Instability Phenomenon in an External-Loop Three-Phase Gas-Liquid-Solid Airlift Reactor

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Three-phase airlift (TPAL) reactors have applications ranging from biotechnology (Heijen et al., 1990) to catalytic hydrogenation. Circulation in a loop consisting of a riser and downcomer with top and bottom connections is induced by injecting gas at the bottom of the riser. The continuous liquid phase recirculates up the riser and down the downcomer, carrying the solid phase in suspension. Main advantages of TPAL reactors include the ability to suspend solid particles at a relatively low gas superficial velocity, elimination of stagnant zones, and the absence of any moving parts or external recirculation mechanism. In general, two airlift reactor configurations can be distinguished: the internal-loop airlift, which consists of two concentric cylinders, and the external-loop airlift, where the riser and downcomer are separate tubes connected at the top and bottom (Chisti and Moo-Young, 1987).

A hydrodynamic model was developed for TPAL reactors (Livingston and Zhang, 1993; Douek et al., 1994), which enables the prediction of main variables of a TPAL reactor (phase holdups and liquid recirculation velocity) as a function of the inlet gas superficial velocity and the solids loading. This model considers a TPAL reactor to comprise riser and downcomer sections alone; the difference in the effective densities between these regions gives rise to the recirculation. As part of a program of experimental work aimed at verifying this model, it was decided to carry out experiments on an external-loop reactor which would generate direct measurements of the required riser and downcomer hydrodynamic parameters. During the course of these experiments, however, a surprising and before now unreported instability phenomenon was observed. This behavior prevented the system from reaching a steady distribution of solids.

In general, instabilities are undesirable since they could adversely affect the system control and performance. The objective of this article is to describe the observed phenomenon and attempt to explain why it occurs.

Experimental Studies

Experiments were conducted using the apparatus shown in Figure 1. The total working volume of the reactor was 35 L, with riser and downcomer sections of approximately 2 m height and a pipe diameter of 8 cm throughout. Gas entered the base of the reactor via an 8 cm sintered glass plate, with a pore diameter of 40 μm. The gap between the bottom of the riser and the gas distributor was fixed at 4 cm. In order to minimize the quantity of glass beads which settle out in the top and bottom flow reversal regions, it was decided to use 45° pipe junctions for these (Figure 1). This geometrical arrangement reduces the influence of the fluid reversal zones on the overall driving force for the recirculation and should therefore enable a better comparison between the experimental results and model-generated predictions.

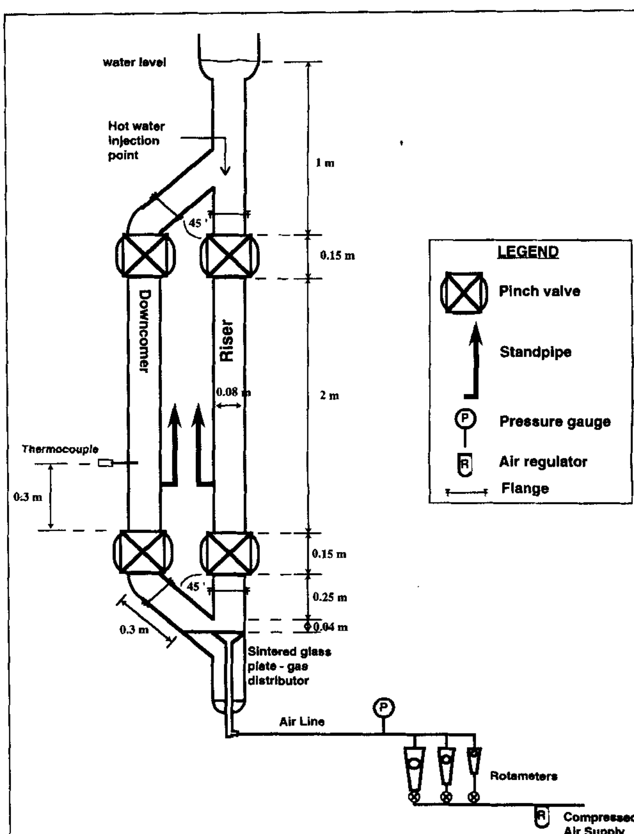

Figure 1. External-loop TPAL reactor experimental rig.

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The rig was operated at standard temperature and pressure, using air as the gas phase, deionized water as the liquid phase, and 500 μm diameter glass beads (density 2,950 kg·m^{-3}) as the solid phase. The gas superficial velocity was measured using a set of rotameters. The average liquid recirculation velocity was obtained using a thermal tracer method, which involves injecting a pulse of hot water into the flowing liquid and plotting the temperature profile at a fixed point in the downcomer on a chart recorder. The distance between successive temperature peaks is then a measure of the average time it takes for a fluid element to complete one loop.

Three different solids loadings have been tested corresponding to concentrations of 40, 70 and 100 kg·m^{-3} (water). Experiments were carried out by visually observing the flow in the system, starting with solids in packed bed mode (where the solids are at rest in the lower extremities of the riser and downcomer), and incrementally increasing the superficial gas velocity U_G until the solids were fully recirculating. Direct measurements of the average phase holdups in the riser and downcomer were obtained using a series of quick-closing pinch valves placed in the flow circuit (Douek et al., 1994).

Results and Discussion

Visual observations

At low gas superficial velocities, when the solids were in packed-bed mode, the liquid recirculation velocity U_{LR} was low and very few bubbles were entrained in the downcomer. As the gas superficial velocity was increased, the solids began to fluidize in the riser decreasing resistance to the flow and thus increasing U_{LR} (Figure 2). At a higher U_G, the transition to the circulated-bed mode occurred; the whole fluidized bed was carried over into the downcomer and began to recirculate round the loop. This was expected to be just a short transition behavior, which would result in a steady solids distribution between the riser and downcomer, with a higher solids content in the riser due to the positive solids settling velocity.

Contrary to expectations, however, an instability was observed to occur during the circulated-bed mode. This took the form of a zone of high solids concentration, which moved round the loop, periodically accelerating and decelerating the flow depending on whether it was traversing the downcomer or riser, respectively. To verify whether this was only a startup phenomenon, the rig was allowed to run uninterrupted overnight; after 14 h of continuous operation, the same behavior persisted, which indicates that this instability was self-sustaining. The onset of the unstable cycle occurs when there is a sufficient gas superficial velocity to carry the fluidized bed over into the downcomer (there exists a net solids superficial velocity in the riser). The cyclical pattern of this instability is represented in Figure 3 and described as follows:

(1) As the solids start falling down the downcomer, they cause a positive buoyancy effect (due to the increased solids concentration in the downcomer) which increases the liquid recirculation velocity (the accelerational phase). This is reflected in an observed increase in the number and size of bubbles that get entrained in the downcomer. The extra bubbles remain stationary in the downcomer until the bulk of the solids cloud reaches the bottom flow reversal zone.

(2) The bulk of the solids reach the bottom of the downcomer and begin to rise up the riser.

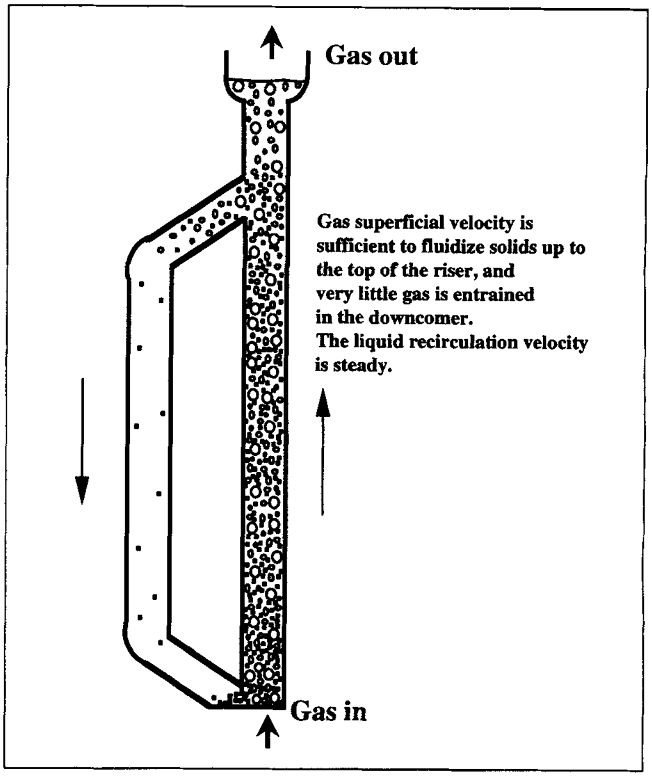

Figure 2. Rig operated in the fluidized-bed mode.

(3) The presence of the solid particles in the riser has a negative buoyancy effect on the loop causing a decrease in the liquid recirculation velocity (referred to as the deceleration phase). This results in some of the solids beginning to settle out onto the bottom gas distributor; simultaneously, the extra gas bubbles which had been entrained in the downcomer during the accelerational phase begin moving countercurrently upward in the downcomer (their terminal rise velocity now being larger than the downward liquid velocity).

After the extra bubbles have dispersed from the downcomer out of the top flow reversal zone, the driving force for liquid recirculation increases, accelerating the flow and picking up the solids which had settled on the gas sparger. The cycle then repeats itself.

During the first set of experiments using a loop-average solids concentration of 40 kg·m^{-3} (water), the transition point to the circulated-bed mode typically occurred at a U_G value of 0.04 m·s^{-1}. An increase in the gas superficial velocity resulted in the region of high solids concentration becoming spatially more elongated, though it was still possible to visually detect the instability. A further increase in U_G above a value of approximately 0.10 m·s^{-1} resulted in a much greater number of bubbles being carried over into the downcomer, making it difficult to determine whether or not the system was still affected by the instability. At these high U_G values, a certain proportion of gas bubbles were completely recirculated indicating that the induced liquid recirculation velocity was relatively large. A value of U_{LR}, which is greater than the variations caused by the uneven solids distribution, may lead to an attenuation of the unstable cycle.

The onset of this instability was first observed by gradually increasing the superficial gas velocity to recirculate the solids,

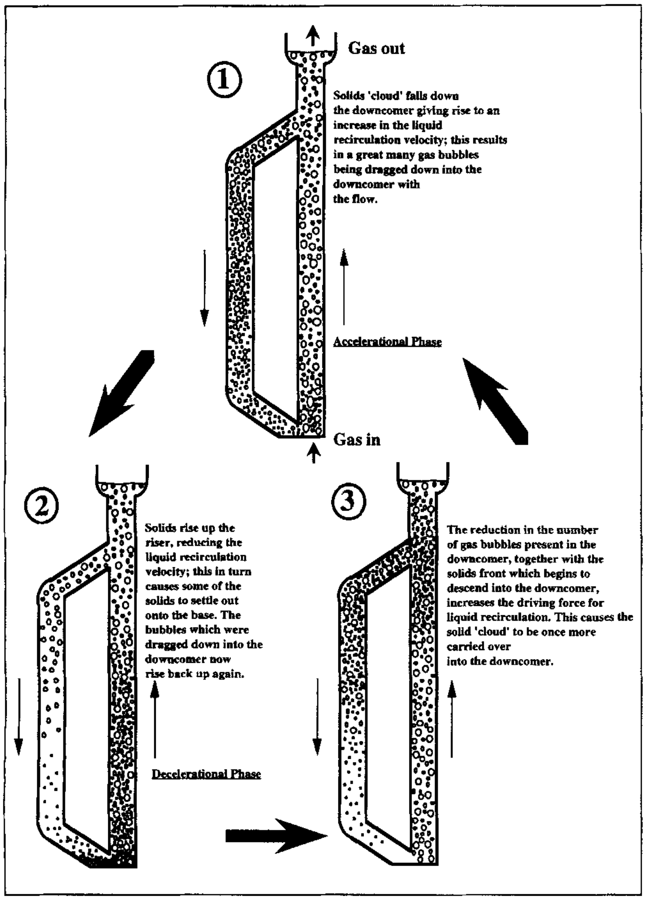

Figure 3. Stages of Instability cycle.

commencing from a fluidized-bed regime. An alternative approach, in which the gas velocity was first raised to a high value (> 0.1 $m \cdot s^{-1}$) and then reduced, showed that the instability occurred whether the 0.04-0.1 $m \cdot s^{-1}$ U_G range was approached from above or below.

An increase in the solids concentration to 70 $kg \cdot m^{-3}$ (water) resulted in the critical gas velocity required to induce solids recirculation increasing to $U_G = 0.06$ $m \cdot s^{-1}$. At this higher solids loading the instability cycle was much more pronounced and easily detectable up to quite high values of U_G. Likewise, a further increase in solids concentration to 100 $kg \cdot m^{-3}$ (water) resulted in a more acute cycle, though at low gas superficial velocities the extra resistance to flow of the large packed bed occasionally caused the gas flow to be diverted up into the downcomer, making it difficult to determine the exact transition point from the fluidized-bed to the circulated-bed mode.

Quantitative data

Taking a U_G value of 0.07 $m \cdot s^{-1}$ at a solids concentration of 70 $kg \cdot m^{-3}$ (water) as being representative, direct measurements of the phase holdups were made during both the accelerational and decelerational phases and these are shown in Table 1. It can be seen that the variation in solids holdup is considerable, changing by as much as a factor of 10 in the downcomer during any one cycle. It should be stated that precise measurements in oscillating flow cannot be expected

Table 1. Phase Holdup at $U_G = 0.07$ m/s for Accelerational and Decelerational Phases of Cycle

For a Solids Conc. C_s of 70 kg /m^3	ϵ_{SR}	ϵ_{LR}	ϵ_{GR}	ϵ_{SD}	ϵ_{LD}	ϵ_{GD}
Accel. Phase	0.03	0.88	0.09	0.03	0.97	0.00
Decel. Phase	0.07	0.82	0.11	0.003	0.96	0.04

since the timing of the measurements in the respective phases of the oscillation was necessarily subjective; nevertheless, gross variations in solid concentration do occur with implications for reactor behavior. The variations in U_{LR} gave rise to an irregular pattern of temperature peaks on the chart recorder, making it difficult also to quantitatively assess the instantaneous values of the liquid recirculation velocity. Values were, however, typically in the range $0.2-0.3$ $m \cdot s^{-1}$. Measurements of the period of oscillation were made using a stopwatch, yielding an average figure of 150 s per cycle (time taken for the cycle described on Figure 3 to repeat itself). This value was found to depend on the mass of solids present in the reactor and on the prevailing gas superficial velocity.

Phenomenological description

To our knowledge, the instability observed in this work has not been reported elsewhere. Generally speaking, most of the information available on instabilities is for two-phase gas-liquid systems (Ishii, 1982). These can be classified as either static or dynamic instabilities, depending on the type of conservation equations used to describe them (Lahey and Podowski, 1989). Static instabilities are nonperiodic and often associated with thermal-hydraulic systems, and can therefore be immediately discounted as potential explanations. Among dynamic instabilities, the only two types which may be relevant to the system studied here are the density-wave and pressure-drop oscillations.

Physical mechanisms associated with density-wave oscillations in gas-liquid systems are well understood. This instability mode is caused by a lag introduced into a system due to the finite speed of propagation of density perturbations, namely the kinematic wave speed. Density variations are present in the system studied here but the observed propagation velocity of the high solids density region is not sufficiently high to suggest a kinematic wave speed. A rough rule-of-thumb used to determine whether a density wave instability is present in gas-liquid flows is to compare the period of oscillation with twice the transit time T_r of the flow. At a U_G of 0.07 $m \cdot s^{-1}$, U_{LR} is typically 0.3 $m \cdot s^{-1}$ and therefore for a path length of 6 m the average T_r is 20 s. The period of oscillation (fundamental frequency) was measured to be approximately 150 s which is much more than twice the transit time. Furthermore, for a constant solids loading the period of oscillation was observed to decrease with the superficial gas velocity U_G, which implies that this phenomenon does not have a fixed frequency characteristic for a given system. It is thus unlikely that density-wave oscillations are involved here.

Pressure-drop instabilities occur in systems with a region where mass can be stored (such as a compressible volume or an accumulator). These types of instabilities are quite common and come in various forms. Quite often, an unusual geometrical feature can drive a system into this unstable mode (Stenning et al., 1967). It was observed in this experimental

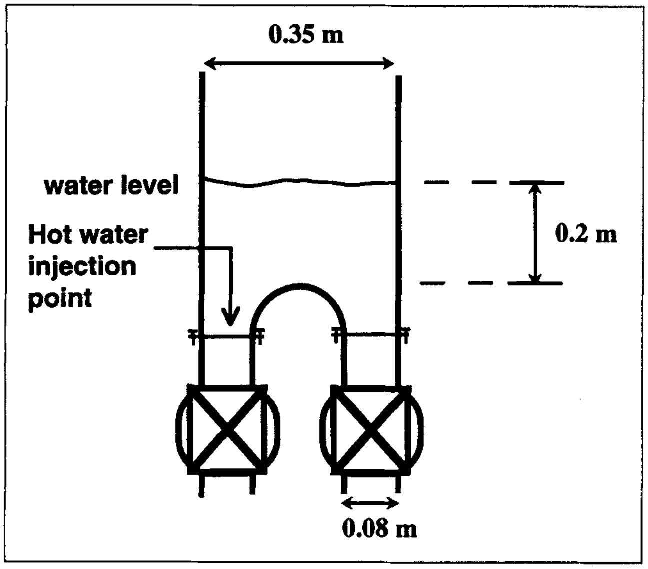

Figure 4. Open tank arrangement for top flow reversal zone.

rig that a fraction of the solids settle out onto the bottom gas sparger during the oscillation cycle. Furthermore, during the accelerational phase, gas bubbles are dragged and stored in the downcomer. The low frequency of the observed instability and the uncommon geometry of the top flow reversal region suggests the presence of a pressure-drop instability. To ascertain whether the rig geometry is related to this behavior, it was decided to replace the top section with an open rectangular tank (Figure 4). After this, the instability disappeared and the rig attained a seemingly steady and continuous solids distribution within a short length of time [under 10 min for $U_G = 0.07\ \text{m}\cdot\text{s}^{-1}$ at a solids concentration of $70\ \text{kg}\cdot\text{m}^{-3}$ (water)]. The presence of a steady flow pattern was verified by carrying out repeated thermal tracer runs and enabled the originally planned investigation of TPAL reactor hydrodynamics using the external-loop reactor (Douek et al., 1994).

The greater resistance to flow of the top 45° bend may have been responsible for driving the rig into an oscillatory mode. One explanation for this is that this region acted as a solids accumulator, causing solids to be fluidized in the vertical section just above the 45° bend. This might then have given rise to a cascade effect where the first solids which enter the downcomer cause a flow acceleration which increasingly drags more solids out of the top junction until the whole solids cloud is brought down. The enhanced mixing which takes place in the open tank arrangement avoids this problem by preventing the solids from spending too long in the top zone.

Conclusions

In industry it is desirable to run TPAL reactors at a gas superficial velocity sufficient to cause the solid particles to recirculate and thus benefit from the close interphase contact created. Too high a gas velocity may cause excessive gas entrainment in the downcomer which lowers the driving force for recirculation and may not necessarily increase the degree of interphase contact. This implies that the desired operational state of a TPAL reactor—operation at low gas velocities near stalling—is most likely to be affected by a loop instability such as the one observed in this study. A preliminary investigation into the nature of the instability reported here suggests that it is not a startup phenomenon, since it occurs with both increasing and decreasing U_G. Instead, it is probably a pressure-drop instability which is due to the particular geometry of the rig used. The frequency and acuteness of the oscillations depend upon the solids loading and the prevailing gas superficial velocity. This phenomenon will be more pronounced when the density difference between the liquid and solid phases is greater, and *vice versa* (since the effect the solids have on the driving force for liquid recirculation will depend on this). The self-perpetuating nature of the oscillations depends on there being a constant timing between the solids cloud passing in the downcomer and the subsequent decelerational phase where the solids concentrate in the riser.

While this note reports on an extreme form of flow instability in a laboratory-scale TPAL reactor, there may be cases in practice where less marked instabilities of this sort occur. In such instances, the effect on the system may be more difficult to detect, but may be important in reactor operation.

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Notation

C_S = concentration of solid particles based on total volume of water in reactor, $\text{kg}\cdot\text{m}^{-3}$
p = pressure, Pa
T_r = transit time, s
U_G = gas superficial velocity, $\text{m}\cdot\text{s}^{-1}$
U_{LR} = liquid superficial recirculation velocity, $\text{m}\cdot\text{s}^{-1}$
W = mass of solid particles added to the reactor, kg
z = distance along loop, m
ϵ_k = fractional holdup of phase k in the column, dimensionless
D = downcomer
G = gas phase
L = liquid phase
R = riser

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