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BOGGING DETECTION IN A FLUIDIZED BED USING PLANNAR CAPACITANCE SENSORS

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ABSTRACT

This paper investigates early bogging detection in a fluidized bed from changes in bubble properties. Bogging has been characterized based on its impact on the breakage of liquid-solid agglomerates in the fluidized bed. Bubble properties such as rise velocity and frequency have been measured in a bubbling fluidized bed of coke particles using non-invasive planar capacitance sensors and the effects of bed agglomeration and fluidization velocity on those variables have been analyzed. Results indicate that the standard deviation of the bubble frequency is highly correlated with the degree of bed agglomeration and can be used to measure the proximity to bogging and, consequently, anticipate its occurrence.

INTRODUCTION

In gas-fluidized processes such as Fluid Coking™ and Fluid Catalytic Cracking, a liquid feed stream is contacted with fluidized particles in the bed. In Fluid Coking, heavy oil is injected into a fluidized bed of hot coke particles, where it undergoes thermal cracking. A high local concentration of liquid in the fluidized bed may result in particles coated with liquid that stick together, which in turn causes bed agglomeration and defluidization, a condition called "bogging".

Several methods have been developed to detect local defluidized zones in fluidized beds. Ropchan (1) measured local heat transfer coefficients of fluidized particles and used their fluctuations to detect defluidized zones of a fluidized bed. These result also confirmed by Marzocchella and Salatino (2). Yutani (3) found that auto correlation of local capacitance signals could be used to find defluidized zones between neighboring gas jets in the grid zone of a fluidized bed. Triboelectric sensors can also be used to detect defluidized zones in the fluidized bed (4). Pressure fluctuations have been used with methods such as the W statistic to characterize the fluidized bed fluidity and detect bogging (5, 6). Chaos analysis of pressure fluctuations was used by Van Ommen et al. to find early agglomeration in the fluidized bed (7). However, this method is expensive, slow and requires several minutes of data.

A warning system for early detection of bogging is of crucial importance in many industrial fluidized beds. Previous studies showed that bubble behavior is greatly affected when the bed material starts agglomerating (5, 6). In this paper, a non-invasive method to detect early bogging is investigated. Early bogging condition in an agglomerating fluidized bed is identified from its impact on the breakage of wet agglomerates, while information on the bubble properties is obtained from planar capacitance sensors.

EXPERIMENTAL SET UP

Experiments were conducted in a fluidized bed 1.97 m high with a trapezoidal cross sectional area, as shown in Figure 1. Two rectangular wooden windows were mounted on two sides of the wall of the fluidized bed to enable capacitance measurement with electrodes on the outside of the bed wall. Coke particles with a Sauter mean diameter of 144 μm and a total mass of 42 kg were used for all the experiments. Measurements have been performed as Volt Esso oil was progressively added to a fluidized bed of coke particles. Volt Esso oil simulates, at room temperature, the properties of heavy oil at high coker temperatures. The bed was fluidized with air at the velocity ranging from 0.1 to 0.2 m/s. In experiments conducted on agglomeration breakage, Varsol was injected with a scaled-down version of an industrial spray nozzle as shown in Figure 1. The whole bed pressure drop was measured with a differential pressure transducer and its signal was acquired at a frequency of 5 kHz.

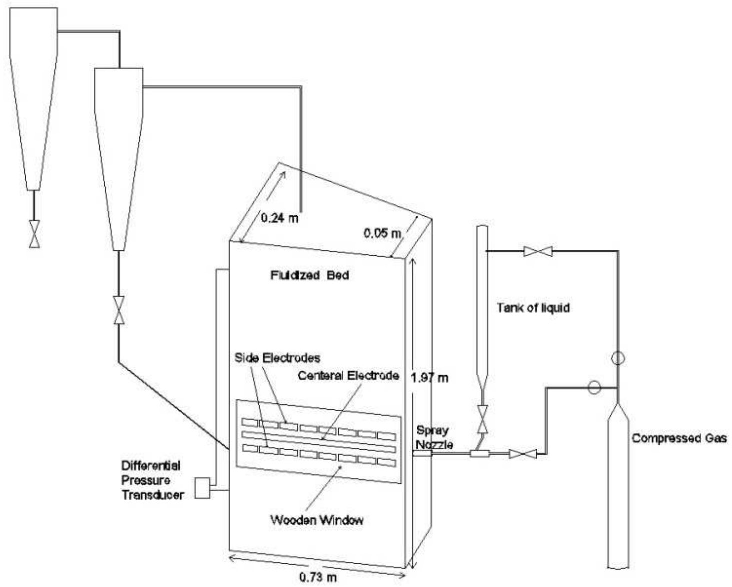

Figure 1 - Schematic of experimental set up

In experiments conducted to characterize bubble properties, voids in the fluidized bed were measured with planar capacitance sensors as shown in Figure 1. The capacitance between the central electrode and each side electrode was measured with an acquisition frequency of 5 kHz during 15 seconds. In experiments conducted to investigate agglomerate breakage, Varsol was detected by measuring the capacitance between a big electrode at one side of the bed and each small electrode at the other side of the bed, with an acquisition frequency of 1 kHz. The capacitance meter was an AC based circuit with a differential noise cancelling system.

EARLY BOGGING CONDITION IN A FLUIDIZED BED

The formation of particle agglomerates in a fluidized bed, which can lead to bogging, is a gradual phenomenon. Therefore in most cases, there is no sharp transition between “fluid” and “bogged” conditions. In a wet bed, the minimum liquid concentration above which the bed becomes bogged depends on each practical application. In this paper the initial point of bogging in the fluidized bed has been characterized by directly investigating the impact of bogging on the quality of fluidization through the analysis of the kinetics of wet agglomerate breakage.

Some calibration experiments were required to measure the mass fraction of the liquid in the fluidized bed that is “free liquid”, i.e. that is not trapped within liquid-solid agglomerates. In these experiments, the relationship between bed capacitance and free liquid concentration has been determined by injecting Varsol into the bed with a special “ideal” spray nozzle operating with an atomization gas to liquid ratio of 50 wt% to prevent the formation of agglomerates.

Normal experiments were performed with a more common atomization gas to liquid ratio of 2 wt%, using a scaled-down version of an industrial spray nozzle. In these experiments, Volt Esso oil was selected as non-evaporating background liquid to generate the bogging condition, while Varsol was injected as foreground liquid. The Varsol mass fraction was calculated with capacitance sensors, using the calibration relationship. After each injection, free Varsol continuously disappears through evaporation and is continuously generated from agglomerate breakage:

$$\frac{d(M_l)}{dt} = \left[\frac{d(M_l)}{dt}\right]_{br} + \left[\frac{d(M_l)}{dt}\right]_e \qquad (1)$$

To determine the agglomerate breakage rate, the evaporation rate was obtained, for each fluidization velocity and free liquid concentration, from calibration experiments.

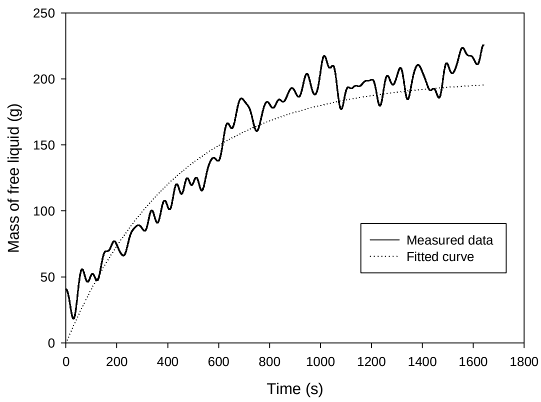

Figure 2 - The mass of total liquid freed from agglomerate versus time

Figure 2 shows the mass of total liquid freed from agglomerates. An exponential curve was fitted to data which can be expressed as:

$$M_l = M_{l0}(1 - e^{-\alpha t}) \quad (2)$$

where M_{l0} is the total mass of liquid initially injected into the bed and α is the natural frequency of agglomerate breakage. Bogging has been determined by measuring α at different oil mass fractions and fluidization velocities.

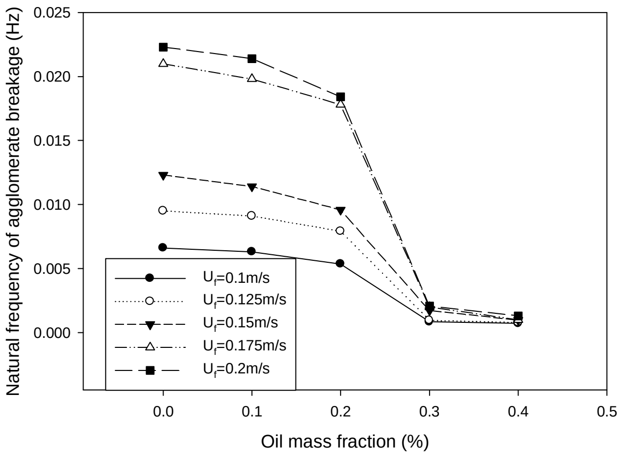

Figure 3 - Effects of fluidization velocity and oil mass fraction on natural frequency of agglomerate breakage

Figure 2 shows that most of the Varsol injected into the bed is initially trapped within agglomerates while the Volt Esso oil was not trapped within agglomerates. As a result, during the Varsol injection, practically all the free liquid, which affects the bed bogging, is in the form of Volt Esso oil and the impact of Varsol on bogging is then negligible.

Figure 3 illustrates the effects of oil mass fraction and fluidization velocity on the natural frequency of agglomerate breakage. The natural frequency of agglomerate breakage increases with increasing fluidization velocity. There are two possible causes: wetter beds may not distribute injected liquid as well as dry beds, and wet beds, by affecting bubble properties, may hinder agglomerate breakage. At higher fluidization velocities, agglomerates are broken more quickly because of the turbulence and shear created by a larger number of gas bubbles. Figure 3 also shows that increasing the oil mass fraction decreases the natural frequency of agglomerate breakage. A sharp drop occurs when the oil fraction reaches 0.3 wt%. This can be explained by the formation of channels in the fluidized bed as a result of bed agglomeration: interactions between particles and the fluidization gas are then reduced which in turn decreases agglomerate breakage. These experiments indicate that bogging occurs when the oil mass fraction reaches 0.2 to 0.3 wt%.

BOGGING INDICES

The objective of this section is to determine how bubble properties, measured with capacitance sensors, are related to the onset of bogging detected from the distribution of liquid sprayed into the fluidized bed. This should also provide a method to detect conditions under which sprayed liquid would no longer be distributed properly and form stronger agglomerates (Figure 3).

Previous studies confirmed that bed agglomeration has a considerable effect on bubble rise velocity, which can be measured directly with planar capacitance sensors (5, 6). In this paper, the rise velocity was determined for each bubble from the ratio of the vertical distance between two electrodes to the measured bubble rise time. Figure 4 shows how the bubble rise time was calculated.

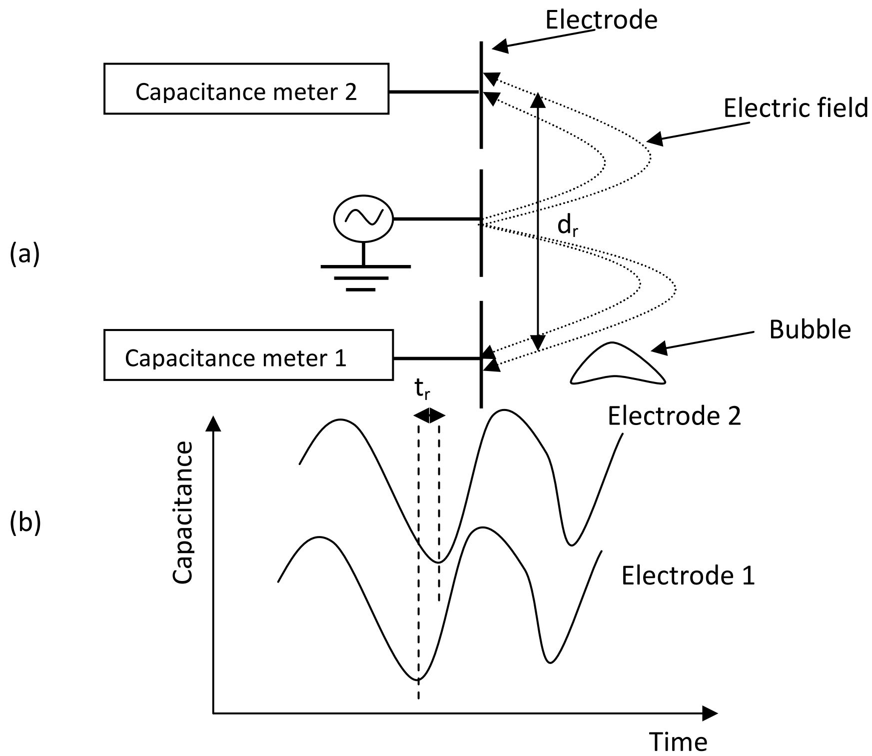

Figure 4 - a) bubble crosses the electric field of three electrodes b) The effect of crossing on capacitance signals – calculation of bubble rise time

Using planar capacitance sensors, one can measure bubble frequency as well as bubble rise velocity. When channeling happens, defluidized zones form at some parts of the fluidized bed which can cause different bubble frequencies at different locations. Therefore, the standard deviation of different bubble frequencies obtained from eight electrodes around the bed can be considered as another bogging index.

In this paper, the bubble rise velocity and standard deviation of bubble frequency are selected as bogging indices.

RESULTS AND DISCUSSION

To investigate the effect of bed agglomeration and fluidization velocity on bogging indices, the fluidized bed was operated with a constant fluidization velocity and Volt Esso oil was added to coke particles in several steps. In each step, the bubble rise velocity and standard deviation of bubble frequency as well as the pressure signal at grid were measured. The same experiments were performed for different fluidization velocities between 0.1 and 0.2 m/s.

In our fluidized bed, the bubble rise velocity was found to be log-normally distributed, as in previous studies (8, 9). Figure 5 shows the effect of bed agglomeration and fluidization velocity on the average bubble velocity.

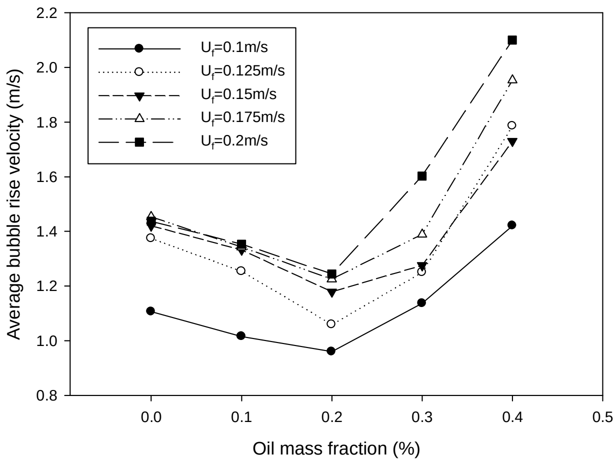

Figure 5 - Effects of fluidization velocity and oil mass fraction on bubble velocity

As displayed in Figure 5, the bubble velocity first decreases with increasing oil content: if bed particles agglomerate, their effective diameter increases resulting in an increase in the minimum fluidization velocity, which explains the decrease in bubble velocity (8). When the oil fraction increases past 0.2 wt%, the bubble velocity starts increasing sharply with increasing oil fraction: this is likely caused by the appearance of channeling. When the channeling begins at some locations of the fluidized bed, the bubble rise velocity increases due to limited routes for the fluidization gas. Figure 5 also indicates that bubble velocity increases with fluidization velocity, as expected (8).

Figure 6 illustrates the effect of fluidization velocity and oil mass fraction on the standard deviation of the bubble frequency, which characterizes the variation of the bubble frequency over the bed width. At first, the standard deviation of the bubble frequency increases slowly with increasing oil fraction. When the oil fraction goes past 0.2 wt% and channeling starts at some locations, the standard deviation of bubble frequency starts increasing much more quickly with increasing oil fraction.

Comparison with W statistic of bed pressure drop

W statistic of a signal characterizes the relative amplitude of small fluctuations (5). In this paper, the W statistic of bed pressure drop has been calculated using a low pass filter with a cut off frequency of 25 Hz. According to Figure 7, the W statistic of the whole bed pressure drop decreases gradually with increasing oil mass fraction. Figure 7 also illustrates that this method cannot indicate when there is bogging, while with capacitance method a sharp decrease was observed at 0.2 wt% oil (Figure 6). While capacitance measurements (Figures 5 and 6) closely track the degradation in the distribution on the fluidized particles of liquid sprayed into the bed (Figure 3), the Wstat of the bed pressure drop cannot. In the original publication (5), a much more sophisticated dynamic pressure transducer was used to directly measure the local dynamic pressure: in most laboratory applications, capacitance measurements are simpler, more convenient and cheaper.

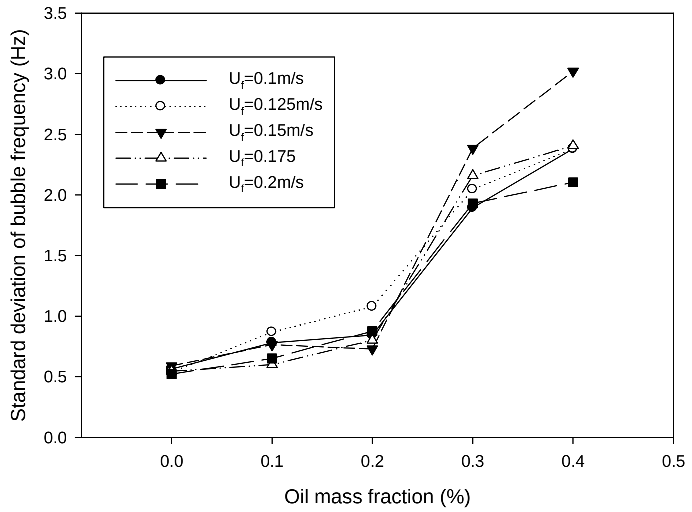

Figure 6 - Effects of fluidization velocity and oil mass fraction on standard deviation of bubble frequency

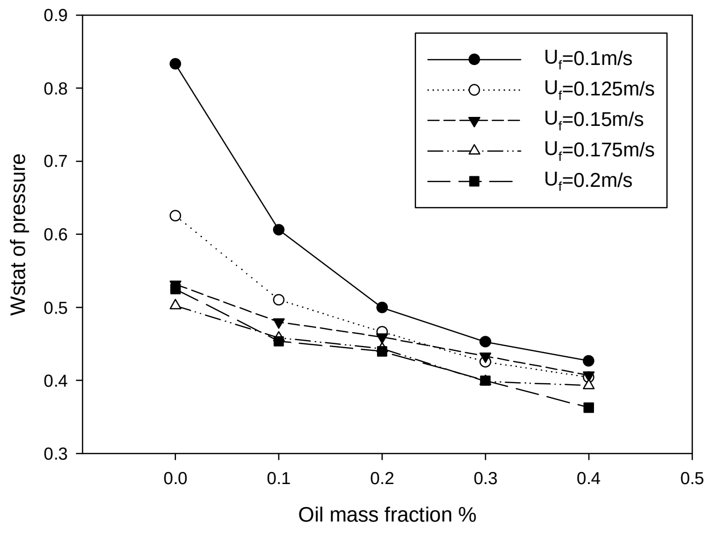

Figure 7 - Effect of bed agglomeration on Wstat of bed pressure drop

CONCLUSIONS

When the liquid concentration in a fluidized bed increases past a critical value, the breakage rate of wet agglomerates slows down, which results in a poorer distribution on the fluidized particles of the liquid sprayed into the bed.

Bubble properties in a wet fluidized bed of coke particles were measured with planar capacitance sensors at different levels of bed moisture and fluidization velocity. Major changes in bubble properties and changes in the kinetics of wet agglomeration breakage occur at the same oil mass fractions. Results indicate that the standard deviation of the bubble frequency can be used as a bogging index, since it increases sharply when the agglomerate breakage drops. This index provides effective detection of bed bogging in a few seconds.

NOTATION

U_f Fluidization velocity

M_l Minimum fluidization velocity

U_b Bubble velocity

$M_{l\,br}$ Mass of liquid of agglomerates

α Natural frequency of agglomerate breakage

D Effective electric field length

d_b Bubble diameter

d_r Bubble rise distance

$M_{l\,ev}$ Evaporated Mass of liquid

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