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Hydrodynamic characteristics in a pilot-scale cold flow model for chemical looping combustion

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ABSTRACT

Chemical Looping Combustion (CLC) in two interconnected fluidized beds, i.e., the air reactor and the fuel reactor has been recognized to be promising. As the CLC setup design is critical and sensitive to oxygen carrier (OC) materials, it is very much essential to investigate hydrodynamics in a specially fabricated cold model set up for the successful development and operational control of corresponding large-scale hot model. In this study, a pilot-scale cold flow model CLC system has been designed and tested. The riser and fuel reactor were operated at circulated fluidized bed and bubbling fluidized bed conditions, respectively and the control of solid circulation between two reactors was done by two loop seals operated in bubbling fluidized bed conditions. The effect of fluidization velocity in the riser on the voidage profiles, solid circulation rate, and pressure profiles were investigated using Indian ilmenite (150–212 μm) as OC. The stable operation of the system was established under various operational conditions. The results will be useful for the development of ilmenite based hot model CLC system. Moreover, the achievable variations of solid circulation rate in the present study in cold model setup will determine obtainable limit of extent of oxygen transport and thermal energy.

1. Introduction

Carbon dioxide (CO_2) is recognized as one of the major greenhouse gas (GHG) responsible for global warming and climate changes. According to the fifth assessment report of Intergovernmental Panel on Climate Change (IPCC), anthropogenic emissions of CO_2 from fossil fuel combustion and other industrial processes contributed ~78% of the total GHG emission increase from 1970 to 2010. Fossil fuel-related CO_2 emissions reached 32 Gt/yr, in 2010, and grew further by about 3% between 2010 and 2011 [1]. It is projected that if the current trend continues, CO_2 emissions from the energy sector will get almost doubled or even tripled by 2050 compared to the level in 2010 [1]. This global concern has motivated an extensive research work towards developing more economical and efficient process for CO_2 capture and sequestration (CCS). Three possible approaches are envisaged for the CO_2 capture from fossil fuel based power plants: pre-combustion, post-combustion, and oxy-fuel combustion [2]. Recently, Chemical looping combustion (CLC), a promising oxy-fuel combustion technique has gained wide attention because it can integrate fossil fuel combustion, inherent CO_2 capture with high thermo-economic efficiency and low-cost. Unlike most other oxy-fuel combustion techniques, CLC negates the requirement of pure oxygen by introducing a suitable metal oxide as an oxygen carrier (OC) that transfers oxygen to the fuel reactor (FR). CLC technology is advantageous over the other combustion technologies as it avoids the direct contact between the air and fuel. An appropriate solid metal oxide as an OC is circulated between the two reactors and transfers the lattice oxygen of the carriers from air reactor (AR) to fuel reactor (FR) as shown in reactions (1) and (2).

$$(2n+m)\,Me_xO_y + C_nH_{2m} \rightarrow (2n+m)\,Me_xO_{y-1} + mH_2O + nCO_2 \tag{1}$$

$$Me_xO_{y-1} + 1/2\ O_2 \rightarrow Me_xO_y \tag{2}$$

where Me_xO_y is metal oxide OC and $Me_xO_{y\text{-}1}$ is the reduced form of metal oxide OC. In the FR, the gaseous fuel such as natural gas, syn-

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Nomenclature

A	decay factor for solid
A	cross section area of stand pipe, m^2
Ar	archimedes number
C	constant
C_D	drag coefficient
d_p	particle diameter, m
D	diameter of riser, m
f_s	solid friction factor
g	gravitational constant, m/s^2
G_s	solid circulation rate, $kg/m^2 \cdot s$
h_{dz}	height of bed in dense zone of riser above distributor, m
h_{sz}	height of bed in splash zone of riser above distributor, m
h_{tz}	height of bed in transport zone of riser above distributor, m
k	decay factor in splash zone in riser
k_∞	particle elutriation rate constant
Re_{mf}	Reynolds number at minimum fluidization condition
Δt	time, s
U_{mf}	minimum fluidization velocity of particles, m/s
U_t	terminal velocity of particles, m/s
U_{pa}	primary air velocity, m/s
U	superficial air velocity in riser, m/s
U_S	solid velocity in riser, m/s
Δz	differential height, m

Greek letters

δ_b	bubble volume fraction in dense bed
ρ_p	solid particle density (kg/m^3)
ρ_g	density of gas (kg/m^3)
ρ_b	bulk density of material, kg/m^3
ϕ	sphericity of particle
ε	voidage
ε_{mf}	voidage at minimum fluidization
ε_∞	voidage in infinite height
ε_{dz}	voidage in dense zone
ε_{sz}	voidage in splash zone
ε_{tz}	voidage in transport zone
μ_g	viscosity of air (kg/m-s)

gas from coal gasification, or solid fuel such as coal is oxidized by the OC to CO_2 and H_2O. The exit gas stream from the FR contains only CO_2 and H_2O, and almost pure CO_2 is obtained after condensation of H_2O. The metal or reduced metal oxide is then transferred to the AR where it gets regenerated, and thus the gas stream leaving the AR contains only nitrogen and unreacted oxygen [3]. The principle concept of the CLC is shown in Fig. 1.

The basic idea of CLC was first introduced by Lewis and Gilliland [4] in 1954 for the production of CO_2. Ishida et al. [5] were the first to introduce the name of CLC in their thermodynamic study. The basic design of CLC reactors based on circulated fluidized bed (CFB) concept was introduced by Lyngfelt et al. [6]. However, the large-scale operation and successful commercialization of CLC is still contingent upon the development of suitable OCs. The design, capital cost, and operation of a CLC unit mainly depend on the properties of OCs [7]. A successful OC material should have high reactivity, sufficient oxygen transport capacity, sufficient mechanical stability under repeated oxidation/reduction cycles, low tendency for agglomeration in fluidized bed reactors, environment benignity, and low production cost. In the last decade, several different metal-based OCs such as the oxides of copper, nickel, manganese, cobalt, iron-single or mixed metal oxide have been investigated under different operating conditions in CLC system [3,8]. These metal-based oxygen carriers have also been combined with inert binders such as Al_2O_3, TiO_2, ZrO_2, etc. to improve the reactivity, durability, and fluidization behavior of carriers. Another recent development is the use of natural OCs based on mineral ores and natural industrial waste or by-products from industry. The benefits of natural OCs over the synthetic OCs are that they are low cost, readily available, non-toxic and environmentally benign. Recently, ilmenite (an iron-titanium mineral ore) has emerged as a potential OC for solid fuel based CLC [3,8–10].

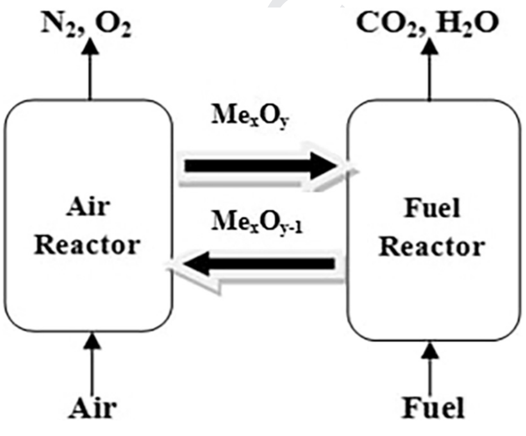

Fig. 1. Schematic of chemical looping combustion principle.

In order to demonstrate the principle of new combustion technology and commercial scale CLC system, it is also necessary to know the design and operation of the reactor system. Several combinations of two-reactor configurations (bench/pilot scale) have been suggested, designed and tested in past in different operational conditions using cold and hot prototype [3,11–17]. The combination of some innovative designs consist of four compartments interconnected fluidized bed (IFB) reactor [15], IFB reactor with alternative valve, periodically operated packed bed reactor, IFB combining fluidized bed and moving bed, IFB combining two bubbling bed, IFB combining riser and bubbling bed, IFB combining riser and turbulent bed etc. Dual circulating fluidized bed (DCFB) system where both the reactors are operated in fast fluidization regime is also proposed and tested for CLC system to achieve better gas-solid contact [14,17]. However, two IFB reactors consisting of a fast fluidized bed air reactor and bubbling fluidized bed fuel reactor, respectively, are believed to be the most promising configuration for successful and stable long-term operation of CLC [6,11]. Various types of non-mechanical devices such as L-valves, loop seals, etc. have been widely used to facilitate the flow of solids between the reactor units in the IFB configurations [12–19]. Generally, the L-valve is used to achieve maximum operational flexibility through solid circulation control; while loop seal is suggested to minimize intermixing of exhaust gases in the solid circulation loop. The effect of various geometrical and particle parameters on the operation of the L-valve have been investigated by Knowlton and Hirsan [20]. Geldart and Jones [21], and Yang and Knowlton [22] have estimated the aeration rate, solids circulation rate, and pressure drop correlations in an L-valve. However, the L-valve may experience flow problems at high temperatures of CLC if particles flowing through the L-valve are Geldart group B particles that lie near the AB boundary. It will not operate automatically over an infinite range of solid flow rates [23]. Therefore, the L-valve is used

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