Magnetic Resonance Imaging and numerical modelling of vibrated bubbling gas-solid fluidized beds

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Introduction: Vibrated gas-solid fluidized beds are widely used in chemical engineering applications involving granular materials, such as tablet coating in pharmaceuticals. Investigating the hydrodynamics is challenging because industrial-scale beds are large, opaque, three-dimensional (3D), and difficult to vibrate, leading many studies to rely on pseudo-two-dimensional setups that do not accurately reflect industrial conditions. In the past Magnetic Resonance Imaging (MRI) was used to resolve bubbles and measure particle velocities in 3D fluidized beds [1,2]. In these previous studies, a microimaging system and a clinical MRI scanner were used, limiting the height and diameter of the sample that can be analyzed and restricting the investigation of vibrated fluidized beds.

Methods: In this work, we used a large vertical-bore MRI system that enables the investigation of vibrated fluidized beds of various diameters. This MRI system offers unique radiofrequency (RF) shielding, allowing for the placement of an electrodynamic shaker, an RF-noise-emitting device, in the axis of the fluidized bed. Vibration was transmitted to the fluidized bed via glass-fiber-reinforced extension tubes (Fig 1.a, 1.b). The impact of vibration frequency (f) and amplitude (A) on bubble properties were investigated. MRI-active fluidized bed particles, agricultural seeds, and porous catalyst support particles of varying sizes loaded with pure water, were used to investigate the impact of particle size on fluidization. A tailored multi-channel receiver array (Fig 1.c, 1.d) for signal detection was used, allowing parallel imaging with Compressed Sensing (CS-SENSE). Gradient echo pulse sequence was used in MRI measurements with echo time of 0.75 ms and repetition time of 1.90 ms. The temporal resolution was 20 ms and the spatial resolution was 4 mm x 4 mm.

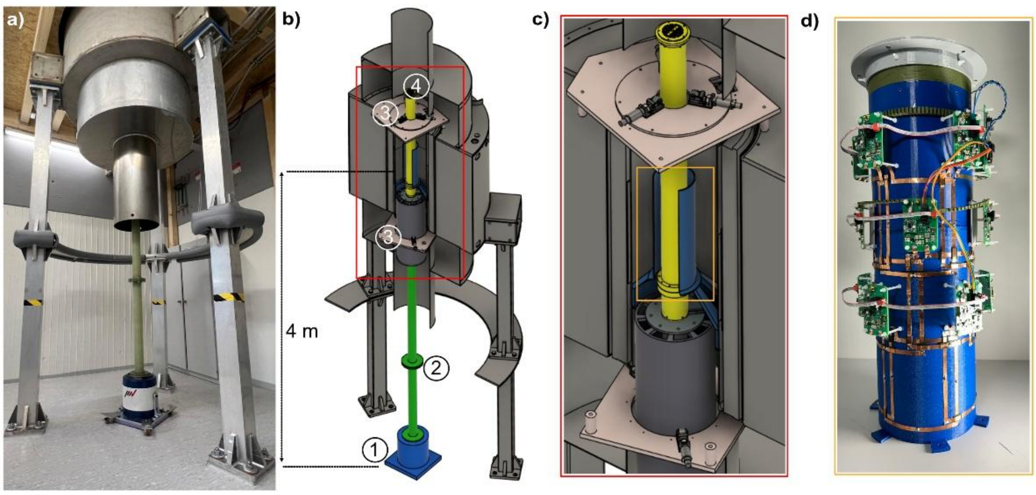

Fig. 1: a) A 3 Tesla large bore vertical MRI system, with the isocenter located 4 meters above ground. An electrodynamic shaker placed on-axis creates sinusoidal acceleration, which is transmitted through glass fiber-reinforced tubes to the fluidized bed. b) A 3D render of the 10 cm outer-diameter fluidized bed used in MRI measurements. 1=Electrodynamic shaker, 2=Vibration transmission tubes, 3=Bearing system, 4=Fluidized bed. c) A receiver array is placed around the fluidized bed in the MRI. The bearing system ensures that the motion of vibration is restricted to the axial direction. d) A 15-channel receiver array was used to detect signal from particles.

Results and discussion: Signal detection with a multi-channel receiver array enabled higher temporal resolution, 20 ms, and an improved signal-to-noise ratio (SNR) compared to the measurements using

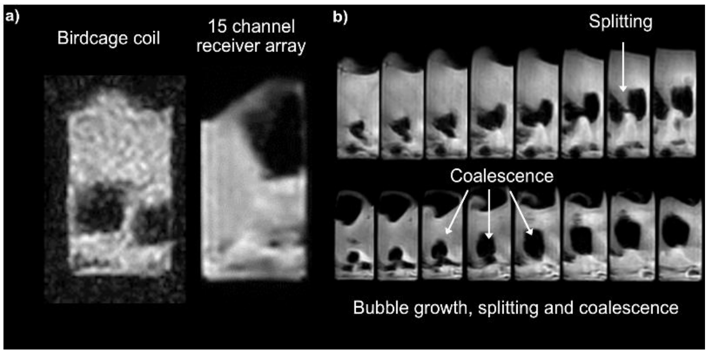

Fig. 2: MRI frames of poppy seeds fluidization in a 10 cm outer diameter fluidized bed a) with birdcage coil (left) and with 15-channel receiver array (right), b) Consecutive MRI frames showing important bubble events.

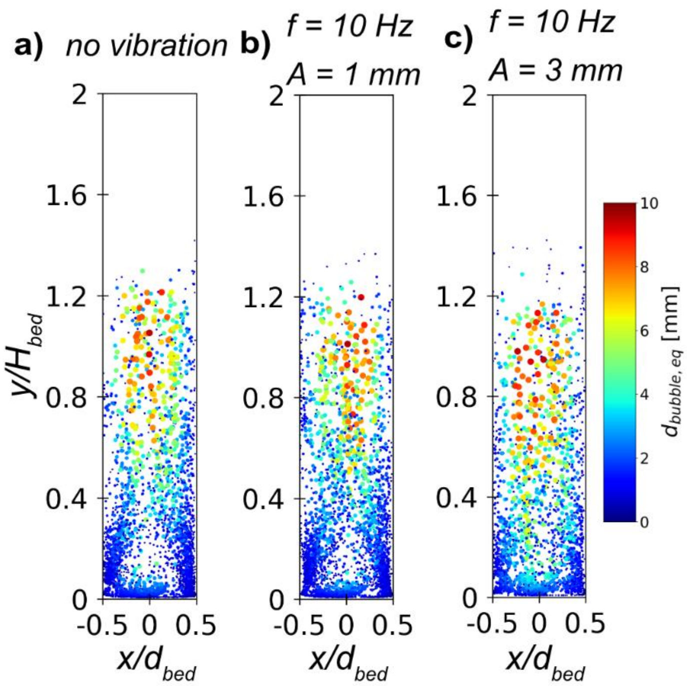

Fig. 3: Bubble size distribution of poppy seeds in the 10 cm outer diameter fluidized bed. Each circle represents a bubble centroid *(x, y)*, and the color indicates the equivalent bubble diameter ($d_{\text{bubble,eq}}$). The figure is normalized on the *y*-axis by the static bed height (*H*) and on the *x*-axis by the bed diameter (*D*).

the magnet's birdcage coil, 60 ms. (Fig 2.a). This enables the observation of important bubble dynamics that influence heat and mass transfer rates such as bubble growth, coalescence and splitting (Fig 2.b).

Agricultural seeds are commonly used in MRI studies of granular materials due to their high oil content, but they typically have similar particle sizes. In industrial fluidized bed applications, fine powders are also commonly utilized. In this work, we extended MRI studies to include a broader range of particles. Powders such as γ-Al_2O_3 were loaded with water and used in fluidized beds.

Impact of vibration on bubble properties were investigated by altering vibration frequency and amplitude. Vibrated fluidized bed resulted in a more homogeneous spatial distribution of bubbles (Fig 3). As the vibration amplitude increased, larger bubbles formed in the bed.

MRI data was further compared with numerical simulations, which combine Computational Fluid Dynamics and the Discrete Element Method (CFD-DEM). Initial results showed that the average equivalent bubble diameters derived from MRI measurements, CFD-DEM simulations, and established literature correlations are strongly consistent.

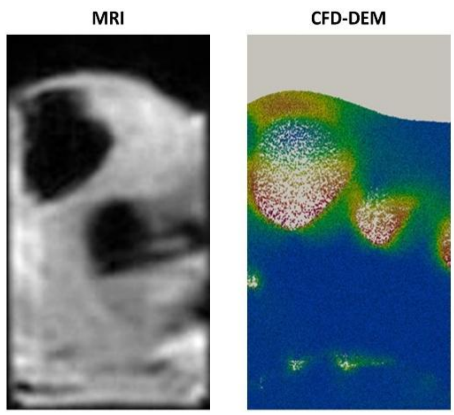

Fig. 4: A frame of poppy seeds fluidization (U/U_{mf} = 1.6) in a 10 cm outer diameter fluidized bed obtained from MRI and CFD-DEM simulation.

Conclusion: Vibrated fluidized beds were investigated with MRI. Custom-built receiver array provided high temporal resolution, enabling the detection of gas bubbles. Besides agricultural seeds, the study included the fluidization of porous fine powders, expanding the scope of fluidized bed applications analyzed with MRI. We found that vibration led to a more uniform bubble size distribution. CFD-DEM simulations showed good agreement with the MRI data and established literature correlations.

References: [1] Müller et al., Physical Review E, (2007). [2] Penn et al., Science Advances, (2017).