Hydrodynamics and Heat Transfer Study of Corrugated Wall Bubbling Fluidized Beds - Experiments and CFD Simulations

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A new concept to harness bubble dynamics in bubbling fluidization of Geldart D particles was proposed. Various geometrical declinations (covering corrugation angles, clearances between the walls and initial rest bed heights) of a cold-prototype corrugated-wall bubbling fluidized bed (CWBFB) were compared at different gas velocity ratios (ratio of gas velocity to minimum bubbling velocity, U_g/U_{mb}) to conventional flat-wall bubbling fluidized bed (FWBFB). In case of CWBFB, locations having minimum/narrowest and maximum/larger clearances between the parallel plates were referred as neck and hip locations, respectively. Hydrodynamic and heat transfer studies were carried out to appraise the effect of triangular-shaped wall corrugation on incipient fluidization, bubble coalescence (size and frequency), bubble rise velocity, gas distribution, pressure drop, operation stability and bed expansion (expansion ratio and transport disengagement height). Digital image analysis technique and fast response heat flux probes (measuring surface temperature and heat flux simultaneously) were employed to experimentally investigate the various features of bubbling fluidized beds. However, full three-dimensional transient Euler-Euler computational fluid dynamic simulations employed with kinetic theory of granular flows were also carried out with the aid of FLUENT 6.3.26 to understand the impact of corrugated walls on the aforementioned hydrodynamic and heat transfer features of the bed. Parallel processing on a core-2-Duo CPU associating 8 processors was used to perform the simulations. Grid generation was made by using GAMBIT. Tetrahedral mesh which would be normally recommended for the complex geometries (like CWBFB in our case) created problems related to the convergence and use of higher order spatial discretization schemes and found computationally expensive too. Then, hybrid hexahedral mesh was generated by virtually dividing the CWBFB into small independent multiple blocks. Simulations were performed with the 3D pressure-based solver in a 2nd order implicit unsteady formulation and gradients were estimated by the Green-Gauss cell based method. Momentum balance and granular temperature equations were solved using *3rd-order MUSCL* discretization scheme, and volume fraction using Quick scheme. Pressure-velocity coupling was made by the phase coupled SIMPLE algorithm. Air was the continuous primary phase, while solid particles were the secondary discrete phase. During hydrodynamic study of CWBFB, difficulties confronted in the use of velocity inlet boundary condition for continuous phase (air) lead to the mass flowrate as inlet boundary condition. Particle velocities (and solids volume fraction) were set to zero at the inlet. The pressure boundary condition at bed outlet was assigned the atmospheric pressure (pressure outlet). The bed walls were treated as no-slip for gas and free-slip for solids phase with granular temperature flux equal zero. Initially, both phases were assigned zero velocities in all directions. Interphase momentum exchange coefficient in the momentum balance equations was calculated by implementing the Gidaspow model (a combination of the Wen and Yu model and Ergun equation). The Gidaspow model for granular viscosity and the Lun et al. model for granular bulk viscosity, solids pressure, and radial distribution, were selected to estimate the secondary phase properties, such as, granular temperature and pressure. Time-averaged results were obtained over periods 25-30 times the mean residence time of gas phase in the bed. It was started after the first 10-15 s simulation time to approach quasi steady-state fluidization conditions in the bed. A comprehensive grid-independence study was also performed by considering various cell sizes.

A decrease in gas flowrate required to achieve the incipient fluidization condition was observed in CWBFB as compared to FWBFB. This was attributed to the increased drag force at the necks as compared to the corresponding locations in FWBFB (via CFD simulations). Bubble size and rise velocity in corrugated-wall beds were appreciably lower, at given U_g/U_{mb}, than in flat-wall beds with equal flow cross-sectional areas and initial bed heights. The decrease (increase) in size (frequency) of bubbles during their rise was sustained by their periodic breakups and reduced excess gas ($U_g - U_{mb}$) while protruding through a network of neck-hip locations between corrugated plates. A trajectography analysis of bubbles displacements (by plotting the time evolution of bubble centroids tracked over 30 s history) and time averaged gas holdup contours obtained by CFD simulations revealed that corrugated walls acted as internal re-distributors and improved the gas distribution than FWBFB. A thorough stability analysis concluded that CWBFB offered a stable gas-solid fluidization operation as compared to the FWBFB. In this regard, standard deviations of dynamic fluctuations for measured indicators such as bed differential pressure, wall-to-bed heat transfer coefficient, bed free surface and bed mean gray scale intensity (via digital image analysis), and simulated indicators such as granular temperature and pressure, and solids volume fraction (via 3-D CFD simulations) were monitored to compare the stability behaviors of FWBFB and CWBFB. CFD simulations further revealed that necks were mainly responsible for the growth of instabilities in CWBFB as compared to hips. Bed expansion behavior in FWBFB and CWBFB at different operational and geometrical configurations was analyzed in terms of expansion ratio (ratio of expanded to initial height of bed, H_f/H_i) and transport disengagement height (TDH) both experimentally using high-speed digital image analysis and CFD simulations to simulate the solids volume fraction and granular temperature in both geometries. It was revealed that for a given U_g/U_{mb}, expansion ratio was barely affected by wall patterning whereas TDH underwent appreciable reduction in CWBFB compared to FWBFB. Regardless of wall shape, both H_f/H_i and TDH increased with increasing U_g/U_{mb} and wall clearance, and with decreasing initial bed height.