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Computational fluid dynamics simulations of a binary particle bed in a riser-based carbon stripper for chemical looping combustion

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ABSTRACT

Chemical-looping combustion (CLC) is a next generation combustion technology that shows great promise as a solution for the need of high-efficiency low-cost carbon capture from fossil fueled power plants. In this paper, numerical simulations are conducted of a binary particle bed associated with a coal-direct CLC system consisting of coal (represented by plastic beads) and oxygen carrier particles and validated against an experimental riser-based carbon stripper. The detailed particle dynamics and solid-gas and solid-solid interactions are investigated using the Lagrangian particle-tracking approach known as the discrete element method coupled with the computational fluid dynamics solution for the flow field. The simulation results of the fluidization behavior and the separation ratio of the particles are in excellent agreement with the experiment. A credible simulation of a binary particle bed is of particular importance for understanding the details of the fluidization behavior; the baseline simulation established in this work can be used as a tool for designing and optimizing the performance of such systems.

1. Introduction

The relationship between the global surface temperature of the earth and the concentration of carbon dioxide (CO_2) in the atmosphere was discovered by Arrhenius [1]. As a result of the rapid combustion of fossil fuels, the level of CO_2 in the atmosphere has risen by almost 30% compared to the pre-industrial times and the Intergovernmental Panel on Climate Change [2] has reported that the "warming of the climate system is unequivocal" and "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Although renewable energy is expected to account for an increasing amount of the energy supply in the future, fossil fuels will remain the dominant energy source for at least the next 25 years [3]. As a result, addressing carbon emissions from power plants has become an active area of research.

One technology that has shown great promise for high-efficiency low-cost carbon capture is chemical-looping combustion (CLC). The CLC process typically utilizes dual fluidized bed reactors termed the air reactor and the fuel reactor and a metal oxide oxygen carrier that circulates between the two reactors, as illustrated in Fig. 1. The primary advantage of CLC is that fuel combustion in the fuel reactor takes place in the absence of air using oxygen provided by the oxygen carrier; the flue stream from the fuel reactor is not contaminated or diluted by other gases such as nitrogen. This provides a high-purity carbon dioxide stream available for capture at the fuel reactor outlet without the need for an energy-expensive gas separation process. The reduced oxygen carrier from the fuel reactor is pneumatically transported to the air reactor where it is re-oxidized by oxygen from air and circulated back to the fuel reactor to complete the loop.

The only energy cost of separation associated with CLC is the cost of solid recirculation. This is considerably lower than the benchmark for pre-combustion technologies for carbon capture such as oxy-fuel combustion where the oxygen separation process can consume about 15% of the total energy. Therefore, CLC holds the answer as the next-generation combustion technology due to its potential to allow CO_2 capture with little to no effect on the efficiency of the power plant. Several studies on the energy and exergy of CLC systems in the literature suggest that power efficiencies greater than 50% can be achieved along with nearly complete CO_2 capture [4,5,6]. Recently, a techno-economic study to assess the benefits of CLC has reported that the cost of electricity for a CLC plant using Fe_2O_3 oxygen carrier is $115.1 per MWh, which compares favorably against the cost of $137.3 per MWh for a conventional pulverized coal boiler when additional amine-based CO_2 absorption is considered [7].

A great deal of early research in the area of chemical-looping combustion focused primarily on the use of gaseous fuels such as natural gas and syngas. However, since coal is projected to remain one of the dominant fossil fuels in the near future [3], the use of coal for CLC has garnered significant interest in recent years. The use of solid coal fuel instead of gaseous fuels in chemical looping combustion introduces

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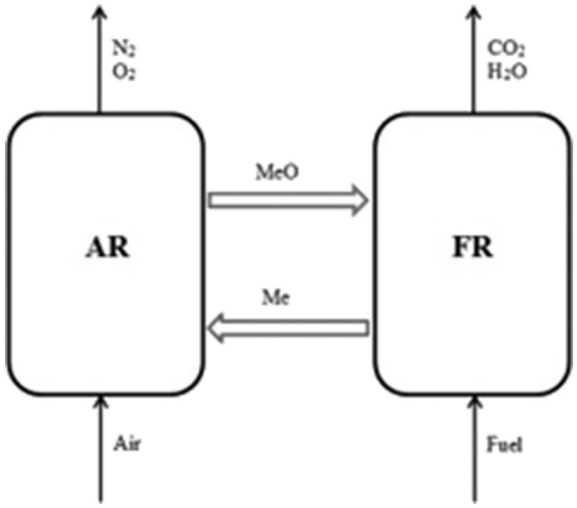

Fig. 1. Schematic representation of a chemical-looping combustion system with interconnected fluidized beds (AR = air reactor, FR = fuel reactor).

additional operational complexities. Unlike gaseous fuel, which is directly combusted by the oxygen carrier, the coal must first undergo a devolatilization process followed by a gasification reaction where the remaining char is reacted by the fluidizing gases consisting of recycled CO_2 and/or H_2O. The products of devolatilization and gasification are then combusted by the oxygen carrier. A typical CLC setup utilizes a cyclonic separator to isolate the oxygen carrier particles from the flue gases after the fuel reactor and the air reactor before transporting the solids between the reactors to continue to loop. Since the char gasification is a slow process [8], unburnt char particles often remain in the flue stream of the fuel reactor. If these are transported to the air reactor along with the oxygen carrier particles, the carbon capture efficiency of the CD-CLC process would be reduced.

Several approaches have been proposed to prevent char particles from reaching the air reactor. One way is to provide sufficient residence time in the fuel reactor to ensure that the gasification reaction is complete. This can be achieved either by increasing the size of the reactor or by reducing the fluidizing gas velocity, but both options can impede the fluidization behavior of the bed, particularly in a spouted bed configuration as discussed in previous work [9]. To avoid the poor fluidization while still maintaining an increased residence time, a multi-staged fuel reaction concept was recently proposed and investigated [10]. A mass and energy balance study of the multi-staged fuel reaction setup conducted using Aspen Plus demonstrated that complete char conversion can be achieved by using multiple smaller fuel reactors in series such that any unburnt char in the system is burnt in subsequent fuel reactor stages before the solids are transported to the air reactor.

Fig. 2 shows the differences in size between the particles of pulverized coal and a typical oxygen carrier (ilmenite) used in CD-CLC operation. The coal and ilmenite particles are considered as spherical

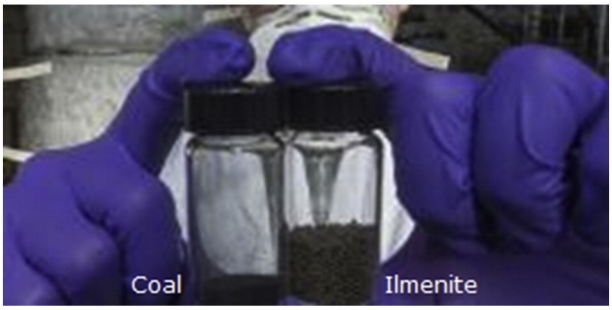

Fig. 2. Size difference between particles of coal and ilmenite used in coal-direct CLC.

of diameter 257 μm and 94 μm respectively. In the simulations all coal and ilmenite particles are considered to be of the same size. One reason of considering the spouted fluidized bed configuration is that it overcomes the limitation of a bubbling or fast fluidized bed to handle particles larger than a few hundred micrometers in diameter [11]. Thus, one way of preventing the leakage of unburnt char into the air reactor is to take advantage of the differences in size and density, and hence the terminal velocity, to separate the lighter char from the heavier oxygen carrier particles. Since char already has a lower density than the oxygen carrier, using pulverized coal particles smaller than or almost of the same size as the oxygen carrier particles should invariably lead to satisfactory separation results. The devolatilization and gasification processes that the coal undergoes further decrease the char particle size, enhancing the separation effect. The device that separates the char particles from the char and oxygen carrier mixture stream exiting the fuel reactor is known as a carbon stripper. The char particles from the carbon stripper can be returned to the fuel reactor to complete the gasification step while the oxygen carrier particles are transported to the air reactor to be regenerated.

By preventing the combustion of the unburnt char in atmospheric air, the carbon stripper also eliminates the formation of pollutants such as CO_2 and NO_X in the air reactor, as highlighted by Kramp et al. [12] and Mendiara et al. [13] and is deemed critical for CD-CLC operation despite the increased hydrodynamic complexity associated with implementing the carbon stripper compared to increasing the residence time in the fuel reactor. It is noted that for other fuels such as biomass where the increase in residence time required for the solid fuel is smaller, the direct increased residence time approach may be more competitive. In recent years, carbon strippers operating with fluidizing velocity in the range of 0.15–0.40 m/s have been incorporated into CD-CLC experiments by Markström et al. [14], Ströhle et al. [15], Abad et al. [16], and Sun et al. [17]. The results of these experiments indicated that the fluidization velocity should be increased further to increase the particle separation.

Later, Sun et al. [18] conducted cold-flow studies using a riser-based carbon stripper operating in the fast fluidized bed regime to investigate the effect of gas velocity on the separation ratio. The goal of Sun et al.'s design [18] was to achieve a high separation ratio to minimize the leakage of char particles into the air reactor with a low fluidizing gas velocity to keep operational costs low. However, the specific nature of the multiphase solid-gas flow inside the carbon stripper and how its geometry affects the design targets is not well understood from the experiment. In order to identify these relationships, a CFD simulation coupled with the discrete element method (DEM) is developed in this paper for a carbon stripper consisting of a binary particle bed of coal and oxygen carrier particles and is validated against the experiment of Sun et al. [18]. In future work, there is considerable scope to optimize the geometry of the carbon stripper to enhance the achievement of these design goals that can be addressed by integrating a multi-objective genetic algorithm with the CFD-DEM code.

2. Description of experimental setup

The carbon stripper used in the cold-flow experiment by Sun et al. [18] consisted of a riser, 4 m tall with a diameter of 0.7 m. A schematic of the experimental setup is presented in Fig. 3. The solids mixture contained 95% ilmenite particles by mass and 5% plastic beads representing the unburnt char particles in the system. The experiment was conducted continuously with stable operation all through the experiment.

The physical properties of ilmenite and plastic beads are listed in Table 1. The riser was fluidized from the bottom by air with the fluidizing velocity u_g in the range of 1.50–2.75 m/s increasing at 0.25 m/s intervals. The gas velocity u_g was selected to fall between the terminal velocities u_t for the ilmenite and plastic beads such that the plastic beads would be carried out of the bed and exit the riser from the top