Effect of Boundaries on Trickle-Bed Hydrodynamics

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Cocurrent downflow of gas and liquid in a fixed bed of particles is widely used in the petroleum and chemical industries. At low liquid and gas flow rates, the trickling regime, in which the liquid trickles down over the packing and the gas phase is continuous, is observed. At high gas and liquid flow rates, a time-dependent flow regime referred to as pulsing is observed. In pilot-scale experiments with nonfoaming systems, pulsing is manifested as alternating bands of liquid-rich and gas-rich regions propagating down through the column (Weekman and Myers, 1964; Beimesch and Kessler, 1971; Chou et al., 1977; Blok and Drinkenburg, 1982; Blok et al., 1983; Rao and Drinkenburg, 1983; Christensen et al., 1986). A fundamental understanding of the origin of this pulsing flow pattern and its characteristics is important for the rational design and scale-up of these process units.

The approaches to rationalizing and modeling the hydrodynamics can be classified into two groups: the microscopic approach and the macroscopic approach. The microscopic approach involves examination of processes that occur at the single-pore level (Sicardi et al., 1979; Ng, 1986; Melli, 1989; Melli et al., 1990). The macroscopic approach starts with a formulation in terms of properties averaged over a volume larger than a single particle, treating the two fluids as separate interpenetrating continua (Saez and Carbonell, 1985; Sundaresan, 1987; Grosser et al., 1988; Dankworth et al., 1990) and views pulsing as the consequence of a loss of stability. In this spirit, the two approaches complement each other. Both approaches seem to capture the onset of pulsing reasonably well (Ng, 1986; Grosser et al., 1988). However, neither one has been able to predict satisfactorily all the details of flow inside the pulsing regime, as will be discussed subsequently.

Experimental observations at the pore level using a specially designed two-dimensional bed (Kolb et al., 1990) reveal pulsing as fluctuations having a characteristic frequency of 50–75 Hz, while experimental observations in actual pilot-scale units yield characteristic frequencies in the range of 1–5 Hz. How and why the rapid fluctuations at the single-pore level lead to much slower fluctuations at the bed level remain to be resolved.

The macroscopic approach has not been able to capture the pulse frequency either (Dankworth et al., 1990). In fact, such an approach applied to an infinitely long bed simply concludes that the bed can support periodic, traveling wave solutions over a wide range of frequencies (0–100 Hz). Which of these is selected (and why) remains unclear. Dankworth et al. (1990) found it unsatisfactory to deduce a criterion from a linear stability analysis around the base (uniform) state that the wavelength, for which the growth rate of linear waves has the largest positive value, will prevail. This perhaps implies that the pulse frequency is not selected by the bed, but by some external conditions. For example, in real units one has to consider the influence of the top and bottom boundaries on the dynamics as well. Such a suspicion is not entirely unwarranted. It is well known that the quality of distribution at the top boundary can have a profound influence on the bed dynamics (Christensen et al., 1986).

When pulsing is observed in pilot units, it is first seen at the bottom of the column, just above the bottom support plate. Upon increasing the flow rates (into the pulsing regime), this point where well-developed pulses first appear moves further and further up in the column (Weekman and Myers, 1964; Blok and Drinkenberg, 1983). It has been implicitly assumed in the past that this is a consequence of the expansion of the gas as it moves down through the column. This, however, has never been established conclusively. One can conceivably take a viewpoint that this feature is indicative of the effect of the bottom boundary.

It follows from the above discussion that we still do not understand if the top boundary, the bed itself, or the bottom boundary (or some combination of these three) dictates the characteristic frequency of the pulses. This note describes an experimental study on this issue, which by no means is meant to be an idle curiosity, since a rational scale-up of pulsing flow is hardly feasible until we can answer this question.

As already mentioned, a poor design of the top distributor and the bottom support plate can alter the flow characteristics completely. In the present study, we will not be concerned with this. Instead, we will "perturb" the top and bottom boundaries, without intentionally creating defective boundaries, and observe if the characteristics of pulsing flow are affected by the imposed perturbations.

Experimental Study

Experiments were carried out in a cylindrical column having an ID of 0.165 m. The packed bed was 1.49-m-high and consisted of 3-mm-diameter glass beads. Care was taken to dis-

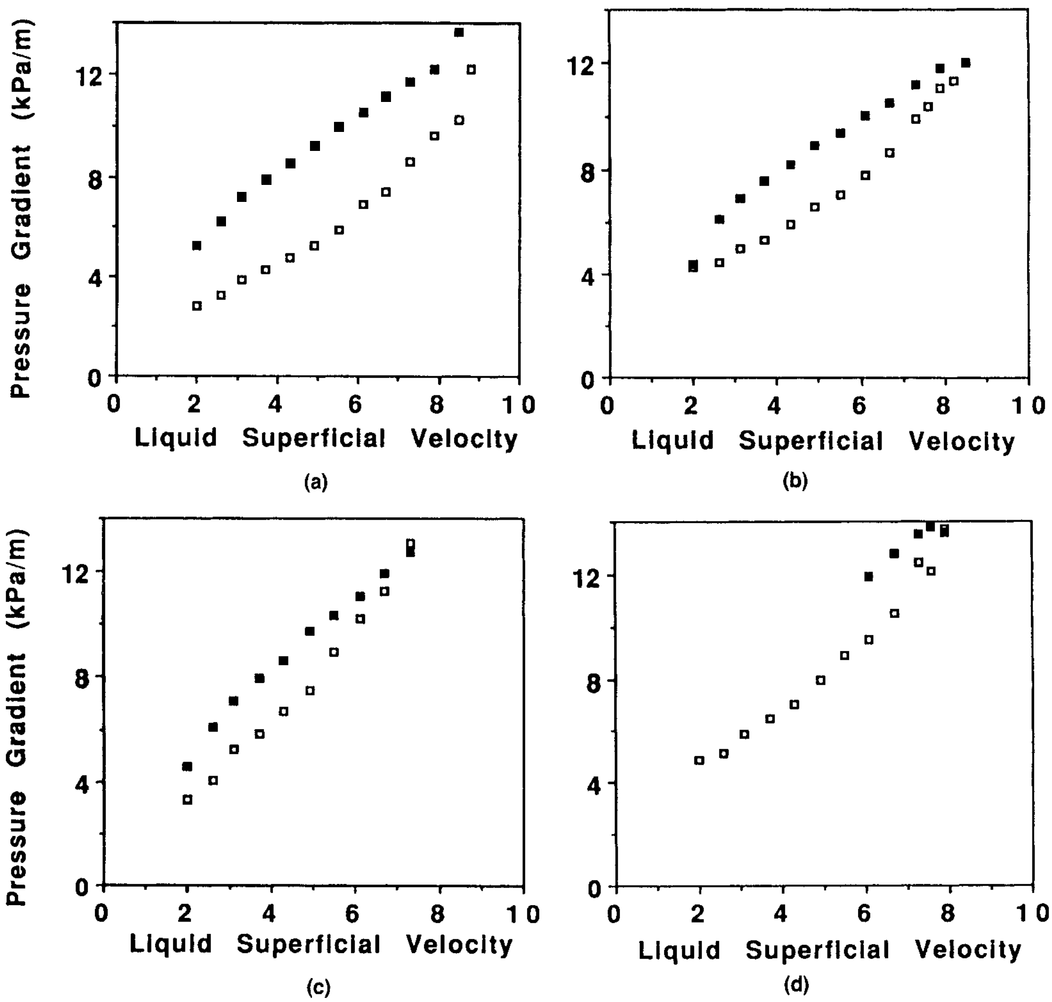

Figure 1. Pressure gradient as a function of liquid superficial velocity.

Gas superficial velocity = 0.22 m/s. ■, increasing liquid rate; □, decreasing liquid rate. (a) bed #1; (b) bed #2; (c) bed #3; (d) bed #4.

tribute air and water uniformly at the top using two distributor plates in series. Further details on the distributor design can be found elsewhere (Szady, 1990). The liquid rained from the distributor for a distance of 5 cm before entering the packed bed. The bed was supported at the bottom using a brass screen mesh (henceforth, referred to as the nonrestrictive support). The holes in it were 2 mm × 2 mm, and its thickness was 1 mm. For some of the experiments, a second finer wire mesh (made of aluminum) was placed on top of the brass screen mesh. The aluminum mesh has 1.5 mm × 1.5 mm opening. We will refer to this double-screen support as restrictive support.

In base-case experiments, the packed bed contained only the 3-mm glass beads (henceforth, referred to as uniform bed). Its voidage was estimated to be 0.37. To perturb the top boundary, a layer of the 3-mm packing (typically 5 to 10 cm) was removed and replaced with (the same height of) 6-mm glass spheres or 6.4-mm rashig rings. The 6-mm glass spheres were packed with essentially the same porosity as the 3-mm beads, so that the only real change is the particle diameter. The voidage of the layer of rashig rings was 0.42.

A second type of perturbation of the bottom boundary involved placing a layer of the rashig rings (on top of the wire mesh) before packing the 3-mm glass beads.

Using various combinations of these perturbations, flow measurements were carried out both in the trickling regime and in the pulsing regime. Pressure gradients in the interior of the bed (away from the boundaries), average liquid saturation, pulse velocity and pulse frequency were determined. Details of the experimental procedures can be found elsewhere (Szady, 1990), and these will not be described here for the sake of brevity. We simply note here that the pulse velocity was determined by measuring the time required for the pulses to traverse a known distance, the pulse frequency by counting the total number of pulses in a prescribed length of time, and the liquid saturation by a simple weighing technique.

Results and Discussion

Trickling regime of flow

It is now well established that a multiplicity of hydrodynamic states can be obtained for a given set of flow rates in the

Table 1. Effects of Boundaries on Hysteresis

Bed #1:	Restrictive bottom support with a uniform bed of 3-mm glass beads
Bed #2:	Nonrestrictive bottom support with a uniform bed
Bed #3:	Nonrestrictive bottom support with a 10-cm layer of rashig rings at the top
Bed #4:	Nonrestrictive bottom support with a 10-cm layer of rashig rings at the bottom
Bed #5:	Nonrestrictive bottom support with a 10-cm layer of 6-mm glass spheres at the top

Table 2. Onset of Pulsing Flow

Gas Superficial Velocity (m/s)	Liquid Superficial Velocity (mm/s)				
	Bed #1	Bed #2	Bed #3	Bed #4	Bed #5
0.18		8.9	8.9		
0.22	7.7	8.0	8.6	7.7	8.3
0.26		7.4	8.0		

trickling regime, depending on how the flows are established (Kan and Greenfield, 1978, 1979; Levec et al., 1984, 1986, 1988; Christensen et al., 1986). This multiplicity has been interpreted as being due to the liquid flowing in two different modes: film flow and rivulet (filament) flow (Christensen et al., 1986; Chu and Ng, 1989).

We examined how the boundaries affected this hysteresis. Figure 1 displays the pressure gradient as a function of liquid superficial velocity for a fixed gas superficial velocity of 0.22 m/s. Results are shown for four different beds (see Table 1). The beds were thoroughly wetted by first flooding the column with liquid and then operating at the desired gas flow rate and a high liquid flow rate (in the pulsing regime). The filled data points in this figure were obtained by gradually decreasing the liquid flow rate. The unfilled data points were then obtained by increasing the liquid flow rate gradually (from zero).

It is readily seen that, at low liquid superficial velocities (away from the pulsing inception points), the pressure gradient in the bed corresponding to the upper branch is influenced only weakly by the changes at the boundary. In contrast, the lower branch manifests a strong dependence on the boundary conditions. When a layer of rashig rings is placed at the top, a pronounced decrease in the pressure gradient results (compare Figures 1b and 1c). We attribute this to a promotion of rivulet flow by the layer of rashig ring at the top. An enhancement of rivulet flow implies a greater segregation (and less interaction) between the gas and the liquid flowing through the column, which leads to a lowering of the pressure gradient (Christensen et al., 1986).

Changes in the lower boundary alters the liquid saturation in the bed. A restrictive support plate makes it more difficult for the liquid to exit at the bottom, causing an increase in the liquid holdup in the bed. This, in turn, increases the pressure gradient required to maintain the two-phase flow (compare Figures 1a and 1b). To illustrate this, the average liquid saturations in beds 1 and 2 (see Table 1) at various liquid and gas superficial velocities are shown in Figure 2. The effect of support plate restrictiveness on liquid saturation is pronounced at low gas flow rates, becoming less pronounced at higher gas fluxes.

It was at first puzzling to see a layer of rashig rings at the bottom should increase in the pressure gradient inside the bed (compare Figures 1b and 1d). The rashig rings are bigger than the glass beads, and this layer has a higher voidage than the bed of glass beads (0.42 vs. 0.37). A plausible explanation is that not all the void space in the rashig ring layer was available for flow. The central hole in the rashig rings was only 1 mm in diameter. It is possible that this cavity was filled with liquid that is essentially stationary. If we subtract the volume associated with this central hole, the remaining porosity in the rashig ring layer was only 0.35 (which is lower than the glass bead packing).

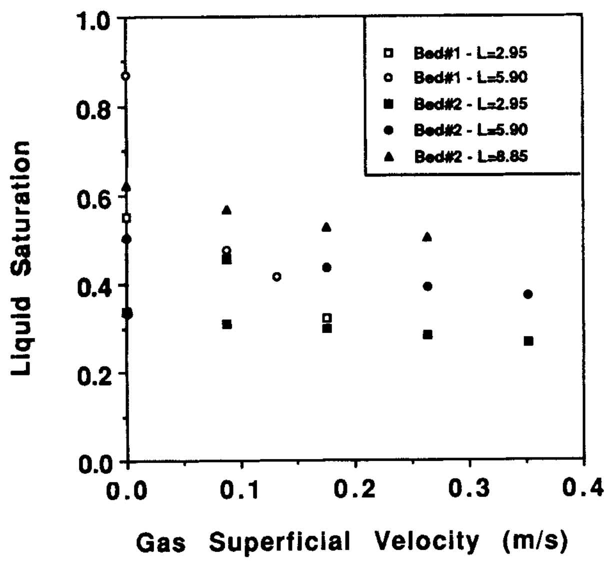

Figure 2. Liquid saturation as a function of gas superficial velocity.

Liquid superficial velocities L are in mm/s.

Trickling-to-pulsing transition

Not surprisingly, the boundaries had an effect on the onset of pulsing as well. This is illustrated in Table 2. Increasing the restrictiveness of the lower boundary results in the inception of pulsing at lower liquid fluxes, and this is attributed to an increase in the liquid saturation. Any enhancement of the rivulet flow (by the upper boundary) necessarily decreases the interaction between the gas and liquid, leading to a delay in the onset of pulsing. Thus, the results shown in Table 2 are easy to understand.

Pulsing regime of flow

The average pressure gradients in the interior of the beds described in Table 1 are plotted in Figure 3 as a function of liquid superficial velocity. The gas superficial velocity was kept constant at 0.22 m/s. It is interesting to note that the top boundary had almost no effect on the average pressure gradient. As the restrictiveness of the bottom boundary increased, so did the average pressure gradient. Similar trends were observed at other gas flow rates as well (Szady, 1990).

Figures 4 and 5 show the effects of changes at the upper

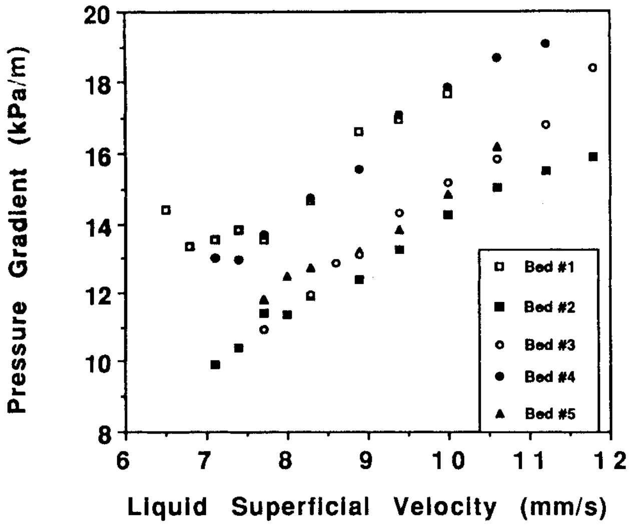

Figure 3. Pressure gradient as a function of liquid superficial velocity.

Gas superficial velocity = 0.22 m/s.

and lower boundaries on the velocity and frequency of pulses in the interior of the bed. It appears that both these quantities increase slightly with increasing restrictiveness of the bottom boundary (Figure 5). An increase in the average pressure gradient with increasing restrictiveness of the bottom boundary is certainly consistent with an increase in the frequency (and/or velocity) of the pulses. The upper boundary exerts a weaker influence on these quantities than the bottom boundary does (compares Figures 4 and 5).

Thus, one can see that the perturbations at the upper boundary have little effect on the pulse properties, while those at the bottom boundary have resulted in changes in the pressure gradient, pulse velocity, and pulse frequency. These changes, however, are not large and these are comparable to the fluctuations found typically in pulsing flow. Conceivably, a more pronounced perturbation of the bottom boundary (than the ones used in our study) may produce larger changes in pulse properties. We could not ascertain this.

It can be seen from Figure 5b that increasing the restrictiveness of the bottom boundary tends to increase the pulse frequency. This appears entirely reasonable, since by increasing

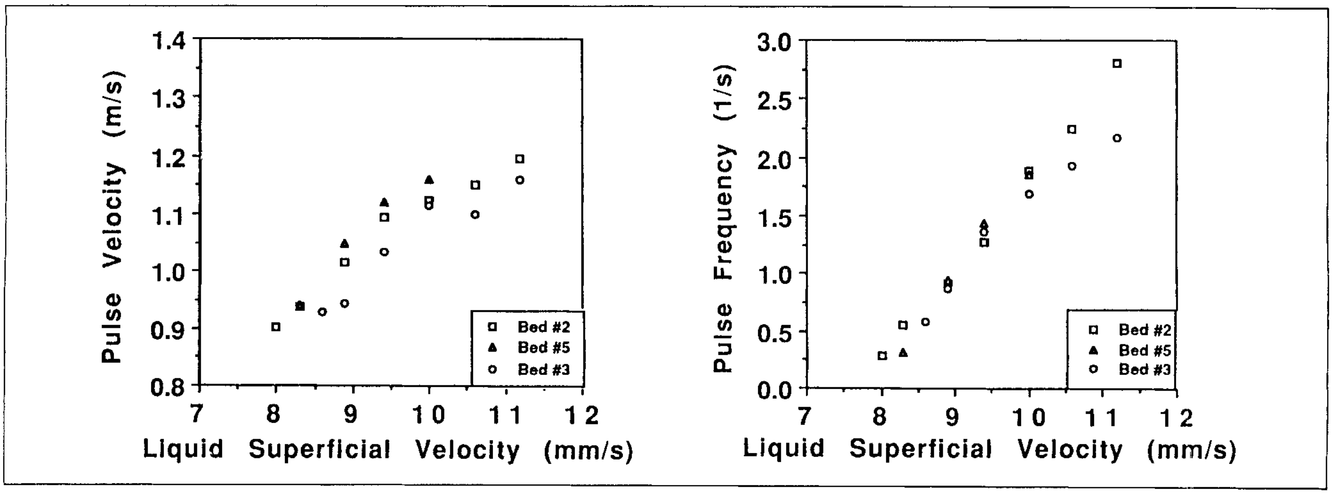

Figure 4. Pulse velocity and frequency as a function of liquid superficial velocity.

Gas superficial velocity = 0.22 m/s.

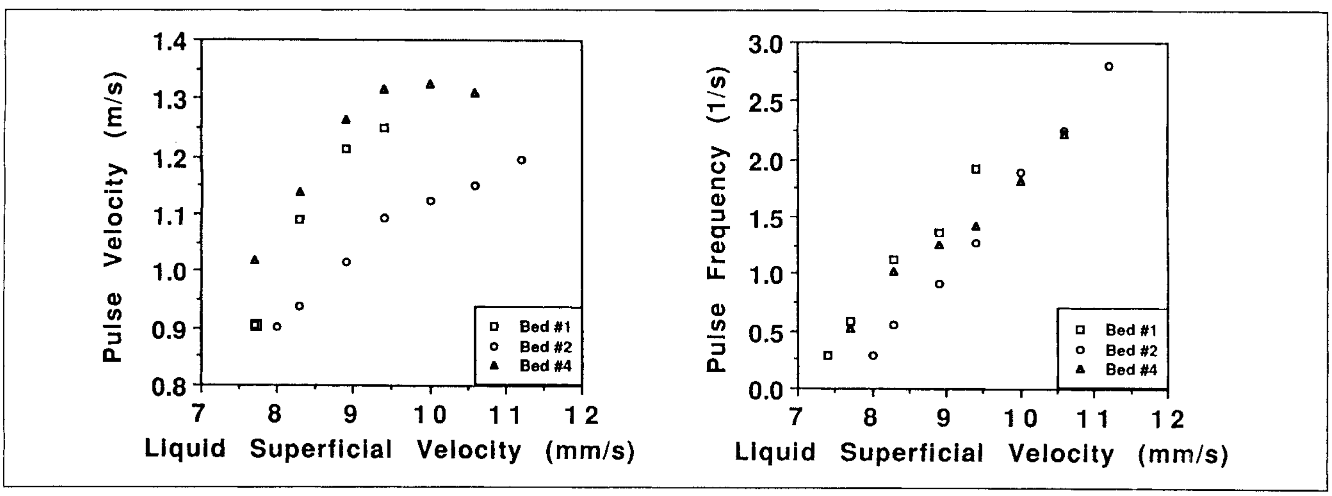

Figure 5. Pulse velocity and frequency as a function of liquid superficial velocity.

Gas superficial velocity = 0.22 m/s.

the restrictiveness of the bottom boundary we increase the liquid saturation there. This then promotes the likelihood and frequency of occlusion of flow channels and hence pulsing.

It is tempting to reject this notion and claim that both boundaries have only a weak influence on the pulsing flow characteristics and that these characteristics are indeed determined by the bed itself. This claim can be maintained by the simple fact that experiments carried out in various laboratories over many decades (who surely would have used quite different support plates at the bottom) have yielded similar estimates for the pulsing flow characteristics. Our experiments have not been able to categorically reject this argument. However, if this is indeed the correct conclusion, we are still left with the puzzling question: If the bed selects the pulse frequency, how does it do it?

Summary

Both the upper and lower boundaries affect the flow characteristics in the trickling regime of flow, such as pressure gradient, extent of rivulet formation, and liquid saturation. They also affect the onset of pulsing. In the interior of the pulsing regime, however, the top boundary has a negligible effect on the flow characteristics. In contrast, a small, but measurable, effect of the bottom boundary on the pulsing flow characteristics was observed in our experiments.

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