Careful Comparison of MRI and Computer Simulations of Bubbly, Particle-Laden Flows

C.M. Boyce
Columbia University, New York, NY, USA

Introduction: MRI has long been used to characterize bubble motion in multiphase flows as well as fluid and particle velocity in particle-laden flows. These measurements can be used to validate or find areas for improvement in computational fluid dynamics (CFD) models. However, the post-processing of CFD data for accurate comparison with MRI measurements is often non-trivial due to complexities of MRI measurements. Here, we discuss development and utilization of MRI techniques to measure a range of bubbly, particle-laden flows as well as use of MRI simulations to identify the best ways to compare MRI measurements with CFD simulations.

Methods: A range of MRI pulse sequences, from single-point imaging to echo planar imaging are used to characterize multiphase flows [1]. Multi-band EPI is introduced to take rapid images of 3D bubble structures [2]. Measurements are conducted in both pre-clinical and full-body MRI scanners. Particle and gas flow are modeled using computational fluid dynamics – discrete element method (CFD-DEM) simulations [3]. MRI simulations are conducted with in-house codes as well as JEMRIS software [4]. Oil inside particles are used to measure particle flow and ^{19}F nuclei inside SF_6 gas is used to measure gas flow [5]. Flow is measured inside fluidized beds [5–7], bubble streams in dense suspensions [2] and analog lava flows (**Fig. 1**) [8].

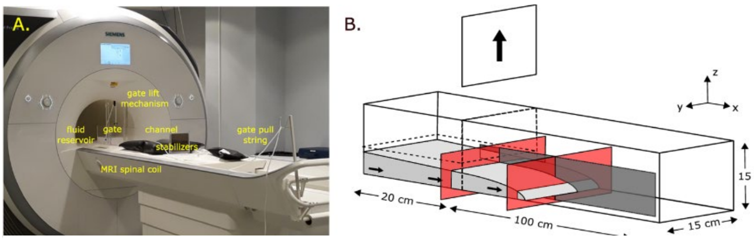

Fig. 1 Experimental setup for MRI of lava analog flows.

Results and Discussion: MRI measurements of fluidized beds show that particle and gas velocities are fastest directly in the line of bubbles, and slowest to the sides of bubbles [5,7]. Simulations of fluidized beds simulated as passing through an MRI pulse sequence reveal the most accurate ways to process particle positions and velocities for comparison with MRI simulations [9,10]. Fully 3D measurement of bubble streams in dense suspensions reveal highly non-axisymmetric bubble shapes, particularly surrounding bubble coalescence [2]. MRI velocimetry of lava analog flows can be used to develop new rheological models for magma [8].

Conclusions: MRI can characterize structural and flow features of bubbly, particle-laden flows. MRI simulations applied to output of CFD simulations reveal the most accurate ways to postprocess CFD data for comparison with simulations. MRI pulse sequences can be tailored to meet the specific resolution requirements of a particular flow system.

References: [1] E. Lev and C. M. Boyce, *iScience* (2020). [2] A. Bordbar, W. Zia, J. Birnbaum, J. Omidi, R. F. Lee, E. Lev, and C. M. Boyce, *Chemical Engineering Journal* (2024). [3] Y. Tsuji, T. Kawaguchi, and T. Tanaka, *Powder Technology* (1993). [4] T. Stöcker, K. Vahedipour, D. Pflugfelder, and N. J. Shah, *Magnetic Resonance in Medicine* (2010). [5] C. M. Boyce, N. P. Rice, A. Ozel, J. F. Davidson, A. J. Sederman, L. F. Gladden, S. Sundaresan, J. S. Dennis, and D. J. Holland, *Phys. Rev. Fluids* (2016). [6] A. Penn, A. Padash, M. Lehnert, K. P. Pruessmann, C. R. Müller, and C. M. Boyce, *Phys. Rev. Fluids* (2020). [7] A. Penn, T. Tsuji, D. O. Brunner, C. M. Boyce, K. P. Pruessmann, and C. R. Müller, *Science Advances* (2017). [8] J. Birnbaum, W. Zia, A. Bordbar, R. F. Lee, C. M. Boyce, and E. Lev, *Journal of Geophysical Research: Solid Earth* (2023). [9] C. M. Boyce, D. J. Holland, S. A. Scott, and J. S. Dennis, *Ind. Eng. Chem. Res.* (2013). [10] A. Bordbar, S. Benders, W. Zia, A. Penn, and C. M. Boyce, *Ind. Eng. Chem. Res.* (2023).