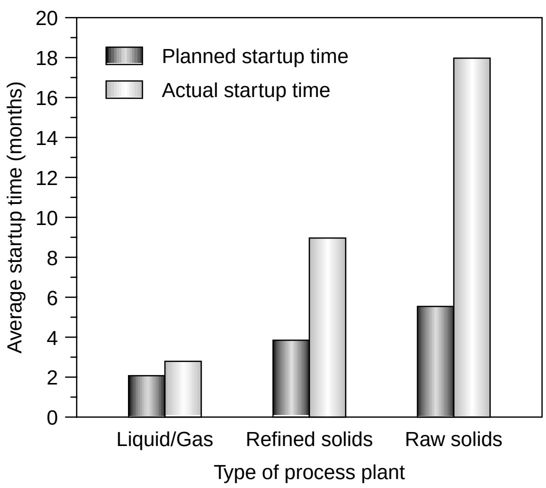

Figure 1

Planned startup time *versus* actual startup time for solids processing plants.

These examples illustrate that solids processing plants are extremely difficult to operate. Because of the difficulty in designing, operating, and troubleshooting plants that process solids, it is important to try to solve these problems using any tools and techniques that are available. One of the most useful tools is the cold model (a simulated section of the commercial plant that operates at ambient temperature). A cold model is extremely useful because it is relatively inexpensive, and it can be constructed relatively quickly.

COLD MODEL OPERATION AND CONSTRUCTION

A cold model is arguably the most useful tool for solving scale-up or troubleshooting problems in the solids transport and fluidization fields. One of the most important features of a cold model is that it can be constructed of clear materials so that the solids movement in the model can be observed. This is an extremely important feature that enables the solids flow patterns or stagnant regions to be observed. Often just viewing how the solids flow or move will enable the problem to be understood.

One useful cold-model visualization technique is to add a colored tracer to the cold model to highlight the solids flow and to allow monitoring of particles motion. This technique is especially useful to view dispersion or mixing of the solids in the cold model. The motion of the colored particles in the model can be photographed and transferred to tape using a camcorder. The video can then be captured on a video capture card and transferred to a compact disk (CD). Using the CD player on a computer, the movie can then be viewed in real time or frozen and advanced frame by frame. A frame is 1/30 of a second for the NTSC format used in the US or 1/25 of a second for the European PAL format. Being able to view the solids motion frame by frame allows the solids motion and/or dispersion to be analyzed in great detail.

There are several ways of constructing a cold model so that solids motion can be seen. The most common is to construct all or part of the model from clear acrylic (Plexiglas, etc.). Acrylic is extremely clear, but it is manufactured as tubing and it is often difficult to mate the tubing to steel or PVC pipe. Clear PVC pipe can also be obtained. It is not as clear as Plexiglas, but fittings can be purchased to easily connect this material to steel or non-clear PVC pipes. This type of pipe can be obtained in diameters up to approximately 20 cm. Clear acrylic can be constructed in tubing sizes of up to about 1 m or more. Often a cold model will be constructed entirely of metal (steel and aluminum are the most common choices) and sight ports added to the model to allow viewing of the solid motion in the model.

In many cold models, the diameter of the pipes transporting the solids are small enough so that the motion of the solids throughout the pipe can be determined. However, this is often not the case for three-dimensional (3D) fluidized beds that are relatively large in diameter. In fluidized beds, the primary solids circulation pattern is for the solids to travel upward in the center of the column and downward at the wall *(Fig. 2)*. Therefore, the solids motion at the wall “hides” the solids motion occurring in the center of the bed. Therefore, viewing a 3D clear plastic bed in operation is often of limited usefulness in understanding bubbles and solids flow patterns in the center of the bed, or even determining the regime of operation of the bed.

If it is desired to view what is happening in the center of the bed, it is better to use a semicircular column. This type of column is often called a *2.5D* bed. Semicircular columns enable the viewer to see what is occurring across the diameter of the bed in the middle of the bed *(Fig. 3)*, and do not “squeeze” the bubbles in the bed as do the very narrow 2D beds.

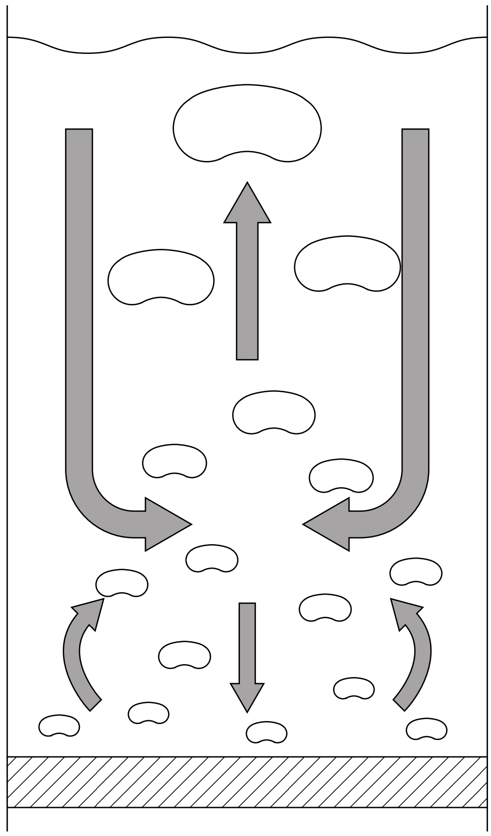

Figure 2

Solids circulation pattern in fluidized beds.

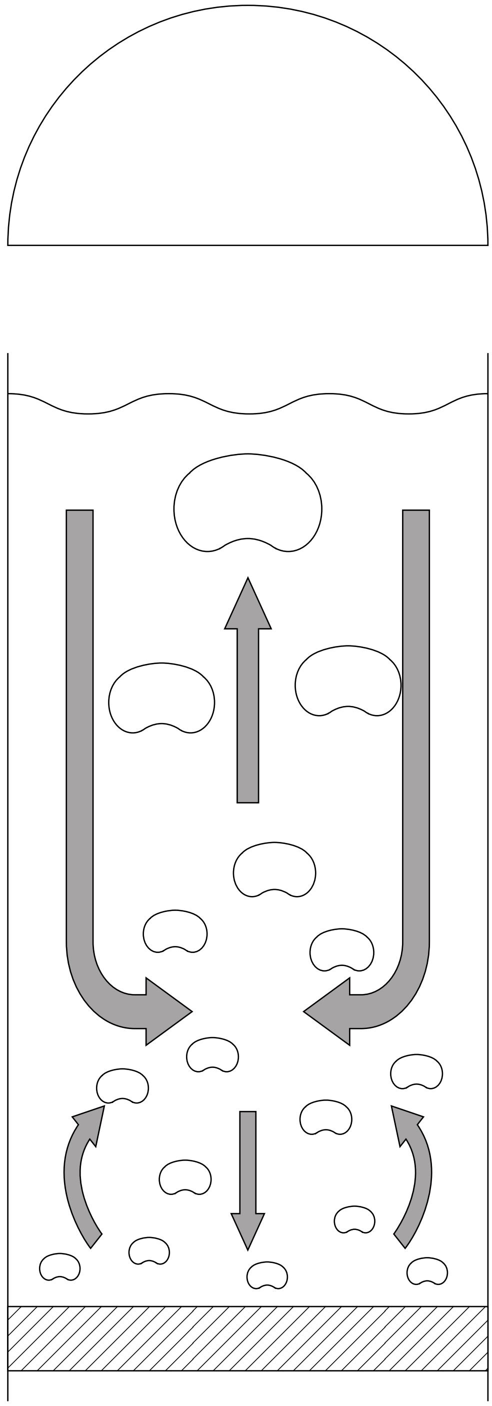

Figure 3

Semicircular columns allow observation of the center of the bed.

Cold models are of much more importance than just as a visualization aid. They can also be used to solve operating problems in a commercial plant. To use a cold model in this manner, the section of the plant experiencing problems is first simulated physically. It is also extremely important that the cold model be able to simulate the problem that is occurring in the commercial plant. If it cannot, the model will be of limited usefulness. However, if the problem can be simulated, it is often easy to solve the problem by changing the system configuration or altering system operating parameters. This is relatively easy to do in a cold model. Also, being able to view the motion of the solids in the system can often help determine what changes should be made. An example of a problem in an operating plant that was solved using a cold model is described below.

A standpipe flow problem was observed in an FCC (fluid catalytic cracking) operating unit. The solids flow rate in the standpipe was significantly below what was expected. Therefore, an existing cold model was modified to simulate the actual standpipe configuration in the commercial system.

The standpipe in the commercial unit was a hybrid, underflow standpipe that consisted of a short vertical section followed by a long angled section. A clear acrylic model of the commercial standpipe was installed in a cold model. When the cold model was operated, it was observed that the gas would separate from the solids in the angled section of

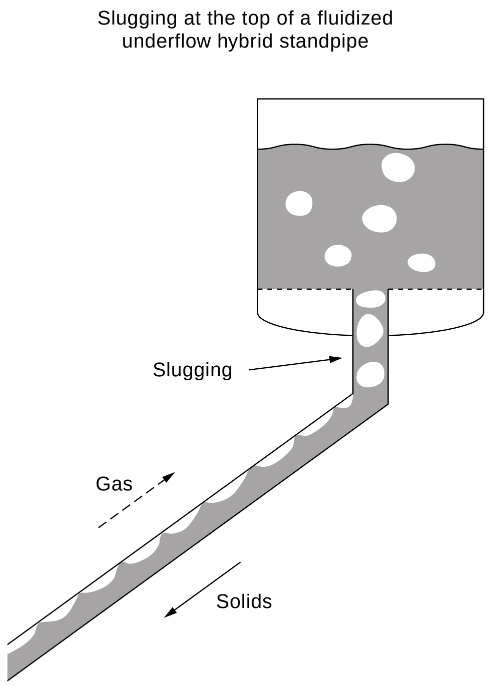

Figure 4

Operation of a hybrid, angled underflow standpipe.

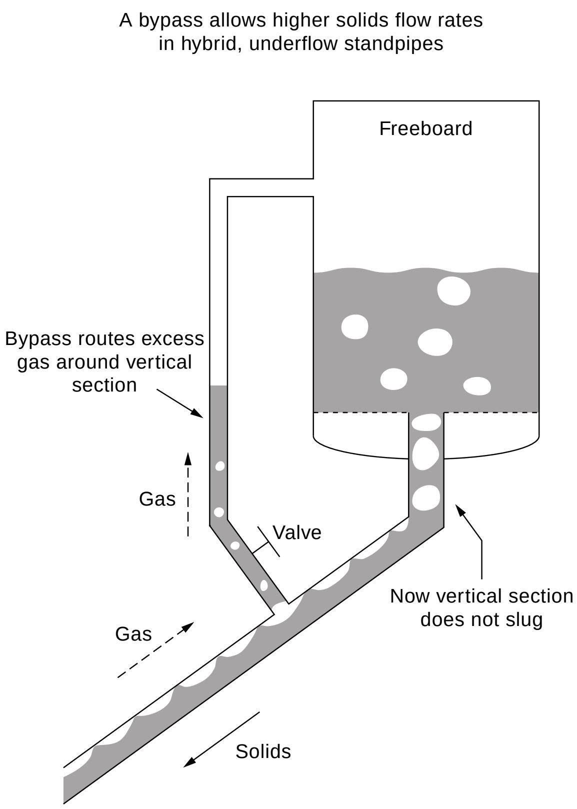

Figure 5

Gas bypass line for a hybrid, angled underflow standpipe.

the standpipe and flow upward along the upper part of the pipe *(Fig. 4)*. When the bubble gas reached the vertical section of the standpipe, it would form large bubbles. The large bubbles occupied so much room in the vertical section of the pipe that they slugged and limited the solids flow rate through the vertical section.

The solution to the problem was to construct a bypass line to route the bubble gas from the angled section around the vertical section of the pipe *(Fig. 5)*. This technique worked well in the cold model and a bypass was designed for the larger commercial standpipe. When the bypass was added to the commercial system, the solids flow rate increased significantly. The solids flow rate improvement was also accompanied by a much smoother operation of the transfer system.

If cold models are too small, wall effects can cause solids bridging in standpipes and/or slugging in fluidized beds. Large cold models eliminate these problems, but large models are expensive and are difficult and time-consuming to modify. Therefore, it is usually better to build a “Goldilocks” cold model (one that is neither too large nor too small) to allow satisfactory operation while containing costs.

In order to construct a cold model that is not too large nor too small, experience has shown that, in general, certain minimum sizes of sections of the cold model should be met. Three important sections of cold models are listed in Table 2 along with their recommended minimum diameters.

TABLE 2

Section	Diameter (cm)
Standpipe	7-10
Fluidized bed	15-20
Riser	10-15

If a cold model is constructed entirely of plastic, static charges will almost inevitably result. These discharges can be painful to a person and potentially dangerous. Static also causes fine solids to build up on the plastic so that solids motion cannot be seen.

With the proper techniques, static charges can be minimized. If a model has metal sections, they should be grounded. However, grounding will not eliminate static buildup for plastic sections because the charge on the inside wall cannot be dissipated by grounding the outside wall.

Humidification of the air will decrease static charges, but usually it is not completely effective in eliminating them. An antistatic powder called *Larostat* can often be used to eliminate static in fluidized beds. This powder is a quaternary ammonium salt coated onto a silica particle that is approximately 20 μm in diameter. In order for the antistat to be effective, the gas in the system requires a relative humidity of approximately 15%. Generally, a concentration of about 50 ppm is enough to dissipate the static.

If systems are operating at elevated pressure, often a cold model also operating at elevated pressure is warranted. Although more expensive than ambient-pressure cold models, pressurized cold models can indicate the tremendous effect that high gas densities have on entrainment [3] and regime transitions in fluidized systems. For example, Figure 6 shows that increasing system pressure from 4.4 to 31.6 bar causes a tremendous increase in entrainment from fluidized beds. Figure 7 presents data that shows that the transition from bubbling to turbulent fluidization is complete at a superficial gas velocity of about 20 cm/s at 40 bar and at a superficial gas velocity of only 14 cm/s at 60 bar. Many correlations developed with data obtained at ambient conditions cannot predict results at high-pressure operation. Operating a cold model at high pressure to determine the effect of gas density will determine the pressure effect and minimize surprises in commercial operation.

As indicated above, pressure has a large effect on regime transitions. At low pressures with particular particle size and gas velocity, a system may operate in the bubbling fluidized-bed regime. At high pressures the system may operate in the turbulent fluidized-bed regime. In one process, a company was mathematically modeling its high-pressure, fluidized-bed reactor as a bubbling bed. Experiencing difficulty in predicting results, the company conducted tests in a cold model at high pressures and found that it was actually operating in the turbulent fluidized-bed regime instead of the bubbling-bed regime *(Fig. 8)*.

One should also be careful when operating pressurized cold models on a very small scale and then translating the results to a large scale. To illustrate the problem that can sometimes occur with small, pressurized cold models, the following example is given. Two studies in the literature have looked at the question of how solids holdup in a riser is affected by system pressure. One study [4] was conducted in a 2.6-cm-diameter riser, and the other [5] in a 30-cm-diameter riser. The results of these two studies are shown in Figures 9 and 10, respectively. The study conducted in the small riser showed that the pressure drop in the riser (usually taken to be proportional to the solids holdup in the riser) increased with system pressure. The study conducted in the larger riser showed that the pressure drop in the riser decreased with system pressure. The apparent contradiction between the two results is because of the high frictional losses in the small riser because of the high gas density. If the gas pressure drop is given as:

$$\Delta P_{fg} = \frac{0.158 U_g^{1.75} L \mu^{0.25} \rho_g^{0.75}}{D_t^{1.25}}$$

then:

$$\frac{\Delta P_{D_t = 2.6 \text{ cm}}}{\Delta P_{D_t = 30 \text{ cm}}} = 21$$

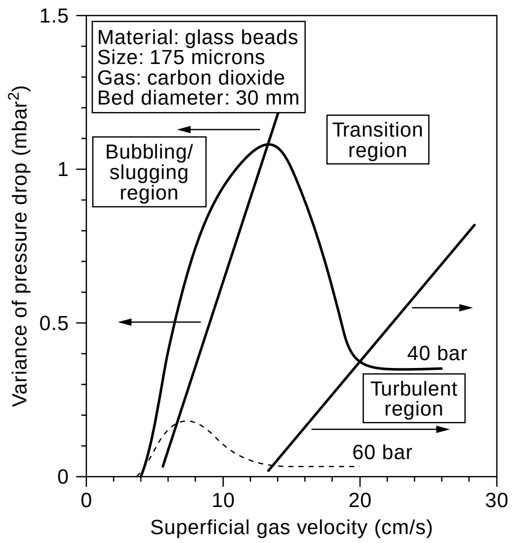

Figure 7

The effect of pressure on the transition from bubbling to turbulent fluidization (Marzocchella and Salatino).

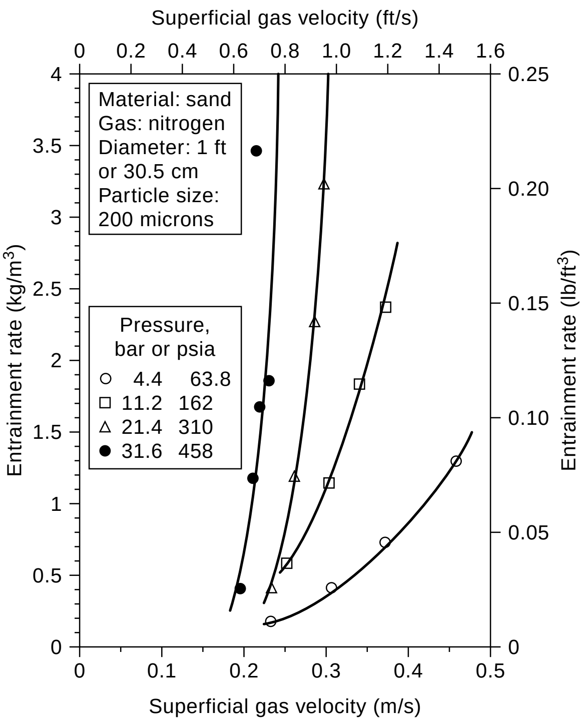

Figure 6

The effect of pressure on entrainment [3].

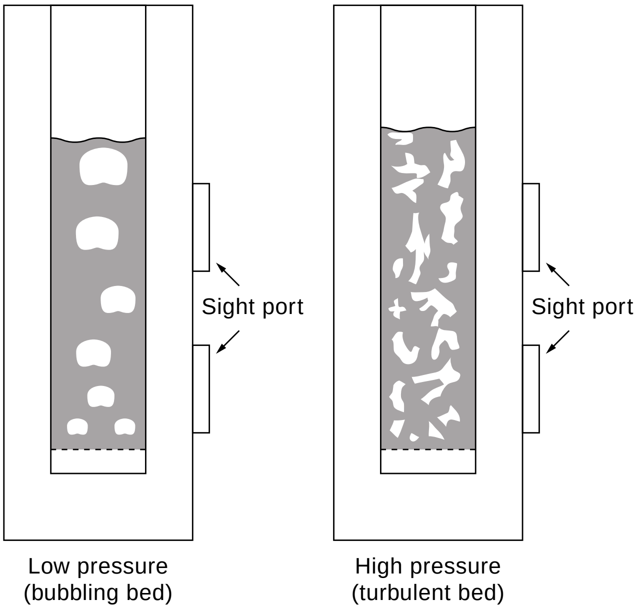

Figure 8

Pressure can cause regime transitions in fluidized systems.

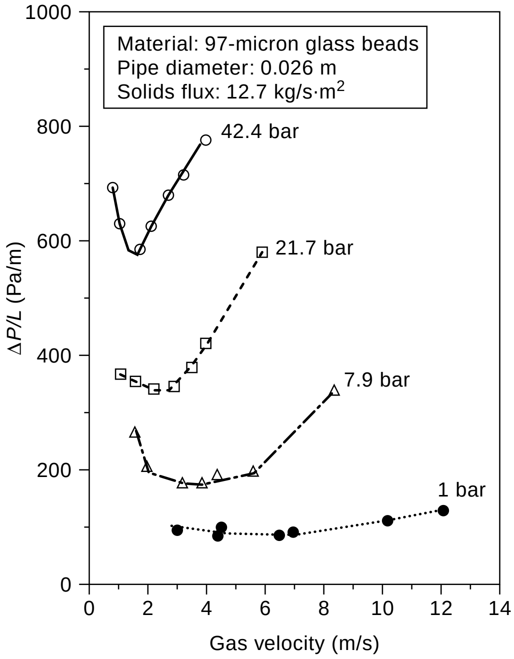

Figure 9

Small riser pressure drop per unit length *versus* gas velocity [4].

Thus, the pressure drop due to gas friction in the small riser was approximately 21 times that in the larger riser, dominated the pressure drop in the small riser and masked the effects of the solids holdup.

Glicksman, Hyre and Woloshun [6] and Horio *et al.* [7] have proposed scaling laws based on dimensionless groups. They claim that similarity is achieved between a small-diameter cold model and a large, hot commercial unit when the dimensionless scaling groups are the same in both systems. The simplified Glicksman scaling parameters for a fluidized bed are:

$$\left(\frac{U_g^2}{g\,D_t}\right),\ \left(\frac{\rho_p}{\rho_g}\right),\ \left(\frac{U_g}{U_{mf}}\right)$$

In addition, the bed geometry must be scaled the same and the particle size distribution should have the same shape in the small unit as in the large unit. The approach used by Glicksman and the approach used by Horio do not take into account static, van der Walls or any other interparticle forces.

Most (limited) studies have shown the scaling laws appear to be valid. If so, the scaling laws are potentially a useful tool to help in designing new hardware or helping solve problems in existing units.

Unfortunately, using the scaling laws often requires that particle size and density be different in the small cold model

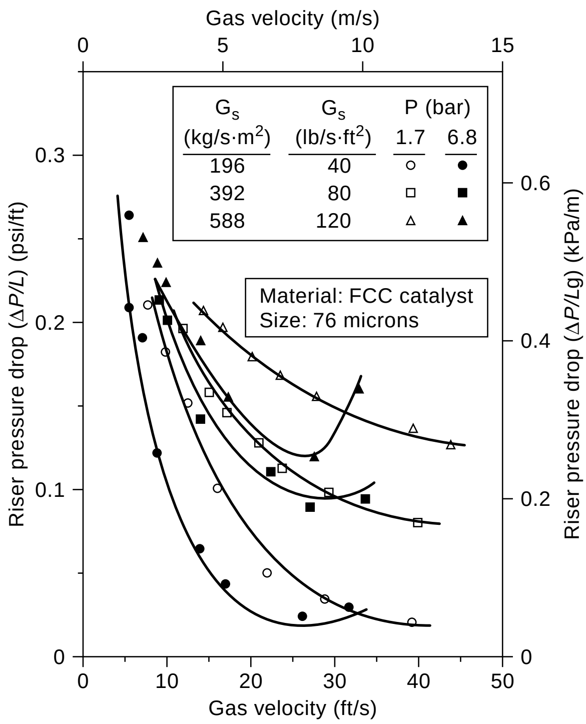

Figure 10

Large riser pressure drop per unit length *versus* gas velocity [5].

than in the large, hot unit. Generally, particle size will be smaller and particle density will be greater in the small, cold unit. If Geldart Group B particles are being utilized in the large, hot unit, the laws often require that Geldart Group A particles be used in the cold, small unit. Because Group B and Group A solids fluidized differently, these laws may not be applicable when particle group changes are required.

The scaling laws are usually not good for process scale-up purposes. Generally, small-scale pilot plants are operated with the same materials that will be used in the commercial plant (not the scaled particle size and density) because it is required to either check the chemistry or to look at attrition, etc., in the pilot plant using the same material.

However, the scaling laws may be very useful whenever an existing plant is required to change a piece of equipment. One example would be when existing internal heat transfer tubes need to be changed to a new configuration. A small-scale, cold fluidized bed operating with the same hydrodynamics as the larger plant could be an extremely useful tool to determine the correct configuration of the tubes.

Pilot plants are useful tools in both helping to scale up to a larger unit or to solve problems on an existing unit. When designing a pilot plant, one is always faced with the question of how large to make it. If the pilot plant is too small, there will be problems with wall effects (slugging, excess friction, etc.). If the pilot plant is too large, the cost will be exorbitant and it will take a much larger time to conduct tests on the larger unit.

There is no single answer to the question of how large to make a pilot plant. The answer will depend on both the regime in which the solids are operating and the particle size of the material. Werther [8] found that for beds of Geldart Group A materials operating in the bubbling regime, bubble residence times were not affected by the size of the bed (wall effects were minimized) when the bed diameter was approximately 300 to 400 mm *(Fig. 11)*. However, this finding cannot usually be applied to Geldart Group B materials because these solids produce larger bubbles that can cause slugging. A larger bed has to be used for these materials if slugging is to be avoided.

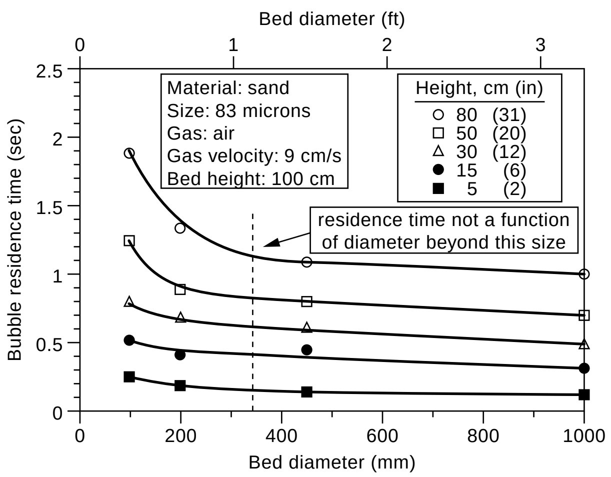

Figure 11

Bubble residence time *versus* bed diameter [8].

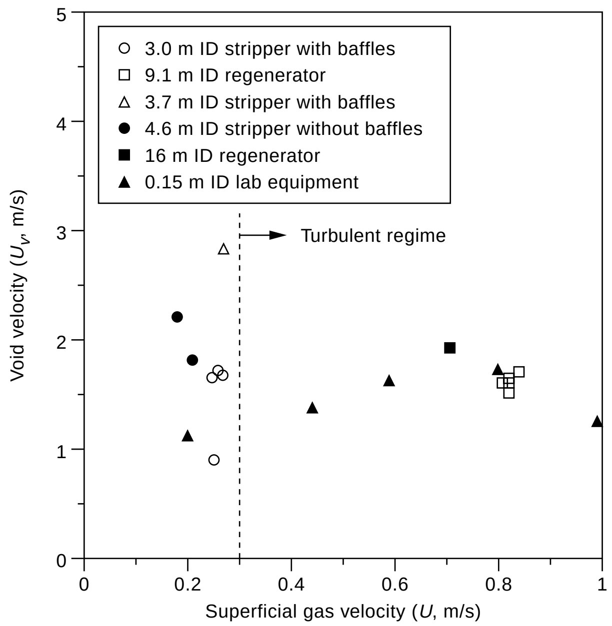

Figure 12

Void velocity *versus* gas velocity for bubbling and turbulent beds (adapted from [9]).

For fluidized beds operating with Group A solids in the turbulent fluidization regime, it has been observed that the void sizes in small beds are similar to those in larger beds *(Fig. 12)*. Thus, a pilot plant can be relatively small and still simulate the hydrodynamics of the large, commercial bed [9] if it is operating in the turbulent regime. Beds of Group B solids operating in the turbulent fluidized-bed regime will also require smaller pilot plants to simulate large bed operation. However, fewer studies have been conducted in turbulent beds of Geldart Group B particles than in beds of Geldart Group A particles. Larger pilot plants for turbulent beds operating with Geldart Group B particles will be required than for pilot plants operating with Geldart Group A particles.

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