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CFD-DEM investigation of particles circulation pattern of two-tower fluidized bed reactor for beam-down solar concentrating system

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ABSTRACT

In this study, a numerical model has been developed by the combined approach of computational fluid dynamics (CFD) and discrete element method (DEM) collisional model to study the particle-fluid flow of the fluidized bed reactor for solar beam-down concentrating system. The contact forces between the particles have been calculated by the spring-dashpot model, based on the soft-sphere method. An experimental visualization of particles circulation pattern and mixing of two-tower fluidized bed system has been presented. A good agreement has been found between the experimental measurements and numerical predictions. To investigate the influence of fluid flow rate and particle size on the flow pattern of the reactor, simulations have been performed for various conditions. The results indicate that the large size particles induce three-dimensional effects as they are accumulated at the central axis region. The average bed height of the left tower increased by 23.4% when increasing the flow rate about 70%.

1. Introduction

Fluidized bed technology is widely used in various industrial applications, including mechanical and chemical industries, due to its superior heat and mass transfer characteristics. Fluidized bed reactors have been used as reactor/receiver and storage systems of concentrated solar plants, which is one of the promising technologies currently undergoing rapid development [1–4]. Solar particle receivers (SPR) were developed to drive the concentrating solar plants (CSP) towards higher operating temperatures and enhance the efficiency of the power cycles. The SPR-based CSP system uses solid particles as the heat transfer medium (HTM) in place of currently used molten salt or steam [5–7]. An experimental and theoretical study of a pilot scale solar fluidized bed receiver was carried out by Flamant et al. [5] at the early stage of development using alumina particles, and the unsteady behavior of the receiver in the temperature range of 550–915 °C was described by a simple heat transfer model. Recently, a tubular fluidized receiver for beam-down solar concentrating system was developed by Matsubara et al. [8]. The fluid dynamics of the prototype receiver was experimentally investigated by 3 kW_{th} solar simulator. Subsequently, a two-tower fluidized receiver was developed for beam down system and an experimental visualization of cold particle-flow prototype was presented [9]. In concentrated solar thermal industry, fluidized-bed technology has also been used to produce hydrogen by thermochemical two step water splitting cycles [2], and synthetic gas by gasification of coal coke [10].

The hydrodynamic behavior of the gas-solid flow plays a vital role in the aforementioned fluidized bed reactors. Thus, in order to measure and study the dynamics of dense gas-solid flow, different kind of techniques have been developed such as particle image velocimetry (PIV), digital image analysis (DIA), positron emission particle tracking, magnetic resonance imaging, electrical capacitance tomography, and etc. However, it's pretty challenging to obtain accurate flow characteristics at reasonable cost [11]. With rapid advancements of computers and numerical algorithms, CFD has become a powerful tool to obtain the flow characteristics of the dense gas-solid flow qualitatively. Various numerical models have been developed in the past few decades to simulate the gas-solid flows. The most widely used models are Eulerian-Eulerian and Eulerian-Lagrangian models. The Eulerian-Eulerian model treats both gas and solid phases as continuum, and uses the kinetic theory of granular flow to calculate the solid phase pressure and viscosity. The Eulerian-Lagrangian (CFD-DEM or CFD-DPM) model accounts the motion of each particle individually in the continuum gas phase. Therefore, the CFD-DEM model is computationally expensive.

In discrete particle model, the particle collisions can be either modelled by soft sphere or hard sphere approach. In hard-sphere (binary collision) approach, collision between two particles or between a particle and the wall is evaluated separately; which is an event driven model since the particles are moved until the next collision occurs. The soft-sphere model is driven by a time step as the particles are moved together with a fixed time step; which allows overlap between the particles and

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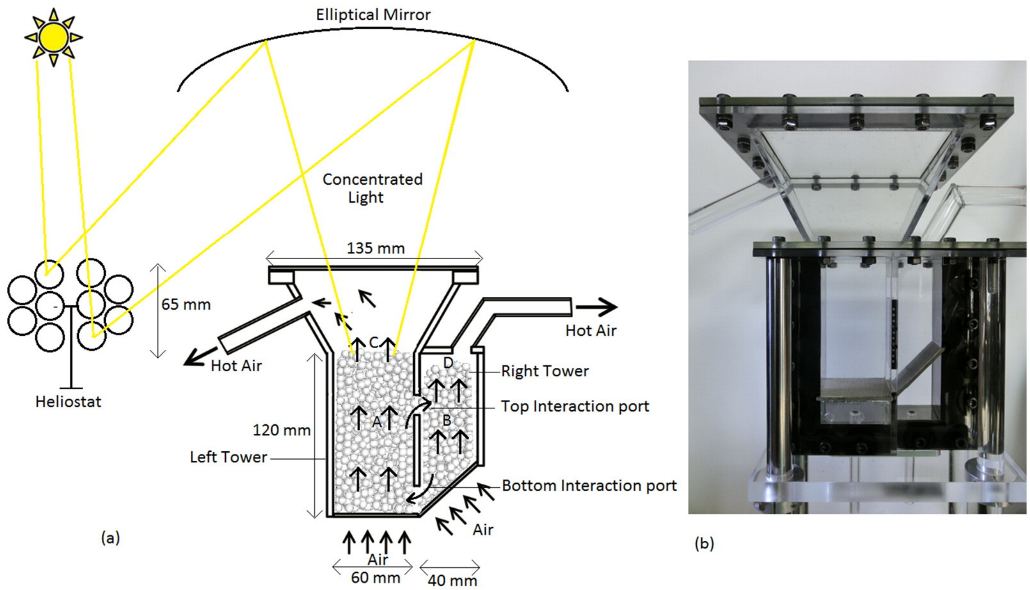

Fig. 1. (a) Schematic of the beam-down concentrated receiver/reactor and (b) transparent experimental setup.

calculates a contact force between the particles by spring-dashpot approach [12]. Initially, Tsuji et al. [13] developed a two dimensional CFD-DEM model for fluidized bed by soft sphere approach. Following their study, various researchers have improved that model extensively with some modifications in the past two decades. In the early stages, the number of simulation particles was several thousand only but now with the vast improved computers and techniques, up to 100,000 particles can be simulated with single core processor. By parallel computing, fluidized bed systems consisting of several million particles have been simulated for different kinds of problems [14,15]. Multi-physics problems coupled with heat transfer and chemical reactions were investigated [16–18]. Turbulent models were coupled with fluidized bed models [19,20]. The dependency of particle–particle collision on turbulence characteristics, such as turbulent kinetic energy (TKE), dissipation rate (TDR), fluctuation and correlated fluctuations were studied [19]. In order to reduce the computational cost, various effective methods and algorithms were proposed [21–23]. Particle-gas flow of complex geometries was investigated [24,25]. Non-spherical particle collision models were presented [26,27].

Despite many studies on the CFD-DEM modeling of fluidized beds for various applications, only a few studies have been reported on modeling and validation of fluidized beds for concentrated solar reactor/receiver. To the best of our knowledge, the CFD-DEM model of two-tower fluidized bed receiver for beam down solar concentrating system has not been developed and studied considerably. Moreover, as the performance of the two-tower reactor strongly depends on the concentrated radiation (sunlight), the complete flow characteristics of the two-tower receiver is required to improve the design of the receiver. Accordingly, in this study, a CFD-DEM model has been developed to investigate the influence of air flow rate on the flow characteristics, particles flow pattern and velocity of the two-tower reactor. The modeling results have been compared with the experimental results for validation.

2. Experimental setup

Recently, couple of fluidized bed reactors have been developed and tested at Niigata University, Japan, for two-step thermochemical water splitting cycles and coal coke gasification using Xe light solar simulator [28–30]. A two-tower fluidized bed system filled with spherical non reacting particles has been proposed as well to use concurrently as receiver and storage system [9]. These fluidized bed systems have been developed for 100 kW_{th} beam-down demonstration plant at Miyazaki, Japan, which consists of 88 heliostats with total area of 176 m^2 and an elliptical reflecting mirror at 16 m height. The schematic of the proposed beam-down reactor/receiver is shown in Fig. 1(a). Both towers filled by spherical particles. The left tower (LT) exposes to the concentrated radiation. Consequently, particles of the left tower receive radiation through the top slit and exchange the thermal energy with other particles and the heat transfer fluid. Subsequently, the heated particles gradually move to the right tower (RT) by fluidization of particles through drag force given by fluid flow with appropriate flow rate conditions at the inlets of left and right towers.

The thermo-chemical reaction/storage of the two-tower reactor strongly depends on the concentrated radiation obtained through the top slit of the LT. The intensity of the radiation is according to the sunlight which depends on the time of the day. Thus, an appropriate flow pattern and the velocity of the circulation should be given according to the sunlight availability (irradiation power). Hence, the complete flow characteristics of the two-tower receiver are required to implement the proposed concept. Thus, in order to investigate the characteristics of circulating flow between the left and right towers and the influence of fluid flow rate on mixing and flow direction (clockwise or anticlockwise), a lab-scale transparent fluidized bed system has been designed and fabricated as shown in Fig. 1(b). As can be seen in the figure, the rectangular shape left tower (60 mm width and depth, and 140 mm height) is extended at the top end as frustum shape to receive radiation through the top slit. In order to prevent the asymmetric effects

Table 1
Properties of particles and gas.

Particles	
Shape	Spherical
Density (kg/m^3)	1040
Coefficient of restitution	0.9
Coefficient of friction	0.3
Total weight of the particles (kg)	0.291
Diameter range (mm)	Mass fraction in range
0.7–0.8	0.82
0.8–0.9	0.03
0.9–1.0	0.03
1.0–1.1	0.03
1.1–1.2	0.03
1.2–1.3	0.03
1.3–1.4	0.03
Gas	
Density (kg/m^3)	1.225
Viscosity (kg/m-s)	1.7894×10^{-05}