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ANALYSIS OF COARSE COAL PARTICLE BEHAVIOR IN LIQUID-SOLID FLUIDIZED BEDS USING COMPUTATIONAL FLUID DYNAMICS

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Abstract: *In this study, a computational fluid dynamics (CFD) model was developed to analyze the behavior of coarse coal particles in a 3D liquid-solid fluidized bed. The model combined a Eulerian-Eulerian approach for the liquid-solid two-phase flow with the kinetic theory of granular flow. First, the study conducted a grid independence analysis to determine the appropriate grid model parameters, ensuring reliable simulation results. Then, the developed CFD model was validated by comparing its predictions with experimental data. Specifically, the expansion degree of both low-density fine particles and high-density coarse particles was examined at various superficial liquid velocities. The simulation results were found to closely match the experimental data, confirming the accuracy of the proposed mathematical model. Next, the study investigated the effects of particle size and density on the fluidization behaviors within the bed. It was observed that low-density fine particles exhibited relatively homogeneous expansion behaviors and were easily fluidized within a certain range. However, for larger and heavier particles, the fluidization process became more complex. Inhomogeneity was observed throughout the bed, characterized by the presence of water voids and velocity fluctuations. Overall, the study provides valuable insights into the hydrodynamic characteristics and fluidization behaviors of coal particles in liquid-solid fluidized beds. By employing a rigorous CFD approach and validating the model against experimental data, the study demonstrates the applicability and accuracy of the proposed methodology for analyzing complex fluidized bed systems.*

Keywords: *Liquid-solid; fluidized bed; coarse coal; computational fluid dynamics*.

1. Introduction

Coal plays a crucial role as a primary energy source for industrial development, and its processing typically involves gravity separation and flotation, which are highly dependent on coal particle size. However, conventional methods face challenges in effectively separating coarse slime with a large particle size range. To address this issue, liquid-solid fluidized beds (LSFBs) have emerged as a promising solution due to their low energy consumption and simplicity of operation. However, understanding the complex multi-phase flow characteristics and multi-scale properties of LSFBs poses significant challenges.

Fluidization technology, including LSFBs, has found widespread application in various industries such as polymerization, mineral/coal separation, and pneumatic conveying. LSFBs involve suspending particles in a liquid medium through the action of drag force, offering advantages like fast mass transfer, high contact conversion efficiency, and efficient heat transfer. Despite the advancements in recent decades, gaining a deeper understanding of LSFBs remains critical for optimizing their performance in various applications, including mineral processing.

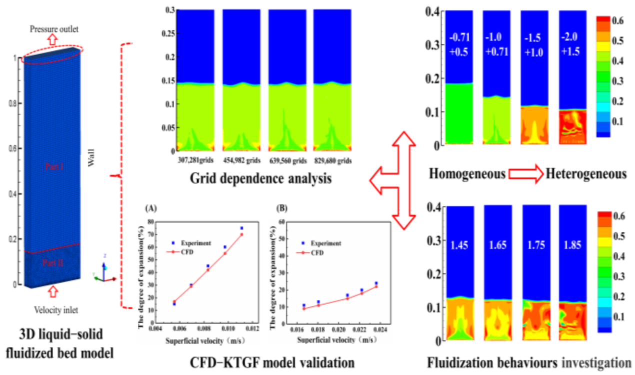

Figure 1: CFD KTGP Model

Modeling LSFBs is challenging due to their complex flow behavior and liquid-solid interactions. Computational fluid dynamics (CFD) simulation has emerged as a powerful tool for studying particle flow characteristics in fluidized beds. Two main types of CFD models are commonly used: Eulerian-Lagrangian models and Eulerian-Eulerian models. The former tracks individual particle trajectories within a fluid continuum, while the latter treats different phases as interpenetrating continua. For LSFBs, where the volume fraction of solids is high, the Eulerian-Eulerian approach is more practical due to its lower computational requirements.
Experimental investigations have also contributed to understanding the hydrodynamic characteristics of LSFBs, particularly in flotation cells. These studies have highlighted the influence of particle morphology, size distribution, and fluid-to-solid density ratio on the heterogeneous behavior of LSFBs. Small particles with low density are more easily fluidized compared to larger and heavier particles, which may exhibit inhomogeneous behavior due to bubble and jet effects. The research described in this study focuses on the hydrodynamic characteristics of coarse coal particles in a 3D LSFB. A Eulerian-Eulerian two-fluid model combined with the kinetic theory of granular flow (KTGF) was employed to investigate the fluidization behavior of these particles. Emphasis was placed on understanding the heterogeneous fluidization phenomena in LSFBs and evaluating the effects of particle size and density on fluidization behavior through CFD modeling and simulation. The results indicated that while low-density fine particles exhibited homogeneous expansion behaviors, large and heavy particles showed inhomogeneous behavior, including water voids and velocity fluctuations throughout the bed. Overall, gaining insights into the fluidization behavior of LSFBs is crucial for optimizing their operation and performance in various industrial applications.

2. CFD Analysis

The fluid dynamics (FD) mathematical model developed for simulating the fluidization of coarse coal particles in a liquid-solid system involves several key components. Firstly, the Euler-Euler liquid-solid two-phase flow model is employed to capture the local characteristics of coarse coal particle fluidization. The model equations encompass the continuity equation, expressing mass conservation for both liquid and solid phases, and the momentum equations, detailing the conservation of momentum considering various forces acting on each phase, including pressure gradients, viscous stresses, drag forces, and external forces. The kinetic theory of granular flow (KTGF) model is utilized to account for the behavior of the solid phase, introducing the concept of granular temperature to consider energy fluctuations. Additionally, a drag model calculates the stress tensor representing fluid-solid interactions, and a turbulent model, specifically the shear-stress transport k–ω model with low Reynolds number modifications, is incorporated to compute turbulent viscosity in transitional flow regimes.
Furthermore, the equations governing solid-phase properties such as pressure, shear viscosity, and bulk viscosity are provided, ensuring comprehensive modeling of the system's behavior. The detailed mathematical framework facilitates a deep understanding of the complex fluidization phenomena occurring within the liquid-solid system. By integrating various models and equations, the FD mathematical model enables the simulation of coarse coal particle fluidization under diverse conditions, providing insights into particle mixing quality and fluidization behavior critical for optimizing industrial processes such as coal processing and mineral separation.
Interphase force models play a crucial role in understanding the complex interactions between fluid and solid particles within liquid-solid fluidized beds. In a study by Zbib et al., a coupled computational fluid dynamics (CFD) and discrete element method (DEM) model was developed to analyze these interactions comprehensively. Among the interphase forces considered, including drag force, pressure gradient, virtual mass, and Saffman lift forces, the drag force emerged as significantly dominant in influencing the macroscopic behavior of the fluidized bed. Consequently, the study focused primarily on drag and lift forces, while neglecting others due to their negligible impact. The Gidaspow drag model and Moraga lift force model were employed in the CFD simulation. The Gidaspow drag model accounts for the drag force exerted by fluid on solid

particles, incorporating parameters such as particle size, density, and fluid velocity, while the Moraga lift force model quantifies the lift force acting on particles due to fluid vorticity. Through these models, the study aimed to gain insights into the dynamic behavior of particles within liquid-solid fluidized beds, crucial for optimizing industrial processes reliant on such systems, such as coal processing and mineral separation.

3. Simulation Details

Figure 1 illustrates the mesh structure of the 3D liquid-solid fluidized bed (LSFB), which was developed and meshed using ANSYS ICEM software version 19.0. The LSFB is partitioned into two sections: Part I and Part II. Part II, the lower section, employs an unstructured grid with a maximum size of 1 mm. The bottom of the fluidized bed serves as a distribution plate with evenly spaced small holes, each having a diameter of 2 mm and constituting 40% of the plate's area. To ensure an adequate mesh resolution around the small holes, densification of the mesh was performed, with the maximum size set to 0.5 mm. Conversely, Part I, the upper section, is meshed using structural elements with a mesh size of 2 mm, aimed at reducing computational costs and stabilizing numerical calculations. In the computational fluid dynamics (CFD) simulation, water and coal particles are designated as the primary and secondary phases, respectively. Initially, coal particles are patched at the bottom of the fluidized bed, which has an initial height (H0) of 100 mm. Boundary conditions include velocity inlet (corresponding to the small holes at the bottom of the bed), pressure outlet, and wall conditions within the fluidized bed reactor. The remaining portion of the bottom plate, not designated as a velocity inlet, is assigned a wall boundary condition.

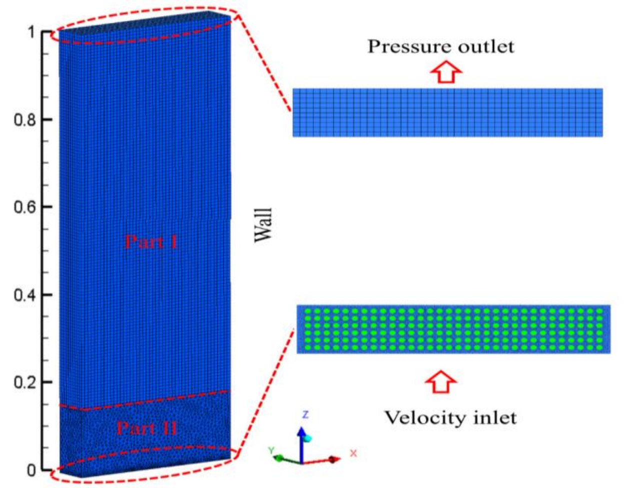

Figure 2. Three-dimensional computational geometry of a fluidized bed

In conducting numerical simulations, the selection of appropriate cell size and time step is crucial to ensure both accuracy and computational efficiency. In this study, the water velocity ranged from 0.25 to 2.5 cm/s, with a corresponding time step of 0.005 s. This choice of time step resulted in a Courant number (Nc) ranging from 0.0125 to 0.125, as per Equation (29). Such values fall within the range commonly accepted by researchers, indicating a reasonable temporal discretization for the simulations. These settings were consistently applied across all computational fluid dynamics (CFD) simulations undertaken in this investigation.

To assess the fidelity of the CFD simulations, the root-mean-square error (RMSE) was employed as a metric, as defined in Equation (30). The RMSE quantifies the deviation between the CFD results and experimental data. In this study, the calculated RMSE values were 3.65 for low-density fine particles and 2.01 for high-density coarse particles. These RMSE values fell within an acceptable range, affirming the accuracy of the CFD results and their alignment with experimental observations.

The numerical solution of the developed CFD mathematical model was carried out using ANSYS Fluent software. The governing equations were discretized utilizing the second-order upwind method, known for its balance between accuracy and computational efficiency. The SIMPLE algorithm was employed to couple velocity and pressure fields, ensuring robust convergence during the iterative solution process. To further enhance convergence, a low-relaxation-factor method was utilized, with specific under-relaxation factors assigned to various parameters. Notably, the under-relaxation factors were set to 0.3 for pressure, 0.7 for momentum, 0.3 for volume fraction, 0.2 for granular temperature, and default values for other parameters. These choices in numerical methods and solver settings were instrumental in achieving reliable and efficient solutions for the CFD simulations, contributing to the accuracy and stability of the computational results.

4. Results and Discussion

4.1. Grid Dependence Analysis

The accuracy of computational fluid dynamics (CFD) simulations is often contingent upon the density of the geometric grid utilized. To assess this, a grid sensitivity analysis was conducted using four different grid resolutions. Contours of solid volume fraction and time-averaged solid volume fractions were examined to gauge the effects of grid resolution. Overall, the simulation results across the different grids exhibited similar trends, especially in bed regions above 0.05 in height. Although

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slight differences were observed at the bottom of the bed, the final bed expansion height and flow state remained consistent across all grids. Notably, medium and fine meshes demonstrated nearly identical local solid-phase volume fractions throughout the bed. Comparison of bed height profiles showed that while coarse mesh results deviated significantly, medium and fine mesh profiles closely aligned with each other and with experimental data. Based on these evaluations, the 639,560 grid resolution was deemed sufficient for fluid dynamic predictions in liquid-solid fluidized beds, balancing accuracy and computational efficiency.

4.2. Model Validation

Validation of the CFD model was performed by comparing simulation results with experimental data, specifically in terms of bed expansion height. Two coal particle types—small and light, and large and heavy—were considered, and comparisons were made at various superficial liquid velocities. The CFD simulations demonstrated good agreement with experimental data across different superficial liquid velocities, indicating the model's efficacy. Notably, bed expansion degree was found to be highly dependent on superficial liquid velocity, with higher velocities resulting in increased expansion degrees. The relative errors of predicted bed heights were within acceptable ranges, further affirming the model's validity.

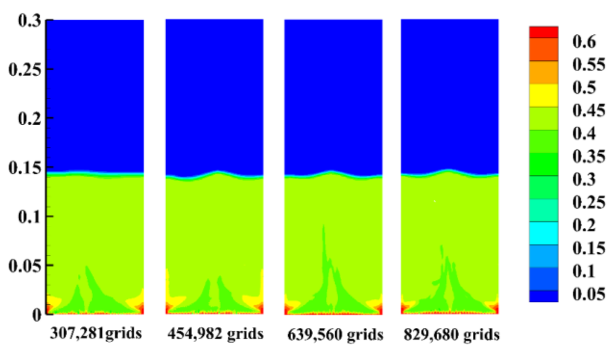

Figure 3. Grid sensitivity analysis: the contours of the solid volume fraction at the time of 50 s at different resolutions.

4.3. Model Application

4.3.1. Effect of Coal Particle Size

Investigating the influence of particle size on fluidization characteristics, simulations were conducted for coal particles of different sizes. Results showed that smaller particle sizes facilitated more homogeneous flow, with stable and regular liquid and particle flows. Conversely, larger particle sizes led to decreased bed expansion heights and increased resistance to fluid flow, resulting in heterogeneous fluidization. As particle size increased, bed homogeneity decreased, disrupting flow regularity.

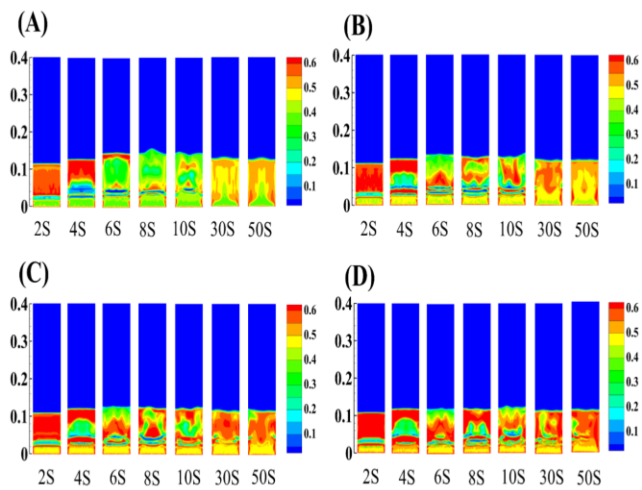

Figure 4. Time evolutions of the volume fraction of the solid phase under the condition of different coal particle densities: (A) 1400–1500 kg/m3; (B) 1600–1700 kg/m3; (C) 1700–1800 kg/m3; (D) 1800–1900 kg/m3.

4.3.2. Effect of Coal Particle Densities

Exploring the impact of particle density on fluidization, simulations were conducted for coal particles of varying densities. Results revealed that increasing particle density led to decreased bed expansion heights and heterogeneous fluidization. Higher particle densities resulted in the concentration of particles at the bottom of the bed, with void motions resembling bubbles observed in gas-solid fluidization systems. Overall, the increased effect of gravity on particles impeded fluidization, with higher particle densities causing practical unfluidized behavior despite the presence of voids.

In summary, the validated CFD model proved effective in capturing fluidization behavior in liquid-solid fluidized beds, enabling comprehensive exploration of key operational parameters' effects on hydrodynamic characteristics. The findings underscore the importance of particle size and density in influencing fluidization behavior, providing valuable insights for optimizing liquid-solid fluidized bed processes.

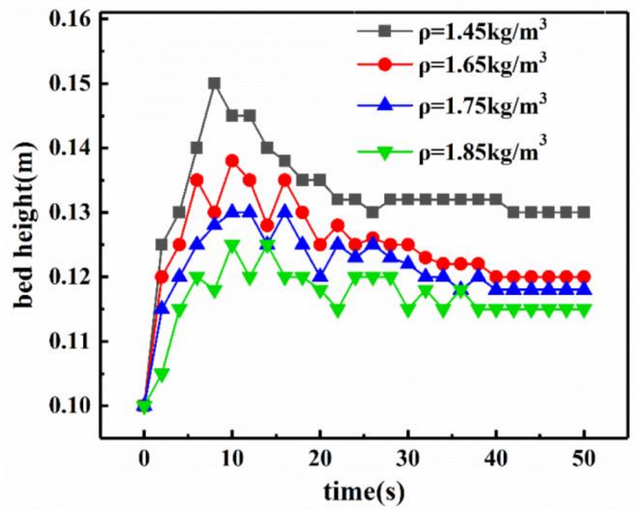

Figure 5. Time evolutions of the bed expansion height under the conditions of different coal particle densities

5. Conclusion

In conclusion, the study successfully investigated the fluidization behavior of coal particles in a 3D liquid-solid fluidized bed (LSFB) using a Eulerian-Eulerian model combined with the KTGF. Grid dependence analysis was conducted to select appropriate grid parameters, ensuring the accuracy of the computational fluid dynamics (CFD) simulations. Validation of the CFD model against experimental data confirmed its reliability, with acceptable root-mean-square error (RMSE) values obtained for both low-density fine particles and high-density coarse particles. Subsequently, the validated CFD model was employed to explore the effects of particle size and density on hydrodynamic characteristics and fluidization behaviors in the LSFB.

The investigation revealed significant impacts of particle size and density on fluidization behavior. As particle size increased, bed expansion height decreased, with heterogeneous fluidization observed at larger particle sizes. Conversely, smaller particle sizes exhibited homogeneous fluidization behavior. Particle density also played a crucial role, with higher densities resulting in decreased bed expansion height. Fluctuations in bed expansion height over time were attributed to the formation and movement of vacuoles within the bed. Specifically, small and light particles demonstrated easier fluidization and homogeneous expansion behaviors, whereas large and heavy particles exhibited increased inhomogeneity throughout the bed, including the presence of water voids and velocity fluctuations caused by vacuoles. The study provides valuable insights into the complex dynamics of LSFBs, highlighting the importance of particle size and density in influencing fluidization behavior. These findings contribute to the optimization of LSFB processes, guiding future research and development efforts in this field.

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