Powder Technology 329 (2018) 167–180

Contents lists available at ScienceDirect

Powder Technology

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

Influence of gas inflow modelling on CFD-DEM simulations of three-dimensional prismatic spouted beds

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ARTICLE INFO

Article history:
Received 1 September 2017
Received in revised form 18 December 2017
Accepted 20 January 2018
Available online xxxx

Keywords:
Spouted bed
CFD-DEM simulations
Particle contact model calibration
Inlet geometry

ABSTRACT

In this contribution, coupled CFD-DEM simulations of a three-dimensional prismatic spouted bed with two tangential, parallel gas inlets are presented. Contact model parameters were calibrated. Simulations with different inlet conditions were performed, whereby an additional degree of freedom by merging the two inlets was found to match the experimentally observed bed behavior. Additionally, it was shown that the inlet slit pressure drop has an important influence on spouting stability. By adjusting the inlet conditions, calibrating the particle interaction model parameters and applying fluid-coarsening correction of the Beetstra drag model, an experimentally validated model was obtained.

1. Introduction

Spouted beds provide an efficient way of contacting solid and gaseous phase and have found many applications in drying, granulation and combustion of otherwise difficult to fluidize particles, like coarse Geldart D particles, as well as fine ones corresponding to Geldart C class. Compared to fluidized beds designed for these purposes, they show excellent stability in handling inhomogeneous systems in regard to particle density, size and shape. Spouted beds are constructed in a variety of geometries: asymmetric, axisymmetric as well as prismatic. All variants have a narrow gas inlet region in common, where the particles are accelerated. The resulting particle jet is the eponymous spout. Due to the broadening of the process chamber over the height of the apparatus, the spout diffuses and the particles fall onto the surrounding bulk, namely the annulus. Due to gravity and the slant geometry of the apparatus walls, the bulk slides towards the spout. A synopsis of different spouted bed geometries was conducted by Piskova et al. [1]. In contrast, the related spout fluidized bed consists of a fluidized bed in which a region shows higher aeration, creating a spout. A comprehensive comparison between spout fluidized beds, spouted beds and fluidized beds can be found in the work of Sutkar et al. [2]. The spout-annulus boundary undergoes cycles of collapse and acceleration of particles, leading to pressure drop oscillations. Pressure drop is experimentally well accessible and thus frequently used for operation regime classification [1], as well as to validate simulations [3]. Axisymmetric spouted beds, as first described by Mathur & Gishler [4] for drying of grains, are typically operated using very high loadings with bed heights by far exceeding the conical region. Draft tubes can be used to stabilize the operation by separating the spout from the annulus by forming a fix spout boundary leading to more regular circulation [5]. Prismatic, or slot-rectangular, spouted beds have a base area equivalent to a cross-section of an axisymmetric spouted bed. They enable scale-up by increasing the depth of the bed while retaining the general bed dynamics [6] that can be approximated using a regime map, which is only applicable for a certain geometry and particle type. The granular dynamics of prismatic spouted beds, are highly complex, especially for shallow beds. Below the minimum bubbling velocity, the bed remains static and the pressure drop obeys the Ergun equation. Above this point, bubbles rise through the bed, creating a complex, irregular pressure signal. Starting with the minimum spouting velocity, the spout appears and the pressure drop decreases significantly while oscillating regularly. This flow regime is named dense or stable spouting pertaining to its steady-state appearance and symmetry. Further increasing the gas velocity leads to alternating spout deflections and incoherence that are reflected in irregularities in the pressure signal. These observations were primarily made in pseudo-two dimensional system possessing little depth [3], lacking a degree of freedom that is present even in lab-scale batch apparatuses. As spouted beds display such complex behavior evading generalizations and quantization by means of algebraic correlations, numerical simulations are highly desirable for scale up and transfer to continuous operations.

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https://doi.org/10.1016/j.powtec.2018.01.048
0032-5910/

1.1. Simulation of spouted beds

Due to the complex granular dynamics and lack of truly predictive correlations, many attempts have been made to capture the behavior of spouted beds using numerical simulations. In the simulation of solid-gas systems Euler-Euler (EE) methods treating both phases as interpenetrating continua and Euler-Lagrange (EL) methods handle the gas phase as a continuum and track the particles in a discrete manner. The most prominent EE method is the Two Fluid Model (TFM), using the Kinetic Theory of Granular Flow (KTGF) by Ding & Gidaspow [7]. Two Fluid Models are solved on a numerical grid and are successfully employed for the simulation of industrial scale fluidized bed systems and implemented in most general CFD codes as well as more specialized ones, such as MFiX (Multiphase Flow with Interphase eXchanges). In these, the motion of individual granules is not resolved, but handled by statistics and closure laws. Their success in predicting granular flows is heavily dependent on choosing the proper closure laws for the flow situation and is prone to difficulties in cases with multiple and changing flow regimes. EL methods circumvent these difficulties by solving the fluid flow on a numerical grid and tracking discrete particles, therefore preserving particle identities and simplifying the analysis of true residence times, segregation and transport processes. Unresolved methods realize phase coupling by means of drag closures and a void fraction field. The unresolved Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) approach resolves the contact between particles through contact laws, as described by Cundall & Strack [8] and is able to accurately depict bulk phases. The Multiphase-Particle-in-Cell (MP-PIC) [9,10] method simplifies particle-particle interactions by employing empirical closures to model inter-particle stresses solely in order to avoid overpacking. As the computationally expensive contact detection is avoided, it allows for the efficient and accurate description of industrial-scale fluidized bed processes, as demonstrated in [11–13], but limited to fully fluidized systems. Due to regions with dense (spout), dilute (fountain) and bulk (annulus) granular flows, the MP-PIC method is not applicable for spouted beds. Thus, they are most commonly simulated using TFM and the CFD-DEM approaches. Gryczka et al. [14] simulated a two-dimensional prismatic dual-inlet spouted bed using the TFM and KTGF implemented in ANSYS FLUENT for Geldart D particles and compared various drag and granular temperature closures. The resulting bed expansions, particle velocities and pressure signals were overpredicted compared to experiments in a pseudo-2D (depth 100 mm) spouted bed. Using the same material and geometry, Salikov et al. [15] performed three dimensional CFD-DEM simulations using EDEM and ANSYS FLUENT to investigate the spouting event. They validated against experimental pressure signal fluctuations and found excellent agreement. In earlier works, Salikov et al. [6] simulated a pseudo 2D version of this apparatus (depth 100 mm) in order to study the influence of the prismatic angle and rolling friction on particle mobility in the spout, albeit without previous experimental validation. Goniva et al. [16] simulated a pseudo-2D single spout fluidized bed using the open source CFD-DEM software CFDEMcoupling that couples the CFD code OpenFOAM to the DEM code LIGGGHTS. While lacking the bulk phase of spouted beds, the necessity of rolling friction modelling in dense particulate flows was shown by comparing granular velocity profiles to data obtained by Positron Emission Particle Tracking (PEPT) experiments.

1.2. CFD-DEM simulations: state of the art

The unresolved CFD-DEM approach combines accurate representation of areas with packed solids and the ability to resolve full range of dense and dilute granular flows. Its applicability to industrial-scale apparatuses and particle system with very small particles is limited due to the number of resolved particle contacts. In order to ameliorate this problem, particle coarsening is often employed, in which computational parcels are tracked instead of the primary particles. Two basic approaches for particle coarsening exist. One possible approach proposed by Bierwisch et al. [17] uses dimensional analysis of contact laws regarding the conservation of the macroscopic coefficient of restitution and stress state by conserving relative particle/parcel overlap in binary contacts. This approach depends on material properties of the primary particles. Another approach, which will be used in this work, is proposed later. Unresolved CFD-DEM simulations require a computational grid with a maximum resolution of about three parcel diameters due to the need to calculate the solids void fraction. This restricts the accuracy of the method in systems with fine flow features. Diffusive smoothing as proposed by [18] can be employed to ameliorate this problem while allowing for more numerical stability at larger fluid phase time steps. In other grid regions with small flow gradients, such as freeboard areas, a coarser grid may be desirable. In such coarse regions, meso-scale interactions, such as particle clustering and strand formation, may not be captured, resulting in an overestimation in drag force for these particles. Radl et al. [19] conducted CFD-DEM simulations using successively refined grids and conducted void fraction dependent filtering, yielding a correction to the Beetstra drag law [20], accounting for grid coarsening.

1.3. Outline of this work

In this work, we present an experimentally verified CFD-DEM model for a commercial spouted bed with a Geldart B-class bed. The open source CFD code OpenFOAM [21] and the DEM code LIGGGHTS [22] were coupled using CFDEMcoupling [16] for conducting the simulations. To accurately represent the bulk phase mechanics, particle bulk properties were determined in various experiments and contact model parameters were automatically calibrated outlined in Section 2.2. For model validation, an experimental regime map was created based on pressure drop analysis. Simulations using a novel approach were conducted for the different regimes and the resulting pressure drop power spectrum distributions were compared to the experimental results.

2. Material and methods

2.1. Experimental set-up

A transparent replica (wall material Europlex®, Evonik, Germany) of a commercial three-dimensional laboratory spouted bed process chamber (ProCell 5, Glatt, Germany) was installed to visually observe the particle flow pattern. A flow chart of the experimental setup is shown in Fig. 1. The particle motion was recorded by a high-speed video camera (NX-S2, Imaging Solutions GmbH, Germany) at a frequency of 100 Hz. Air was sucked through the apparatus by an exhaust fan (SKG 420-2V, Elmo Rietschle, Germany) that was controlled by a frequency converter. The air enters the process chamber through two adjustable horizontal slits with maximum height of 3.5 mm. By moving the rotatable cylinders, the inlet pressure drop can be adjusted by reducing the height of the slits. All experiments and simulations were performed at constant slit height of 3.5 mm. The gas flow rate was calculated from the air velocity measures by an anemometer (EE65, E + E Elektronik, Austria) in the connecting pipe between the apparatus and the fan. The pressure drop was measured in the freeboard above the particle bed with a high-speed differential pressure detector (PD-23/8666.1, Keller, Germany). The sensor was connected to a signal converter and a data acquisition system as shown in Fig. 1.

For analysis of the spouting stability, the measured gas pressure fluctuations were analyzed in the frequency domain by means of Fourier transformation $\mathcal{F}$, which is defined as follows:

$$\mathcal{F}p(t)(\omega_k) = \frac{1}{N_{data\ points}} \sum_{m=0}^{N_{datapoints}-1} p(t_m) e^{-\frac{2\pi mk}{N_{datapoints}} i}, \qquad (1)$$