Powder Technology 245 (2013) 314–323

Contents lists available at SciVerse ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Study of hydrodynamic characteristics of particles in liquid–solid fluidized bed with uniform transverse magnetic field[☆]

Shuyan Wang [a,*], Yanli Shen [a], Yimei Ma [a], Jinsen Gao [b], Xingying Lan [b], Qun Dong [a], Qinglin Cheng [a]

[a] *School of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, China*
[b] *State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China*

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form 5 April 2013
Accepted 29 April 2013
Available online 4 May 2013

Keywords:
Magnetic fluidized bed
Transverse magnetic field
Simulation
Discrete element method
Fluidization

ABSTRACT

Flow behavior of solid phases is simulated by means of DEM-CFD in a liquid–solid fluidized bed with magnetization of preliminarily fluidized bed mode (LAST) along a transverse uniform magnetic field. By changing the magnetic field strength, the distribution of particles is studied within the bed. The distributions of velocity and volume fraction of particles are analyzed at the different magnetic field intensities. When the magnetic field strength is increased to a value at which the fluidization of strings starts, the particles are found to form straight-chain aggregates along the direction of the magnetic field. At very high magnetic field strengths, the densification of particles is observed, and the liquid channels are forming between the magnetic chains. Simulations indicate that the granular temperature of particles decreases with the increase of magnetic-flux density. The drag force is determined at each particle at the low magnetic field. With an increase of magnetic field strength, magnetic force becomes main force among particles.

1. Introduction

The application of an external magnetic field on a ferromagnetic particle bed significantly changes its fluidization behavior. The application of a magnetic field to beds of ferromagnetic particles induces cohesive forces between them and imposes anisotropy in their arrangement along the field lines [1]. The influence of an external field depends both on the intensity and on the orientation of the field lines [2]. Magnetic can be used either as stirring promoter or as stabilization generator. Magnetic fluidized beds (MFB) of magnetically susceptible particles are considered as one of the technologies developed to eliminate the drawbacks of fluidized beds. Imposing a magnetic field on a bed of magnetizable particles could suppress or delay bubbling of these particles. The MFB deals with two basic magnetization modes: Magnetization FIRST (preliminary magnetization of fixed bed and consequent fluidization) and Magnetization LAST (magnetization of preliminarily fluidized beds). Penchev and Hristov investigated that two main effects can be obtained by applying an external magnetic field transverse to the gas flow, which are the minimum fluidization velocity increasing in proportion to magnetic field intensity and the bed expanding greatly before the onset of fluidization [1]. Rosensweig postulates that the magnetic stabilization is possible in an axial field only. This conclusion was derived on the basis of the linear theory of stability, and corresponds to the experimental results obtained in axial fields [3]. Hristov obtained results that show that stabilized beds can be created under different orientations of homogeneous magnetic fields [2]. Under a transverse magnetic field, the slug outbreak was postponed, and the outbreak intensity was also reduced [4]. Thivel presented an investigation of the hydrodynamic behavior of a gas–solid magnetically stabilized fluidized bed made up with a mixture of ferromagnetic and glass particles and submitted to a uniform magnetic field transverse to the gas flow. This work established that it is possible to obtain an effect of magnetic stabilization on a mixture of particles with a transverse magnetic field [5]. Hamby and Liu indicated that the magnetic stabilization was possible over a wide range of gas velocities. The minimum fluidization velocity and the pressure drop at minimum fluidization increase slightly with increasing field intensity, possibly due to the occurrence of the field-induced particle agglomeration. The transition velocity is greater in an axial field compared with a transverse field, and it increases with increasing field intensity [6]. Gros et al. studied liquid–solid fluidization subjected to an external transverse electromagnetic field. Key parameters of the bed (superficial velocity, pressure drop, porosity and particle movement) were used to describe the influence of electromagnetic field and mass fraction on fluidization and bed behavior, while changing orientation fields do not produce any positive effect [7]. The stability of the bed can be influenced by several factors, including liquid velocity, magnetic field strength, solid and liquid density, solid magnetic susceptibility and solid particle size distributions [8].

Numerical simulation has evolved into a useful tool to obtain detailed information about the flow phenomena in magnetic fluidized

---

[☆] This is an open-access article distributed under the terms of the Creative Commons Attribution-NonCommercial-No Derivative Works License, which permits non-commercial use, distribution, and reproduction in any medium, provided the original author and source are credited.

* Corresponding author.
E-mail addresses: wangshuyan@dqpi.edu.cn, wangshuyanhit@126.com (S. Wang).

0032-5910/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2013.04.049

bed. Computational fluid dynamics (CFD) studies have become popular in the field of gas–solid two phase flow. The detailed information about the local values of phase hold-ups and their spatial distributions, liquid phase flow patterns and the intermixing levels of the individual phases are either difficult or impossible to obtain from experiments. Such information can be useful in the understanding of the transport phenomena in magnetic fluidized beds. However, to date, the applications of two-fluid gas–solids models, discrete element method (DEM) and direct numerical simulation are very popular to predict flow behavior of particles. In the two-fluid model (TFM) both the gas and solids phase are described as continuous inter-penetrating fluids. Xiong et al. investigated particle–fluid fluidization using TMF, and that numerical schemes and implementation details were described with emphasis on the drag force and the solids stress [9]. Wang et al. studied flow behavior of gas and particles in a 2-D riser using improved TMF incorporated particle rotation using a kinetic theory for rough spheres [10]. Wang et al. proposed revising the EMMS model based on TMF to simulate fluctuation characteristics of solid concentration in CFB risers [11]. Direct numerical simulation (DNS) involves the numerical solution of the equations that govern fluid flows. It is a research tool that provides us with an extremely detailed description of the flow field. Xiong et al. observed distinct particle-rich dense phase and gas-rich dilute phase with direct numerical simulations of gas–solid suspensions [12]. Xiong et al. presented DNS of gas–solid suspensions to observe multi-scale clustering of particles, which gave quantitative support to the EMMS model for heterogeneous multi-phase systems [13].

Eulerian–Lagrangian models describe the fluid flow using the continuum equations, and the particulate phase flow is described by tracking the motion of individual particles [14–16]. Discrete particle models (DPM) have been used for a wide range of applications [17]. In a hard-sphere system [18], the trajectories of the particles are determined by momentum-conserving binary collisions. The interactions between particles are assumed to be pair-wise additive and instantaneous. In the simulation, the collisions are processed one by one according to the order in which the events occur. Note that the possible occurrence of multiple collisions at the same instant cannot be accounted for. At high particle number densities, it will lead to a dramatical increase in collision number of particles. In that case, like in the present case with agglomeration of particles, the hard-sphere method becomes useless. The soft-sphere models or discrete element method (DEM) allow for multiple particle overlap although the net contact force is obtained from the addition of all pair-wise interactions. The coupling of the DEM with a finite volume description of the gas-phase based on the Navier–Stokes equations was first reported in the open literature by Tsuji et al. [19] using soft-sphere model. Renzo et al. [20] predicted the layer inversion by means of DEM-CFD in a liquid–solid fluidized bed. Definitely, DEM-CFD may allow a more detailed study of the local particle flow field, comparing with TMF and DNS, which is thought to be the mechanism responsible for mixing of particles in the bed. As for magnetic fluidized beds, the studies of trajectories of particles and interaction between the magnetic particles and non-magnetic particles are critical in predicting the flow behaviors of liquid–solid, therefore DEM-CFD is the best selection to hydrodynamics simulation of magnetic fluidized beds. However, detailed investigations of flow characteristics in magnetic liquid–solids fluidized bed are still lacking. In the present study, the flow behavior of solid phases is simulated by means of DEM-CFD in a liquid–solid fluidized bed with LAST mode along a transverse uniform magnetic field. The hydrodynamics of liquid–solid fluidized beds with uniform magnetic field is simulated. By changing the magnetic field strength, the distribution of particles is studied within the bed. The distributions of velocity and volume fraction of particles are analyzed at the different magnetic field intensities. The distribution of granular temperature of particles is analyzed with the increase of magnetic-flux density in MFBs.

2. Eulerian–Lagrangian liquid–solid flow model

The DEM-CFD approach is relatively well documented in the literature [14–16,21], so here the salient features of the model equations used will be summarized. Our DEM-CFD implementation uses a rather standard coupled approach based on the particle-scale Discrete Element Method for the solid phase [17] and a local average CFD approach for the fluid phase [18,21]. To simplify, it is assumed that: (1) solids phase consists of mono-sized particles with the same diameter and density; and (2) both liquid phase and particles are assumed to be isothermal without reactions.

2.1. Equation of motion for liquid phase

Generally in numerical simulation of two-fluid flow, the fluid phase flow is solved by a locally averaged approximation of the continuity and Navier–Stokes equations with an averaging scale of the order of the computational cell. The equations of conservation of mass and momentum for liquid phase are:

$$\frac{\partial(\rho_l\varepsilon_l)}{\partial t} + \nabla\cdot(\rho_l\varepsilon_l u_l) = 0 \tag{1}$$

$$\frac{\partial(\rho_l\varepsilon_l u_l)}{\partial t} + \nabla\cdot(\rho_l\varepsilon_l u_l u_l) = -\varepsilon_l\nabla P + \varepsilon_l\nabla\cdot\tau_l + \varepsilon_l\rho_l g - F_{pl} \tag{2}$$

where g is the acceleration due to gravity, P is the liquid pressure, ε_l is the liquid volume fraction, τ_l is the viscous stress tensor and ρ_l is the density of liquid. The coupling term F_{pl} between particle phase and liquid phase is estimated as the sum of the drag on each particle within the corresponding fluid control volume. The stress tensor of liquid phase can be represented as

$$\tau_l = \mu_l\left[\nabla u_l + (\nabla u_l)^T\right] - \frac{2}{3}\mu_l(\nabla\cdot u_l)I \tag{3}$$

where μ_l is the viscosity of liquid phase, and is equal to 1.0e-03 Pa s.

2.2. Equation of motion for a particle

Spherical particles of uniform size are investigated in the present work. The particles are tracked individually based on the Newton's second law of motion. Each particle has two types of motion, translational and rotational motions. The motion of each individual particle is governed by the laws of conservation of linear momentum and angular momentum, expressed, for the i-particle, by

$$m_i\frac{dv_i}{dt} = -V_p\nabla P + m_i g + f_{di} + f_{mi} + \sum\nolimits_{j=1}^{N}\left(f_{lj} + f_{cj} + F_{mj}\right) \tag{4}$$

$$I_p\frac{d\omega_i}{dt} = \sum\nolimits_{j=1}^{N} T_{pij} \tag{5}$$

where m_i and v_i are the mass and velocity of a particle, and V_p is the volume of a particle. T_p is the torque arising from the tangential components of the contact force. I_p and ω are the moment of inertia and angular velocity of a particle, respectively. The terms of the right-hand side of Eq. (4) are the liquid pressure gradients, gravity, drag force exerted from the fluid, virtual mass force, lubrication force, contact force and magnetic force by the introducing external magnetic field, respectively. These inter-particle forces and torques are summed over the N particles in contact with particle i. The contact force between particles is calculated based on the soft-particle method.

The liquid–solid interaction force, or drag force, is determined at each particle. The drag force depends on not only the relative velocity between the solid particle and fluid but also the presence of neighboring