The Variation of the Bubble Phase Properties of a FCC Fluidized Bed at High Temperature

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THE VARIATION OF THE BUBBLE PHASE PROPERTIES OF A FCC CATALYST FLUIDIZED BED AT HIGH TEMPERATURE

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ABSTRACT

Some important characteristics of the bubbling regime, relevant to a cut of FCC catalyst with an average size of 110 µm were investigated at 100, 400 and 700 °C. This was achieved by employing data of bed collapse tests as well as images of the bubble eruption at the free surface of the bed by varying fluidization velocities and bed aspect ratios. The results show that a smoother regime of fluidization is observed at superambient temperature.

INTRODUCTION

Industrial fluidized bed units are often operated in the bubbling regime at high temperatures, like in the case of catalytic reactors, combustors or gasifiers. In spite of that, current descriptions of their hydrodynamics are still widely based on the results of investigations carried out at room conditions.

Very little is known, therefore, on the specific relationship that links operating temperature and general properties of the bubbling regime of a fluidized bed, a lack of information also connected to the difficulty of producing experimental data by affordable diagnostic techniques. A noticeable uncertainty exists, for instance, on the nature and the behaviour of the bubble phase at elevated temperatures, as bubbles flow across a particulate phase whose properties are definitely influenced by temperature, T.

Literature studies have reported so far some contradictory results, possibly due to the frequent use of intrusive techniques or to the adoption of indirect measurements. With beds of Geldart B particles in the temperature range 20-300°C, Geldart and Kapoor (1) observed that the diameter of bubbles, measured at their eruption, decreased by 15-25%. Sitthiphong et al. (2) reported opposite results for beds of larger particles. Stubington et al. (3), who used a three-dimensional resistivity probe, determined bubble sizes in a coal bed at temperatures ranging from 20 to 1000°C: the equivalent sphere diameter exhibited a 5-15% reduction as T was raised from ambient level to about 300°C. Sishtla et al. (4) used pressure probes to determine bubble frequency, velocity and size in fluidized beds of solids of various particle size (100-400 µm) and density (1.25-2.56 g/cm³) at temperatures up to 980°C. They
reported that the average pierced length of bubbles, as well as their frequency and velocity, did not change with T.

Hatate et al. (5), who analysed the behaviour of cuts of sand in the range 75-521 µm, found that the effect of temperature on the properties of the bubble phase was significant only for fine particles. With coarser solids, instead, the dependence of the equivalent bubble diameter on variables such as bed height and excess gas velocity did not differ from that observed at ambient conditions. Llop et al. (6) investigated the influence of temperature on bubble hold-up in beds of particles of Geldart’s groups B and D. With the former type of solids, the bubble fraction was found to diminish as T increased, whereas an opposite trend was obtained with D particles.

Contradictory results were obtained by Cui and Chaouki (7), whose measurements were carried out by an optical fiber probe immersed in the fluidized bed. They reported that both the frequency of the cycle and the ratio of the dilute/dense phase duration were enhanced by high temperature, with the consequent increase of bubble frequency and size. On this basis, their questionable conclusion was that at elevated temperatures the fluidization behaviour of a solid like FCC catalyst, which belongs to Geldart’s group A, becomes that typical of B particles.

Given the relative inconsistency of the few studies that have tried to characterize the bubble regime at high temperature, the main aim of the present study is that of providing some clear result by non-invasive measurements based on image analysis.

EXPERIMENTAL

The present investigation addresses the influence of temperature on the overall properties of the bubble phase as well as on some characteristic of the individual bubbles erupting at the free surface of the bed. Bed collapse tests and video-recording of bubble eruption at the free surface of the bed were carried out in a transparent column (ID=90mm). In either case, image analysis procedures were used. Both techniques were applied at different values of fluidization velocity, bed aspect ratio and temperature.

Each collapse test provides a diagram of bed height versus time capable of describing the bed deaeration process that follows the instantaneous interruption of gas feed. From it, several parameters are determined: the dense phase voidage $\varepsilon_d$, the average velocity $u_d$ of the gas flowing through it, the volumetric bubble fraction $\delta$ (otherwise termed “bubble hold-up”), and the average gas velocity in the bubble phase, $u_b$.

At the same operating conditions, images of the upflowing bubbles as they reach the free surface of the fluidized bed, were recorded and processed to determine the bubble frequency $f_b$, and the distribution of their diameters at eruption; from these data, the average bubble diameter $d_{b,av}$ was also evaluated.

The present investigation was focused on a specific system, i.e. a cut of FCC catalyst fluidized by air. Solid density was 1600 kg/m$^3$; the average particle diameter
was 110 µm and fines were practically absent ($F_{25}=0$ and $F_{45}$=0.02). The estimated value of particle sphericity, equal to 0.99, was assumed as that capable to give the best fit of data of minimum fluidization velocity at ambient conditions. This assumption was confirmed by SEM analysis, that showed that the catalyst particles were substantially spherical. The experiments were carried out at 100, 400 and 700 °C. The fluidization velocity was set equal to 1.6, 2.1, 2.7, 3.2, 4.2 and 5.3 cm/s, with corresponding values of the excess velocity equal to 1.1, 1.6, 2.1, 2.7, 3.7 and 4.8 cm/s respectively. Given that the minimum fluidization velocity is nearly independent of temperature, the same is true for $u-u_{mf}$ in the field 100-700°C. At each experimental temperature, the bed aspect ratio $H_0/D$ of the particle bed was fixed at values of 3, 3.8 and 4.6.

**RESULTS**

Bed collapse experiments show that the expansion of the dense phase of the fluidized bed past incipient fluidization is independent of bed height (see Fig. 1) and that at relatively high gas velocity (above 4 cm/s) the dense phase properties become insensitive to further increases of the fluidization velocity (see Figs 2 and 3).

![Figure 1. FCC catalyst collapse curves at varying $H_0/D$ and $T$; $u-u_{mf}$=4.8 cm/s.](image)

![Figure 2. FCC catalyst fluidization maps at varying temperature.](image)
As illustrated by the fluidization maps in Fig. 2, at T=100 and 400°C the transition to the bubbling regime occurs with a contraction of the dense phase voidage whereas at 700°C the high level of voidage attained by the dense phase of the bed becomes stable. After the commencement of bubbling the properties of the particulate phase apparently depend only on operating temperature and their trends of variation are different from those of the corresponding minimum fluidization parameters (see Fig. 3): the dense phase voidage $\varepsilon_d$ is constantly higher than $\varepsilon_{mf}$ and the interstitial gas flows at a velocity $u_d$ higher than $u_{mf}$.

![Graph 1](image1.png)

![Graph 2](image2.png)

Figure 3. Dense phase properties at varying temperature.

These results confirm that with solids of Geldart’s Group A, application of the two-phase theory to the behaviour of the fluidized bed should account for the fact that the actual excess gas velocity $u-u_d$ is significantly different from $u-u_{mf}$. Thus, running experiments at constant $u-u_{mf}$ corresponds to working with $u-u_d$ that increases with T. The dense phase porosity is constantly higher than that of the bed at incipient fluidization, but the properties of the particle emulsion noticeably change over 400°C, a thermal level past which any further growth of $\varepsilon_d$ is accompanied by the progressive diminution of the gas velocity through the emulsion phase. As this should cause a remarkable increase of the excess gas flowing in the form of bubbles, it is expected that the bubble phase characteristics vary accordingly.

To this regard, Fig. 4 illustrates the variation of the hold-up of bubbles as function of the excess velocity at different values of temperature and of the bed aspect ratio $H_0/D$. The volume fraction of bubbles strongly increases over 400°C. Over this temperature thermally induced interparticle forces are likely to be much stronger, as shown by the corresponding fluidization map of Fig. 2 where $\varepsilon_d$ is much higher than at lower T. The increase of interparticle cohesion may thus be thought to stabilize the dense phase structure, so that the same excess gas is converted into a more abundant bubbly flow.

As for the effect of changing the bed aspect ratio, its increase is associated to a reduction of the volumetric extension of the bubble phase. As this occurs without the excess flow rate being varied, increasing the bed height appears to give place to a different partition of the total gas flow rate into the two phases.
Measurements of the average velocity of the bubble phase confirm that temperature has an influence on this parameter: the velocity reduction observed at high T (see Fig. 5) indicates that the flow section of bubbles becomes larger (consistently with the correspondent growth of $\delta$). Similarly, the increase of $u_b$ at large values of $H_0/D$ is coherent with the parallel decrease of bubble hold-up already shown in Fig. 4.

In order to confirm this hypothesis, the images of bubbles erupting at the free surface of the bed were recorded. It has to be mentioned that the analysis could not be conducted at all the operating velocities employed for running the collapse experiments, due to the excessive turbulence encountered at high velocities.

Observations are thus limited to the lower bound of the velocity field, namely to values of $u=1.6$ and 2.1 cm/s (i.e. $u-u_{mf}=1.1$ and 1.6 cm/s, respectively). The eruption diameters were calculated by converting the surface limited by bubble perimeter into that of an equivalent circle and the diagrams of their distribution reconstructed at varying operating conditions.
This procedure allows stating that the distribution of bubble diameters depends on the bed aspect ratio as well as on temperature (see Fig. 6), a result consistent with those previously provided by the bed collapse experiments. The two series relevant to different superficial velocity appears quite similar, then only data for \( u-u_m = 1.6 \text{ cm/s} \) are shown. At any temperature level increasing the bed height has no significant influence on the amplitude of bubble size distribution but causes the increase of the average diameter of the bubbles, possibly due to the enhanced role played by coalescence.

At any given bed height, on the other hand, raising the process temperature lowers both limits of the bubble size distribution while also their average diameter is reduced. Such effects constitute an indirect confirmation of the fact that high temperature changes the nature of the dense phase of the bed, making bubbles flow through a medium characterized by an increasingly cohesive behaviour.

The two plots of Fig. 7 show the variation with \( T \) of the properties of the bubbles that flow across the bed, at a fixed value of the excess velocity. It is observed that their average diameter reduces as much as the operating temperature is raised while
their frequency of eruption accordingly increases; these seem two clear findings in a field where literature results are few and rather controversial.

Altogether the results presented so far clearly indicate that temperature plays a key role in determining the characteristics of the bubbling regime in that it changes the properties of the two phases of the fluidized system.

CONCLUSIONS

Measurements conducted in a fluidized bed of FCC catalyst operating at high temperature show that temperature influences the quality of bubbling. The results provided by the bed collapse technique indicate that bubble hold-up increases in response to the temperature increase as a consequence of the decrease in the gas velocity through the dense phase. Connected to that is the fact that the average gas velocity in the bubble phase decreases with T, while bubble diameters, as determined by image analysis at their eruption, become smaller. Such phenomena, more easily recognizable over 400°C and influenced also by bed height, are associated to the tendency of the dense phase of the bed to become increasingly cohesive due to thermally induced interparticles forces (7, 8).

On the whole, the different quality of the bubbling regime at high temperature, with a larger number of smaller bubbles travelling across a more permeable particulate phase, makes clear that substantial corrections have to be introduced in modelling the performance of fluidized bed reactors characterized by significant thermal effects.

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NOTATION

- $d_b$: Bubble eruption diameter, cm
- $d_{b,av}$: Average bubble eruption diameter, cm
- $f_b$: Bubble frequency, -
- $F_{22}$: Fine fraction under 22 µm, -
- $F_{45}$: Fine fraction under 45 µm, -
- $H$: Fluidized bed height, mm
- $H_0$: Static bed height, mm
- $D$: Column diameter, mm
- $H_0/D$: Bed aspect ratio, -
- $N_b$: Bubble fraction, %
- $t$: Time, s
- $T$: Temperature, °C
- $u$: Superficial velocity, cm/s
- $u_b$: Bubble phase velocity $[=(u-u_d)/\delta]$, cm/s
- $u_d$: Emulsion phase velocity, cm/s
- $u_{mb,e}$: Maximum velocity of homogeneous expansion, cm/s
- $u_{mb,s}$: Minimum velocity of a stable bubbling regime, cm/s
\( \mu_{mf} \) Minimum fluidization velocity, cm/s
\( \delta \) Bubble hold-up, -
\( \varepsilon \) Bed voidage, -
\( \varepsilon_d \) Emulsion phase voidage, -
\( \varepsilon_{mf} \) Minimum fluidization voidage, -

REFERENCES