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SIGNIFICANCE OF THE GAS RELEASE ON THE MIXING OF LARGER PARTICLES IN BUBBLING FLUIDIZED BEDS

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Abstract

The mixing of larger particles (e.g. fuel particles) in dense regions of bubbling fluidized bed units is governed by the interplay of buoyancy forces and the drag from the surrounding solids, whose movement is induced by the bubble flow. The contribution of the gas released from the converting particles (from e.g. drying or devolatilization) to their own mixing is often overlooked. This experimental study aims to evaluate the influence of the gas release from larger particles on their mixing with the bed solids. In this work, experiments are performed in a fluid-dynamically scaled cold flow model resembling typical conditions for the thermochemical conversion of solid fuels (more specifically, the pyrolysis of biomass at 700 °C in a bed of sand fluidized by flue gas). Magnetic particle tracking is used to obtain the trajectory of a large particle resembling biomass properties, while freely moving in the bed. The work uses tracer particles loaded with dry ice to yield a gas release that mimics that of a biomass particle during drying and devolatilization, and compares them with particles of similar physical properties but without the ability to release gas. Different fluidization velocities are examined, revealing that the gas-releasing tracers tend to a deeper immersion within the dense bed at low fluidization velocities, whereas higher fluidization velocities render the gas-releasing tracers more buoyant.

Keywords: Solids mixing, Solids segregation, Fluid-dynamic scaling, Stefan flow, Fluidized bed

1. Introduction

Fluidized beds are extensively used in various industrial processes (e.g. thermochemical conversion of fuels, synthesis, calcination of ores, particle drying and coating, agglomeration, etc.) owing to their efficient mixing capabilities and high heat and mass transfer rates. Understanding the intricate dynamics of particle mixing within fluidized beds is crucial for optimizing their performance and enhancing process efficiency. Previous investigations have given valuable insights into understanding the mixing dynamics in fluidized beds of particles other than the bulk solids. Bubbles have shown to play a pivotal role in the mixing dynamics of fluidized beds, with much research done on understanding the solids mixing/segregation dynamics driven by them (Woollard & Potter, 1968). The bubbles are integral to the behavior of dense fluidized beds, but they not only emerge from the fluidization gas, called exogenous bubbles. Bubbles can also arise from gases that are produced by the chemical reactions or physical transformation of materials in the bed, these are known as endogenous bubbles. Existing research indicates quite some similarities in the structure and behavior of both types of bubbles (Iannello, Macri, et al., 2023). Several studies have looked at biomass particles to explore the characteristics of endogenous bubbles (resulting from the drying and devolatilization processes) and their role in uplifting fuel particles to the bed surface (Fiorentino et al., 1997; Iannello et al., 2022; Iannello, Bond, et al., 2023; Salatino & Solimene, 2017;

Solimene et al., 2003). These investigations focused on beds under minimum fluidization conditions and with the gas-releasing particles being fed under the bed (Fiorentino et al., 1997; Iannello, Bond, et al., 2023), thereby making it possible to observe their lifting enhancement by the formation of the endogenous bubbles.

However, fluidized bed operation under typical industrial conditions involves fluidization numbers (FN, defined as u/u_{mf}) well beyond 1, and the feedstock feeding above the bed. Moreover, larger particles (such as fuel in thermochemical conversion processes) are prone to be readily segregated to the surface of the bed due to their comparatively lower densities. It is thus of critical importance to comprehend the impact of gas release from such larger feedstock particles on its mixing and under the representative conditions of industrial units (i.e. lighter larger feedstock, above bed feeding, bubbling conditions), even in the scenarios where the formation of endogenous bubbles may not occur.

This research aims to investigate the significance of gas release on the mixing behavior in bubbling fluidized beds of particles larger and lighter than bulk solids. To attain this, experiments are carried out at fluid-dynamically downscaled conditions using a gas-releasing tracer as a reference for a biomass particle undergoing a typical pyrolysis process. The tracer is fed at the top of the bed and different fluidization velocities are applied in the study.

2. Experimental Setup

Fig. 1 schematizes the cold flow model used in this work, featuring a cross-section of $0.17 \times 0.17 \text{ m}^2$ and a 0.04 m-high bed (at rest) consisting of air-fluidized bronze particles with an average size of $189 \text{ }\mu\text{m}$ and a density of 8492 kg/m^3 (yielding a minimum fluidization velocity of 0.084 m/s). By applying laws for fluid-dynamic scaling (Glicksman et al., 1994), this set-up resembles pyrolysis at $700 \text{ }^\circ\text{C}$ in a large-scale bed ($0.71 \times 0.71 \text{ m}^2$ and a height of 0.16 m) of sand fluidized by flue gas. Table. 1 lists the scaling of operational conditions and gas and solids properties.

Table. 1: Scaling of operational conditions and gas and solids properties.

| Parameters | | Hot Reactor | | Cold Reactor | |
|----------------------------|-------------------------------------|-------------|------------------|------------------|------------------|
| Operating Parameters | Temperature [$^\circ\text{C}$] | 700 | | 20 | |
| | Pressure [atm] | 1 | | 1 | |
| | Minimum Fluidization Velocity [m/s] | 0.17 | | 0.084 | |
| Fluidizing Gas | Density [kg/m^3] | Flue Gas | 0.36 | Air | 1.20 |
| | Viscosity [N/m.s] | | $4.07\text{e-}5$ | | $1.83\text{e-}5$ |
| Bed Material | Density [kg/m^3] | Sand | 2600 | Bronze | 8492 |
| | Particle Size [μm] | | 789 | | 189 |
| Fuel Particle | Density [kg/m^3] | Biomass | 300 – 700 | Synthetic Tracer | 990 – 2300 |
| | Particle Size [mm] | | 1 – 90 | | 0.26 – 23.76 |
| Scaling factors (cold/hot) | Length | | | 0.24 | |
| | Time | | | 0.49 | |
| | Mass | | | 0.05 | |

To investigate the significance of the gas release of larger particles in the bed on their mixing, two types of tracer particles are used: gas-releasing tracers and blank tracers. The tracers selected for the study are cylinders of 12 mm in diameter with an L/D ratio of 1.5 and a density of $\sim 2000 \text{ kg/m}^3$. The gas-releasing tracers consist of a cylindrical case holding a small cylindrical magnet in the center and containing dry ice in both ends. The cylinder is closed with porous caps to allow the release of sublimated CO_2 , to mimic the release of gas (i.e., of moisture and volatiles during drying and devolatilization). The blank tracers are constructed in

the exact same way but omitting the dry ice filling. Four fluidization numbers are tested: FN 1.5, 2, 3.5, and 5.

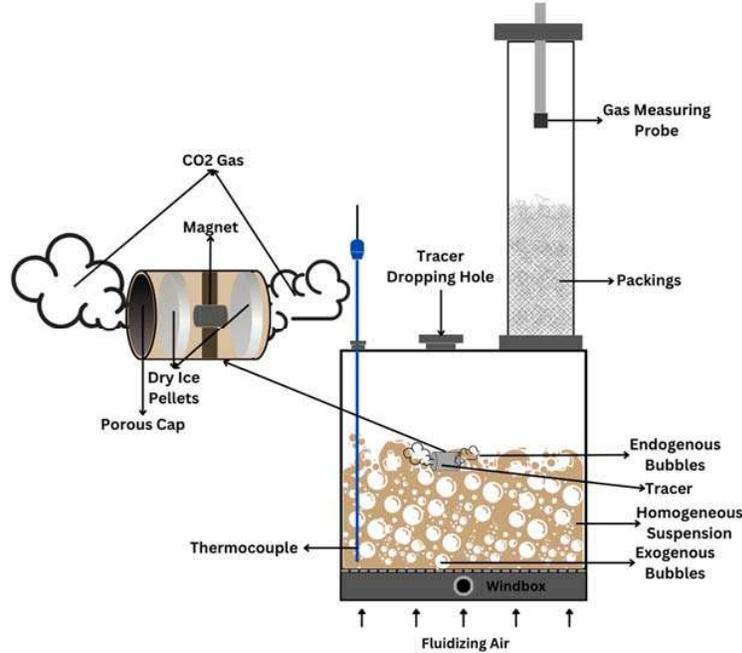


Fig. 1: Experimental setup and depiction of the gas-releasing tracer.

The magnetic particle tracking (MPT) technique (Sette et al., 2015) is used to track the position and orientation of the tracer particle. This technique provides the spatial location of a magnetic tracer with an accuracy of 1 mm, and for this work, a sampling rate of 20 Hz is applied. The core of the tracer consists of a 3×3 mm cylindrical magnet, for which a magnetic field is detected by eight sensors placed outside the bed walls. The gas-releasing tracer is tracked until all the CO₂ sublimates - approximately 15 - minutes and the experiment is repeated 5 times for every set of conditions to ensure the statistical robustness of the acquired data. Blank tracers are tracked for at least 60 minutes. The mixing behavior of the tracers is characterized through the probability density function (PDF) of their vertical location in the bed.

The gas release rate from the tracers is monitored by means of a probe sampling (at 1 Hz) the concentration of CO₂ at the gas exit duct. To ensure representative sampling, packings were placed upstream of this probe, promoting mixing in the outlet gas stream, and thereby eliminating local concentration biases. The time delay characteristic of the measurement system is assessed and accounted for in the data processing. These concentration measurements are later used to analyze the influence of the CO₂ release rate on the mixing. The bed temperature is monitored with a thermocouple to ensure uniform conditions throughout the experiment and in between repetitions.

3. Results and Discussion

As shown in Fig. 2, the probability distribution of vertical locations for FN=2 indicates that the gas-releasing tracer predominantly takes positions slightly below the bed surface, while the blank tracer is observed to be more likely to float on the surface of the bed. Additionally, the gas-releasing tracer exhibits a wider distribution of vertical positions, suggesting enhanced vertical mixing. This finding suggests enhanced contact between the gas-releasing particles and the bed solids suspension, which has the potential to alter heat transfer and mass transfer in comparison to particles without significant gas release. These aspects need to be added to the consideration of the presence of a Stefan flow when evaluating the mass and heat transfer between the particle and the surrounding bed.

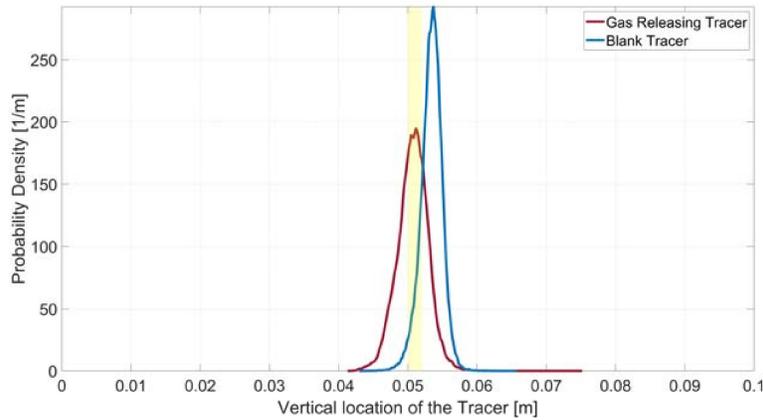


Fig. 2: PDF of the vertical location of the tracer. The yellow band indicates the bed surface interval. FN=2.

In order to further understand the effect of the gas release on the particle-bed mixing, the average vertical position of the tracer is plotted against the release rates of CO₂ and is shown in Fig. 3. The data plotted for gas release rate equal to zero, corresponds to the blank tracer as an allusion. In contrast, the gas-releasing tracer penetrates deeper into the dense bed at intermediate release rates, while for the highest release rates, a tendency of increased buoyancy is observed, although the limited number of data points for such high release rates must be noted.

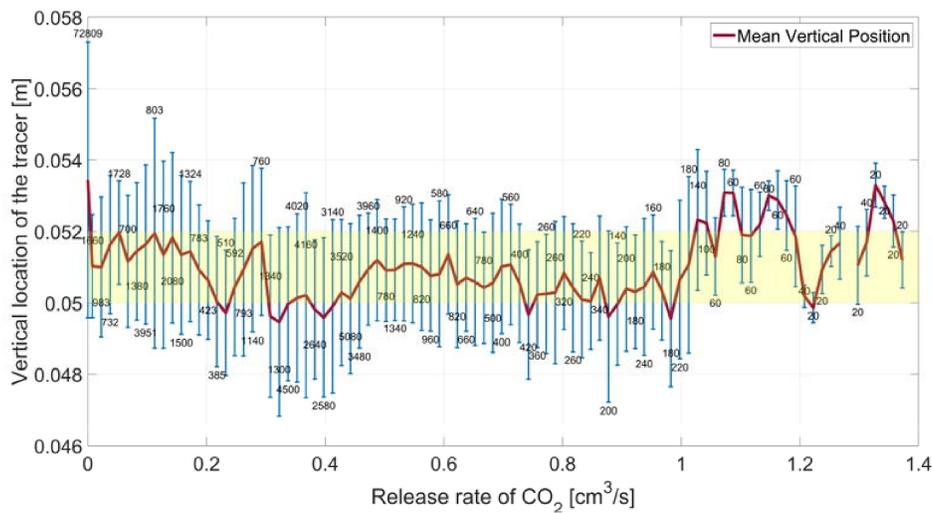


Fig. 3: Vertical position of tracers as a function of the release rate of CO₂. FN=2. The bars indicate the standard deviation in the data distributions corresponding to each release rate bin, and number tags indicate the amount of data points in each distribution. The yellow band indicates the bed surface interval.

According to measurements by Iannello et al. (2023), the local velocity of volatiles released from biomass at hot conditions ranges within 0.01-0.1 m/s. In this study, the gas release rates attained (refer to the x-axis in Fig. 3 for release rates in the cold model) reach velocities which on an up-scaled basis correspond to values up to 0.02 m/s.

Fig. 4 compares the vertical distributions of gas-releasing and blank tracers for all the fluidization velocities tested. Note that for gas-releasing tracers, the data contains the whole range of releasing rates. The general shift of the distributions towards higher values as the fluidization velocity is increased is attributed to the bed expansion, which sets the bed surface level at a higher location. As seen in the figure, for lower fluidization velocities (FN≤2) the gas-

releasing tracer is found to immerse the dense bed more than blank tracers. However, under higher fluidization conditions ($FN \geq 3.5$) the gas-releasing tracers exhibit a slightly higher buoyancy than blank tracers. This contrasting impact of the gas release at different fluidization velocities can be explained by the following: at higher fluidization velocities, the excess gas velocity becomes sufficiently large to generate a bubble flow that dominates the fluid-dynamics of the bed, making the influence of the gas released from the particle negligible. Thus, the gas-releasing tracers behave roughly the same as blank tracers.

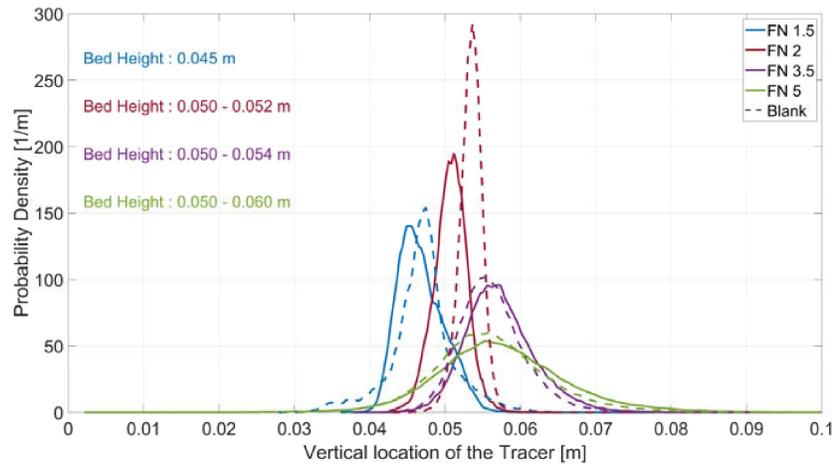


Fig. 4: Probability density function of the vertical location of the tracers for different fluidization numbers. Dashed curves indicate blank tracers.

Fig. 5 exemplifies typical horizontal tracer trajectories for $FN=5$. As seen, the blank tracer tends to remain in the same horizontal position only fluctuating across the vertical dimension. Instead, the gas-releasing tracers show strong lateral dispersion, with trajectories covering wide areas of the horizontal cross-section of the bed.

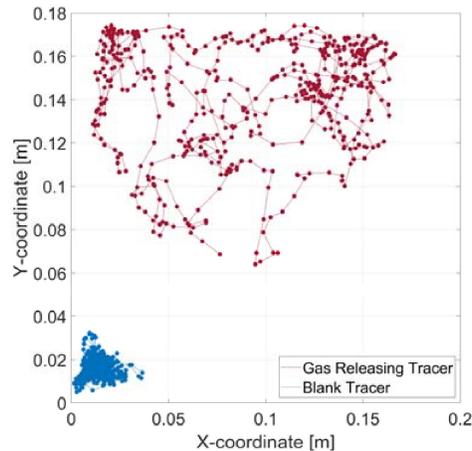


Fig. 5: Horizontal trajectories of the two types of tracers used. Data representing 25 s (500 data points). $FN=5$.

The horizontal dispersion coefficients of the particle, under each FN value have been calculated using the Einstein equation for a length threshold of 0.02 m and are presented in Table. 2 below. At lower fluidization conditions ($FN \leq 2$), the lateral dispersion is too small to make meaningful comparisons. At $FN=3$, the dispersion coefficient is comparatively similar for both tracers. However, at $FN=5$, the dispersion coefficient for the gas-releasing tracer is nearly 40% larger than that of the blank tracer, thus the impact of the gas release overcomes the constraints of bed dynamics at FN values above 3.5.

Table. 2: Horizontal particle dispersion coefficients for tested fluidization numbers.

| Tracer | Horizontal dispersion coefficient (m ² /s) | | | |
|---------------|---|----------|----------|----------|
| | FN 1.5 | FN 2 | FN 3.5 | FN 5 |
| Gas-releasing | 1.42e-05 | 2.04e-05 | 4.04e-04 | 1.1e-03 |
| Blank | 8.19e-07 | 1.97e-04 | 4.57e-04 | 7.90e-04 |

4. Conclusion

The significance of gas released from the particles on the mixing of larger and lighter particles is studied at different fluidization conditions. Magnetic particle tracking is used in a fluid-dynamically downscaled unit to precisely measure and then analyze the movement of gas-releasing particles and non-releasing particles. Results show that at low fluidization velocity, the gas-releasing tracers are more immersive into the dense bed than the blank tracers. While, at higher fluidization numbers the difference between gas-releasing and blank tracers becomes insignificant in terms of vertical mixing. Analysis of the horizontal tracer trajectories at higher fluidization velocities illustrates a higher horizontal mixing rate of gas-releasing tracers compared to blank tracers, which typically were trapped in corner regions. This insight also sets the direction for future work exploring the impact of higher gas release rates and the lateral mixing of gas-releasing tracers.

Acknowledgment

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