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Three-dimensional full loop simulation of solids circulation in an interconnected fluidized bed

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ABSTRACT

3-D full loop CFD simulation of solids circulation is conducted in a complicated circulating-fluidized bed, which consists of a riser, a bubbling bed, a cyclone and a loop-seal. The effects of operating gas velocity, particle size and total solids inventory on the solids circulation rate are investigated based on the system pressure balance of an interconnected fluidized bed. CFD results indicate that the gas velocity in the riser plays a dominant role in controlling the solids circulation rate, whilst the gas velocity in the pot-seal influences in a narrow operating range. The solids circulation rate is strongly influenced by particle size and total solids inventory, but becomes insensitive to the operating conditions in the bubbling bed when the gas velocity is higher than the minimum fluidization velocity.

1. Introduction

Chemical looping combustion (CLC) is a novel and economic technology for CO_2 capture, which has been intensively investigated over the past twenty years [1,2]. Comparing with other CO_2 capture strategies, oxygen is transferred from air to fuel through oxygen carriers in a CLC plant, avoiding direct contact between air and fuel. Generally, a CLC system consists of two separate reaction zones, as shown in Fig. 1. Metal (Me) particles are oxidized to metal oxide (MeO) particles in air in the oxidation zone, which is then transferred to the reduction zone where the fuel reduces them into CO_2 and H_2O. There is no or little energy loss for the separation of CO_2 in the CLC process [3], because the relatively pure stream of CO_2 can be obtained after condensing and purifying H_2O. The circulation of oxygen carriers between the two reaction zones not only plays an important role in transporting oxygen needed for the combustion, but also maintains the system heat balance. The heat carried by the oxygen carriers from the oxidation reaction zone is supplied to the endothermic reaction in the reduction zone. Thermodynamically, the total amount of heat from the two reactions is the same as that from conventional combustion, where the fuel is in direct contact with air [4]. Stable circulation of oxygen carriers between the two reaction regions is critical to achieve a high thermal efficiency and high CO_2 capture efficiency.

Chemical looping combustion is a typical dual fluidized bed (DFB) application that metal oxide is circulated between the two fluidized bed reactors. Quite a few CLC configurations have been proposed based on the DFB technology [4–9]. The interconnected fluidized bed configuration, which is based on the principle of circulating fluidized bed including a high-velocity riser (air reactor) and a low-velocity bubbling bed (fuel reactor), has been identified as one of the promising choices [4,10,11]. For this design, a higher particle residence time for the reduction reaction and a lower particle residence time for oxygen reaction can be achieved based on the oxygen carrier reactivity [12]. It can provide excellent gas–solids contact in each reactor, and also handle particles at an adjustable circulation rate between the two reactors. However, the gas leakage between the air reactor and the fuel reactor is a major problem, which decreases the reliability and efficiency of CLC systems. As the gas leakage is closely related to the solids circulation rate [13], it is essential to understand the solids circulation behavior and the influence of various operating conditions in order to achieve better design and operational efficiency for any interconnected fluidized bed.

Computational fluid dynamic (CFD) is regarded as a promising technology for predicting the complex hydrodynamics and related characteristics in a fluidized bed. Some efforts have been carried out on the CFD simulation of chemical looping combustion processes [8,14–27]. However, only a few investigations have been focused on the full loop simulation of the interconnected fluidized bed, due to the complexities in geometry and flow physics, which requires large computational resources [1,26]. Kruggel-Emden et al. [18] applied the exchanges of mass, momentum, heat and species sinks through time-dependent

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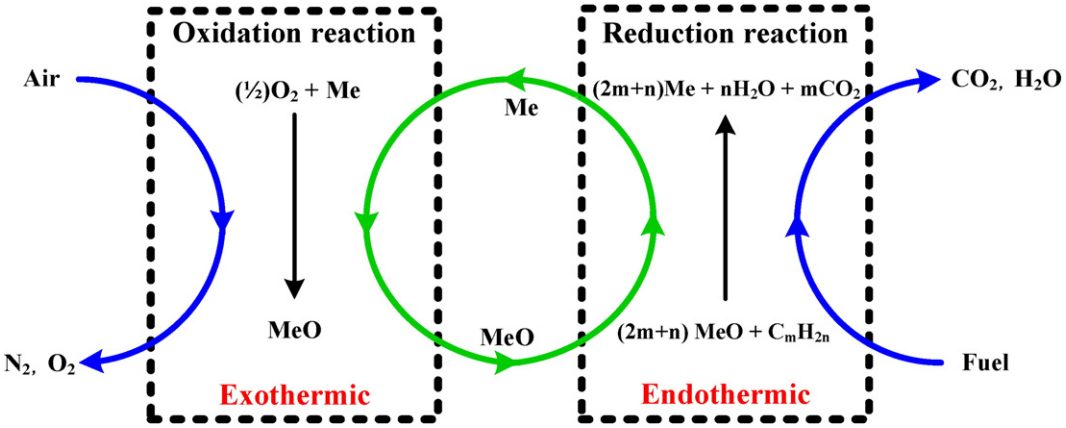

Fig. 1. Schematic of chemical looping combustion process.

inlet and outlet boundaries to couple the fuel reactor and air reactor. Seo et al. [8], Wang et al. [19] and Nguyen et al. [22] conducted a 2-D full loop simulation of the interconnected fluidized bed to investigate the hydrodynamic behaviors and compared it with experimental data. However it is questionable to apply 2-D simulation data to a 3-D operation due to the influences of the bed walls and geometry of non-symmetric flow [28,29]. For the 3-D full loop simulation of the chemical looping combustion process, Parker et al. [24] predicted the gas–solids hydrodynamics, thermal characteristics and reaction efficiency by the computational particle fluid dynamics (CPFD) method. Very recently, a 3-D full loop simulation was conducted to investigate the solids circulation in a dual circulating fluidized bed composed of a riser and a turbulent bed [27]. In our previous work, the Eulerian–Eulerian method was employed to predict the hydrodynamics in a 3-D full-loop interconnected fluidized bed for CLC applications, and the coupled effect of operational conditions on the fluid dynamics was explored between the riser and the bubbling bed [26]. The work compared the effect of various drag models, and revealed a non-uniform distribution of the solids volume fraction in the riser and bubbling bed, without considering the detailed information on solids circulation rate, which is essential to prevent gas leakage and achieve a reliable operation for any CLC plant. Continuing from our previous work, this study is focused on the solids circulation rate in a 3-D full loop interconnected fluidized bed, where detailed solids circulation characteristics and the influence of solids property and operational condition, including particle diameter, total solids inventory and operating gas velocity, were simulated. Predicted results were carefully analyzed based on the system pressure balance in the interconnected fluidized bed, and the implication to the CLC operation was revealed.

2. CFD simulation

2.1. CFD modeling

The Eulerian–Eulerian model together with the kinetic theory of granular flow (KTGF) is used to predict the gas–solids flow in the interconnected fluidized bed. In the two-phase model, the gas and solids phases are mathematically treated as interpenetrating continua with appropriate interaction terms. The volume fraction represents the space occupied by each phase, and the conservation equations of mass and momentum for each phase are derived with similar structures. Table 1 gives details of the conservation equations. Eqs. (1) and (3) are the continuity conservation equations for gas and solids phases, respectively. Here, α is the volume fraction ($\alpha_g + \alpha_p = 1$), ρ is the density and $\vec{u}$ is the velocity vector. The gas phase momentum conservation equation is expressed by Eq. (2), where β is the gas–solids inter-phase momentum transfer coefficient, $\vec{g}$ is the acceleration due to gravity, and $\bar{\bar{\tau}}_g$ is the gas phase stress–strain tensor and expressed by Eq. (6). The standard k-ε turbulent model is used for modeling turbulence of gas phase where μ_{gt} is the turbulent viscosity; k and ε represent the turbulent kinetic energy and dissipation rate of turbulent kinetic energy. The constants in Eqs. (9) and (10) are $C_\mu = 0.09$, $C_1 = 1.44$ and $C_2 = 1.92$ respectively. The turbulent Prandtl numbers for k and ε are $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$. G_k is defined as the generation of turbulent kinetic energy due to the mean velocity gradients. See Table 2

Eq. (4) is the solids phase momentum equation, where $p_{p.}$ is the solids pressure and $\bar{\bar{\tau}}_p$ is the solids stress–strain tensor. The kinetic theory of granular flow is used to describe the rheology of the particle phase. Eq. (5) is solved to account for the conservation of solids fluctuating energy. The two terms on the left hand side of Eq. (5) describe the accumulation and convection of kinetic fluctuation energy, respectively. The first term on the right hand side describes the production of kinetic fluctuation energy due to irreversible deformation of the velocity field, the second term describes the conductive transport of kinetic fluctuation energy, the third term represents the fluctuation energy dissipation due to inelastic particle–particle interactions, and the last term represents the exchange of fluctuation energy due to interphase momentum transport. The solids pressure $p_{p.}$, which represents the normal force due to particles interaction, is calculated by the expression from Lun et al. [30]. The first term on the right hand side of Eq. (13) is the kinetic term and the second term represents the particle collisions. The solids shear viscosity is defined as the sum of the collisional viscosity, kinetic viscosity and frictional viscosity as expressed in Eqs. (14)–(17). The bulk viscosity for the particle phase accounts for the resistance of granular particles to compression and expansion, and the Lun et al. [30] expression is used in this work. The radial distribution function of solids

Table 1
Conservation equations of gas–solids flow.

Gas phase	
Continuity equation	
$\frac{\partial}{\partial t}(\rho_g \alpha_g) + \nabla\cdot(\rho_g \alpha_g \vec{u}_g) = 0$	(1)
Momentum equation	
$\frac{\partial}{\partial t}(\alpha_g \rho_g \vec{u}_g) + \nabla\cdot(\alpha_g \rho_g \vec{u}_g \vec{u}_g) = -\alpha_g \nabla P + \nabla\cdot\bar{\bar{\tau}}_g - \beta(\vec{u}_g - \vec{u}_p) + \alpha_g \rho_g \vec{g}$	(2)
Solids phase	
Continuity equation	
$\frac{\partial}{\partial t}(\rho_p \alpha_p) + \nabla\cdot(\rho_p \alpha_p \vec{u}_p) = 0$	(3)
Momentum equation	
$\frac{\partial}{\partial t}(\alpha_p \rho_p \vec{u}_p) + \nabla\cdot(\alpha_p \rho_p \vec{u}_p \vec{u}_p) = -\alpha_p \nabla P + \nabla\cdot\bar{\bar{\tau}}_p - \beta(\vec{u}_p - \vec{u}_g) + \alpha_p \rho_p \vec{g} - \nabla p_p$	(4)
Granular temperature conservation equation	
$\frac{3}{2}[\frac{\partial}{\partial t}(\rho_p \alpha_p \Theta_p) + \nabla\cdot(\rho_p \alpha_p \vec{u}_p \Theta_p)] = (-p_p \bar{\bar{I}} + \bar{\bar{\tau}}_p) : \nabla \vec{u}_p + \nabla\cdot(k_{\Theta_p} \nabla \Theta_p) - \Upsilon_{\Theta_p} + \phi_{gp}$	(5)