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# A CFD-DEM study of hydrodynamics with heat transfer in a gas-solid fluidized bed reactor for solar thermal applications

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ABSTRACT

The particles flow and heat transfer characteristics of a high temperature solar thermochemical fluidized bed reactor have been studied for solar beam-down concentrating systems. A numerical model has been developed by the combined approach of computational fluid dynamics (CFD) and discrete element method (DEM) collisional model since it is an effective approach for studying the gas-solid flow. The discrete ordinate model has been used to solve the radiation heat transfer. 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. The effect of gas superficial velocity, bed mass and inlet gas temperature on the flow pattern and temperature characteristics of the bed have been investigated. The results showed that the maximum and average temperature of the bed, depends on the top layer position and focal point of the concentrated radiation, decreased when increasing the total mass of the bed.



## 1. Introduction

In solar thermochemical applications of dense gas-solid fluidized beds, mixing and segregation processes play a vital role on reaction rate and efficiency. The mixing and segregation behavior of fluidized beds is determined by the particles flow characteristics and bubble dynamics [1–4]. Considerable efforts have been made to develop advanced techniques for measuring dynamics of dense gas-solid flow in fluidized beds such as particle image velocimetry (PIV), digital image analysis (DIA), positron emission particle tracking, magnetic resonance imaging, electrical capacitance tomography, etc. However, it's pretty challenging to obtain accurate flow characteristics at reasonable cost [5]. 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 quantitatively. 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.

In discrete particle model, the particle collisions can be either modelled by soft sphere or hard sphere approach. Initially, Tsuji et al. [6] 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 [7,8]. Multiphysics problems coupled with heat transfer and chemical reactions were investigated [9–11]. Turbulent models were coupled with fluidized bed models [12,13]. The dependency of particle–particle collision on turbulence characteristics, such as turbulent kinetic energy (TKE), dissipation rate (TDR), fluctuation and correlated fluctuations were studied [12]. In order to reduce the computational cost, various effective methods and algorithms were proposed [14–16]. Particle-gas flow of complex geometries were investigated [17,18].

Fluidized bed reactors have been used as receiver and storage systems of concentrated solar plants, which is one of the promising technologies currently undergoing rapid development [19,20]. Solar particle receivers (SPR) were developed to drive the concentrating solar plants (CSP) at 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

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place of currently used molten salt or steam [21,22]. An experimental and theoretical study of a pilot scale solar fluidized bed receiver was carried out by Flamant et al. [21] 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. In order to improve thermal performance of fluidized beds for concentrated solar power plants and thermal energy storage applications, various numerical and experimental investigations were carried out [23–26]. In concentrated solar thermal industry, fluidized-bed technology has also been used to produce hydrogen by thermochemical two step water splitting cycles [19], and synthetic gas by gasification of coal coke [27]. Recently, couple of fluidized bed reactors have been developed for two-step thermochemical water splitting cycles and coal coke gasification [28–30] using 100 kW beam-down demonstration plant at Miyazaki, Japan. A tubular fluidized receiver for beam-down solar concentrating system was developed by Matsubara et al. [31]. The fluid dynamics of the prototype receiver was experimentally investigated by 3 kW solar simulator. Subsequently, A two-tower fluidized bed system filled with spherical non-reacting particles has been proposed [32] to use concurrently as receiver and storage system as shown in Fig. 1a.

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. Furthermore, the thermo-chemical reaction/storage of the two-tower reactor strongly depends on the concentrated radiation obtained through the top slit of the left tower. 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 is required to implement the proposed concept. Accordingly, in this study, the Euler-Lagrange model has been developed to investigate the influence of gas velocity, gas temperature, incident radiation and bed mass on the flow characteristics, particles flow pattern and temperature of the two-tower reactor.

## 2. Modeling of gas-solid flow

To simulate the hydrodynamics of the gas-solid flow, the Euler-Lagrange model is developed, which treats the fluid phase as a continuous fluid and the particle phase as discrete elements. The flow of the gas-phase is solved based on the Navier-Stokes equations, while the particle movement is solved using Newton's equation of motion.

### 2.1. Gas phase modeling

The mass conservation for gas phase is included by multiplying each term of the standard continuity equation with the corresponding volume fraction of gas phase as given below:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f) + \nabla.(\alpha_f \rho_f \vec{u}_f) = 0 \tag{1}$$

where $\alpha_f$, $\rho_f$ and $\vec{u}_f$ are volume fraction, density and velocity of gas phase respectively. The momentum conservation equation is extended by the volume fraction and the interaction term $F_{DEM}$, which couples the gas phase with the corresponding solid phase. The gas phase momentum equation can be written as:

$$\frac{\partial}{\partial t}(\alpha_f \rho_f \vec{u}_f) + \nabla.(\alpha_f \rho_f \vec{u}_f \vec{u}_f) = -\alpha_f \nabla p + \nabla.(\alpha_f \bar{\bar{\tau}}_f) + \alpha_f \rho_f \vec{g} + \vec{F}_{DEM} \tag{2}$$

where $p$ and $g$ are the pressure and acceleration due to gravity respectively. The stress–strain tensor of gas phase is given as;

$$\bar{\bar{\tau}}_f = \alpha_f \mu_f (\nabla \vec{u}_f + \nabla \vec{u}_f^T) + \alpha_f \left(\lambda_f - \frac{2}{3}\mu_f\right) \nabla.\vec{u}_f \bar{\bar{I}} \tag{3}$$

where $\mu_f$ and $\lambda_f$ are respectively shear and bulk viscosity of the gas phase and $\bar{\bar{I}}$ is the unit vector. The coupling term $F_{DEM}$ considers the

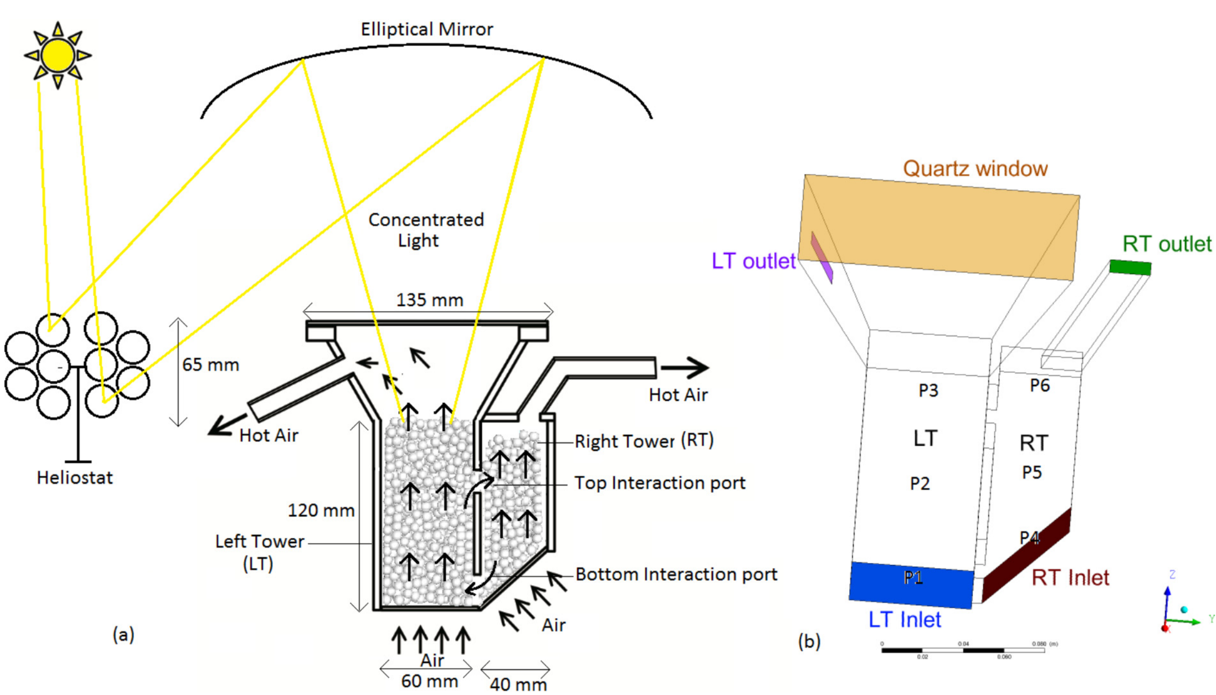


**Fig. 1.** (a) Schematic of the beam-down concentrated receiver/reactor and (b) computational domain.