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Numerical and experimental study on granular flow and heat transfer characteristics of directly-irradiated fluidized bed reactor for solar gasification

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ABSTRACT

Solar gasification is one of the promising techniques to convert the carbonaceous materials to clean chemical fuels, which offers the advantages of being transportable as well as storable for extended period of time. In this study, thermal performance of a recently developed 5 kW_{th} fluidized bed reactor for solar gasification has been investigated and reported. Discrete element method (DEM) has been used for modeling the granular flow, and computational fluid dynamics (CFD) method has been used for modeling the multiphase flow. To validate the developed model, experiments were preformed and compared with modeling results. Discrete ordinate radiation model has been used to solve the radiative transfer equation. The thermal performance of the reactor and particulate flow behavior have been predicted and the effect of particle size, particle size distribution and gas flow rate are analyzed. The results indicate that the performance of the bed increases when fluidizing the annulus region particles as the high porosity increases the diffusion rate of radiation throughout the bed.

Introduction

Gasification is a process in which carbonaceous materials are reacted at high temperatures (>700 °C) with a controlled amount of oxygen and/or steam to produce syngas, which is a gas mixture consisting primarily of hydrogen, carbon monoxide and carbon dioxide. When practiced at an industrial scale, the energy required for the heat of reaction is supplied by burning a significant portion of the feedstock, consequently which releases significant amount of CO_2 to the atmosphere. In order to reduce CO_2 emissions, the clean high temperature energy from concentrated solar radiation has been used to supply the process heat of gasification [1–3]. The synthesized gas by solar energy may be burned directly in gas engines, stored in long-term storable energy carriers, used to produce

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methanol and hydrogen, or converted into synthetic fuel via the Fischer-Tropsch process. Thus, for solar gasification and pyrolysis, various thermochemical reactors have been developed [4–6]. In these reactors, the concentrated solar radiation is received either directly through a window [7,8], or indirectly through an emitter plate absorbing the concentrated solar radiation and re-emitting IR radiation [9,10].

Greg et al. [7] first demonstrated the gasification process by a fixed bed reactor using 23 kW solar furnace. The reactor was filled with coal particles and the solar radiation was directly passed through the front side of the L shape reactor. Steam and/or CO_2 was passed through the heated coal bed of the gasifier. The performance of the reactor was investigated from 4 to 23 kW solar power. The product gases from the reactor were mainly CO and H_2; and the temperature at the front area of the coal bed was between 1175 and 1425 K. Taylor et al. [8] also developed a packed bed reactor to demonstrate charcoal gasification by a 2 kW solar furnace with steam and/or CO_2. The packed bed was directly irradiated and pushed upwards by the plunger. The steam was generated by spraying water directly on the surface of the charcoal. At an optimum rate of water injection, half of the steam was reacted with carbon. The chemical storage efficiency range was around 35 ± 5%, almost similar as that observed by Gregg et al. [7]. Storage efficiencies of the fixed bed solar coal gasifiers were around 30–40%. Moreover, the fixed bed reactors suffer from some technical drawbacks, such as long solid residence time, limitations of mass and heat transfer, and ash buildup which slow down the reaction rate. Thus, Epstein et al. [11] suggested that fluidized bed reactors could provide better performance than the fixed bed reactors. Hence, several fluidized bed reactors were developed and demonstrated. Kodama et al. [4] and Peter at al [12]. reviewed the recent developments of particle fluidized bed reactor and solar-driven gasification processes with carbonaceous materials. Recently, for liquid chemical looping gasification, thermodynamic and thermochemical analysis were carried out to evaluate the potential of liquid metal oxides [13–15].

For solar thermochemical gasification of coal coke to produce CO + H_2 synthetic gas, several reactor designs have been proposed, fabricated and tested under beam down orientation for about a decade in Niigata University, Japan [16–20]. The beam-down system consists of secondary elliptical reflector at the tower which directs the concentrated radiation collected by the heliostats downwards and offers the concentrated radiation source close to the ground. One of the advantages of beam-down orientation is conventional fluidized bed systems can be coupled with the beam down optics, whereas it is problematic in concentrated solar towers since the radiation enters the reactor through a transparent quartz window in horizontal direction [4]. To conduct the lab scale experiments, various solar simulators were designed and fabricated at different scales in beam-down orientation; 3, 5 and 30 kW_{th}. The gasification of coal coke particles with steam was studied by lab scale reactors using Xe-light concentrated radiation and the production rates of CO, H_2 and CO_2 were reported [16–18]. A detailed understanding of the gas-solid interaction coupled with heat and mass transfer is required to enhance the performance of these reactors further. This could be obtained either by detailed numerical simulations or performing dedicated experiments. Generally to obtain flow characteristics of the fluidized beds experimentally, the following techniques are used; particle image velocimetry (PIV), magnetic resonance imaging, digital image analysis (DIA), electrical capacitance tomography, positron emission particle tracking, and etc. However, computational fluid dynamics has been considered as one of the promising tools to obtain reasonable particulate flow and heat transfer characteristics at reasonable cost [e.g. 21–22]. So, various mathematical models were developed to predict the solid-gas flow and heat transfer behavior. Most of the models were based on two approaches; Eulerian-Eulerian and Eulerian-Lagrangian. The main difference between these two approaches is based on the particulate dynamics formulation. Moreover, Eulerian-Lagrangian approach allows to define particle size distribution and couples the radiation models [23]. Hence the fluidized bed reactors filled with different size of particles could be modeled by CFD-DEM method based on Eulerian-Lagrangian approach [22–24].

Tsuji et al. [25] were among the pioneers in developing the CFD-DEM model. A two-dimensional soft-sphere approach was applied to investigate the gas-solid fluidized bed, where the linear-spring/dashpot model originally developed by Cundall and Strack [26] was employed. The soft-sphere method uses a fixed time step and consequently the particles are allowed to overlap slightly. The contact forces are subsequently calculated from the deformation history of the contact using the contact force scheme. Kawaguchi et al. [27] extended this model to three dimensions and compared the particle motions predicted by two and three dimensional models. The effect of wall on the particle motion was reported. Then, their model was extended by Iwadate and Horio [28] and Mikami et al. [29] by incorporating Van der Waals forces to simulate fluidization of cohesive particles. Den et al. [30] and Zhou et al. [31] extensively reviewed the CFD-DEM model developments for fluidized beds and particle-laden flows. Zhong et al. [32] reviewed the recent theoretical developments of CFD-DEM modeling of non-spherical particulate systems.

Despite a number of CFD-DEM studies have been carried out on gas-solid flow and heat transfer characteristics of fluidized beds, considerable studies have not been reported at high temperature ranges for solar thermal applications. Recently, Morris et al. [33] developed a laboratory scale solar particle receiver, which contains arrays of hexagonal heat transfer tubes, and carried out discrete element method simulations for different geometric configurations, hexagon apex angles, particle sizes, and mass flow rates. The simulation results showed that the heat transfer strongly depends on the particle size and solid concentration near the heat transfer surfaces. Early designs of particle heating receivers (PHR) utilize a falling curtain of particles which directly absorbs the concentrated solar radiation. However, falling curtain receivers have several disadvantages including significant heat and particle losses and short residence time within the irradiation zone. So a new “impeded flow PHR design” was proposed, in which the particles flow over, around, or through a series of obstacles in the flow path. To better understand these flows, two different numerical modeling approaches – the discrete element method (DEM) model, and a two-fluid

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