Dynamic particle clustering in pulsed gas-solid fluidized beds: A study of mesoscopic granular structures

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Highlights

- Structured flow can be obtained in 2D fluidized beds through the use of pulsed gas flow.
- The energy dissipation through friction aids in stabilizing a dynamic flow pattern.
- Bubble properties are strongly correlated to the nature of the oscillatory signal.

1. Introduction

Efficient gas-solid heat and mass transfer is a tough technical challenge in reactor engineering. Fluidized beds tackle it by suspending the solids phase into flowing gas. They are applied in non-reactive processes, e.g., agglomeration and drying, and multi-phase reactors, e.g., combustion and FCC. Performance relies on good transport of chemical species and heat. At the microscale, this is limited by the size of the solid particles and their microstructure. At the macroscale, resistances stem from inefficient mixing. The dissipation of energy through particle collisions leads to a complex flow. Spouting, channeling, jetting or bubbling are examples of flow features that respond to magnitude of the cohesive forces acting in different materials. Despite decades of fluidization research, design tools only provide reasonable approximations when models can be adjusted with a large amount of data. Many local flow features cannot yet be described, which limits our ability to optimize gas-solid reactors. Gas-solid bubbling beds are good examples. Mixing owes to the solid circulation around rising gas bubbles. Theoretical frameworks study the instabilities behind bubble nucleation, but crucial effects such as shape, inertia or polydispersity are poorly understood. Kinetic theoretical models are used for full-scale design, but they rely on a description of particle interactions limited to inelastic binary collisions in a dilute flow. Multi-particle interactions or an anisotropic distribution of contacts cannot yet be accounted for. This is relevant when in regions of a reactor where the solids concentrate and enter dense or quasi-static regimes. Current scale up tools remain unequipped to describe mesoscale phenomena such as clustering, which not only affect flow but also local transport phenomena.

2. Methodology

Fluidized beds reactors exhibit chaotic hydrodynamics. In recent years, we have proposed several nature-inspired ways to try to remedy this and introduce a certain degree of structure and reproducibility. One of these includes the use of a pulsating gas flow in a bubbling gas-solid bed. The methodology is based on modifying the time and spatial scales of the particle and particle-fluid interactions at micro and mesoscales in order to induce a dynamically structured flow in the macroscopic bed. Ripples in sandy beaches or dunes in deserts are examples of other dynamic granular structures that emerge in response to repeated flow perturbations, such as tides and waves, wind gusts and eddies. Transferring this principle to the operation of quasi-2D beds, we have shown that, under specific conditions, gas bubbles nucleate in an orderly manner, organize in a 2D spatial pattern and render reproducible flows. However, it is only recently that the fundamental principles behind this pattern formation are being elucidated. This work discusses the formation of dynamic bubble patterns during the fluidization of Geldart B particles under pulsed flows in a laboratory quasi-2D bed. The insights gained provide a fingerprint for fluidized bed modeling approaches [1].

3. Results and discussion

At specific conditions, bubbles nucleate in alternative sites at subsequent gas pulses, forming a triangular tessellation that extends throughout the bed (Fig. 1a). The pattern propagates vertically and becomes unstable

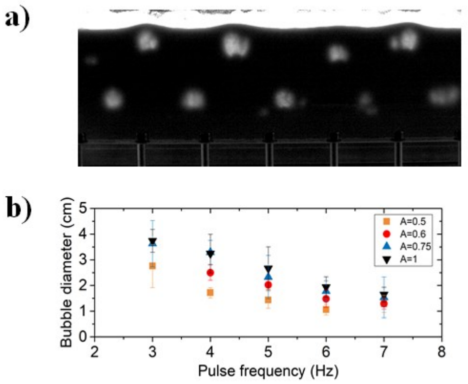

Figure 1. Example of (a) an experimental bubble pattern, (b) variation of bubble size with pulse frequency in a structured state.

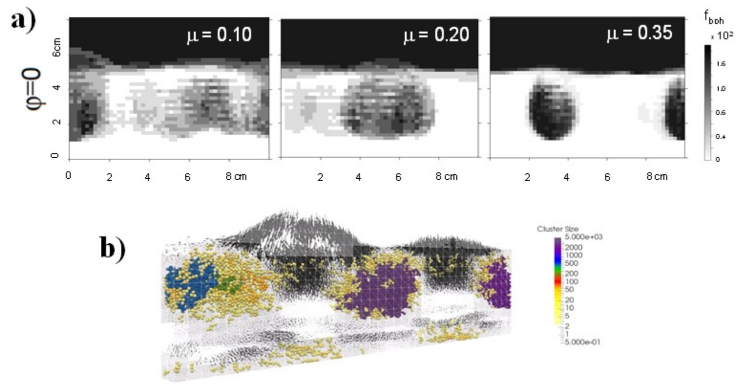

Figure 2. (a) Probability density of the bubble phase under pulsed flow at the same phase angle ϕ (position in the pulse) for increasing μ. (b) Example of clusters formed in the wake of rising bubbles at constant flow, CFD-DEM.

as bubbles grow near to the freeboard. As opposed to fluidization at constant flow, in a structured state much narrower bubble size and wavelength distributions are obtained, which are independent on the bed dimensions and correlated to the frequency, f, and amplitude, A, of the oscillation (Fig. 1b). Experimental data in a quasi-2D pulsating bed are compared with numerical studies under different flows, inter-particle friction factors, μ, and heights. The numerical work is conducted using computational fluid dynamics coupled with discrete element method (CFD-DEM). Kinetic theories extended with the common closures for the solid frictional stress have been shown ineffective in capturing the bubble self-arrangement [1], while Eulerian-Lagrangian methods can reproduce it [2]. The numerical results show that the dissipation of energy throughout the solid phase due to frictional contacts plays a crucial role in the stabilization of the bubble dynamics (Fig. 2a). The ability of a Langrangian formulation of the solid phase to more effectively solve the local granular rheology allows for CFD-DEM to track the formation and breakage of local dense regions in the bed. This work focuses on studying this phenomenon, identifying the mesoscopic granular structures (Fig. 2b) that form through the cycle of nucleation, rise and rupture, and examining the interplay between the characteristics of the dense regions locked in the plastic regime and the prevention of a bubble's lateral movement, key in the pattern stabilization. The formation, breakage and growth of large particle clusters is tracked numerically and discussed along experimental bubble nucleation and propagation mechanisms.

4. Conclusions

The use of oscillating gas flow in bubbling fluidized beds introduces a temporal dynamic in the particle drag that can be utilized to suppress the instability of the coupled flow system. In this way, stable dynamic bubble patterns emerge, synchronized with intermittent dense granular structures. In this "structured" state, bubble properties, such as size, velocity and separation, can be better predicted and manipulated by modifying the properties of the oscillating signal. It is reasonable to believe that once the process is scaled up, control over the bubble dynamics is a precursor to control over to heat and mass transport and, ultimately, reaction processes. This could open a new pathway for process intensification, design new devices or retrofit existing ones under the principle that the underlying process dynamics could be tuned during normal operation.

References

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Keywords

Fluidization, clustering, dynamic self-organization, granular rheology