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Review of reactor for chemical looping combustion of solid fuels

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ABSTRACT

Chemical Looping Combustion (CLC) is one of the important techniques used to combine fuel combustion and almost pure CO_2 production. Significant progress has been made with respect to the utilization of solid fuels in CLC in the last ten years. The key technical challenges of using solid fuels in CLC involve several aspects: reducing unburnt volatiles and gasification products escaping out of fuel reactor, enhancing solid fuel conversion in fuel reactor and minimizing char slip to air reactor, and ash handling. These aspects are closely related to reaction kinetics of oxygen carriers in particulate systems as well as the design and operation of CLC reactors which are widely accepted as interconnected fluidized beds. In this study, an overview of reactor of CLC using solid fuels is given. Detailed descriptions of the bed types and configurations of air reactor, fuel reactor and carbon stripper are illustrated in industrial scale. The available operating experience in the fields of energy and chemical engineering such as deciding solid fuel feeding position and bed internals is demonstrated to address the existing operational problems.

1. Introduction

1.1. Chemical looping combustion of solid fuels

The increasing threat due to global warming, together with the requirement of securing energy supplies have led to the development of Chemical Looping Combustion (CLC) which is known as one of the low-cost technologies to produce energy. CLC, as an option of CCS (Carbon Capture and Storage), is used to combine fuel combustion and almost pure CO_2 production, meanwhile allowing CO_2 sequestration. The process principle was originally proposed by Lewis and Gilliland (1954) in producing high-purity CO_2 from fossil fuels.

The concept of CLC is based on the use of oxygen carrier materials in oxidation-reduction cycles. It develops as a well-accepted approach to conduct chemical looping process in two reactors (Fuel reactor and Air reactor) connected by solid transportation lines. Between these two reactors, the oxygen carriers are transported and cyclically used to supply oxygen. Hence the direct contact between fuel and air is avoided. In this way, the exit gas from the fuel reactor is mainly CO_2 of high concentration and the steam. After the steam is condensed, nearly pure CO_2 is readily obtained, and then compressed as a liquid for storage. In practical operation, loop-seals are commonly used between two reactors to prevent gas-leakage.

Solid fuels have been widely used in the CLC systems, especially coal. As shown in Fig. 1, the current well-accepted approach of CLC using solid fuels is to introduce the solid fuels directly to the fuel reactor where oxygen carriers are consumed by gasification products, thus separate gasification and separation steps are avoided. The fuel reactor involves series of complex reactions of fuel devolatilization (R1) and char gasification (R3), (R4) as well as their gaseous products being oxidized to CO_2 and H_2O (R2), (R5) and (R6) by oxygen carrier particles. In the air reactor, the reduced oxygen carriers are regenerated by air through the strong exothermic reaction (R7). Part of the releasing heat in the air reactor can be steadily used for the reactions in the fuel reactor and solids transfer lines.

$$Solid\ Fuels_{(s)} \xrightarrow{devolatilization} Volatiles_{(g)} + char_{(s)} \tag{R1}$$

$$Volatiles_{(g)} + Me_xO_{y(s)} \rightarrow Me_xO_{y-1(s)} + CO_{2(g)} + H_2O_{(g)} \tag{R2}$$

$$C_{(s)} + CO_{2(g)} \rightarrow 2CO_{(g)} \tag{R3}$$

$$C_{(s)} + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)} \tag{R4}$$

$$Me_xO_{y(s)} + CO_{(g)} \rightarrow Me_xO_{y-1(s)} + CO_{2(g)} \tag{R5}$$

$$Me_xO_{y(s)} + H_{2(g)} \rightarrow Me_xO_{y-1(s)} + H_2O_{(g)} \tag{R6}$$

$$Me_xO_{y-1(s)} + O_{2(g)} \rightarrow Me_xO_{y(s)} \tag{R7}$$

Steam is preferred as gasification agent to CO_2, since the gasification rate is higher. Therefore, steam is commonly used in most of the CLC pilots as gasification agent in the fuel reactor and fluidizing agent in the

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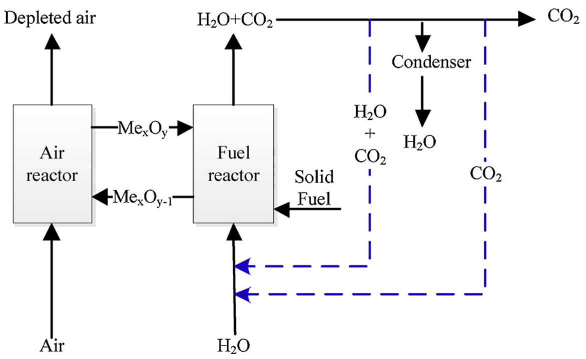

Fig. 1. Scheme of CLC process for solid fuel.

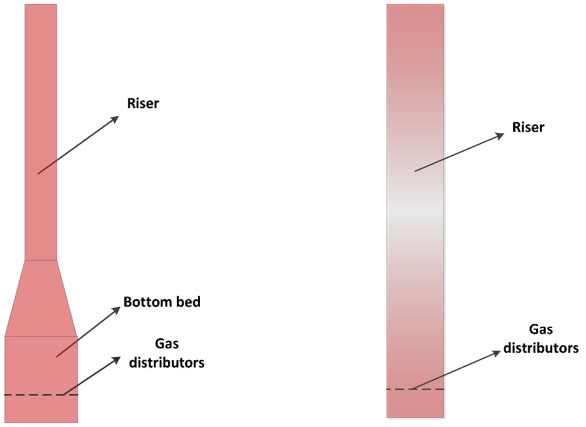

Fig. 2. Scheme of air reactor. Left: a bottom bed with a riser; Right: a single riser.

loop-seals. However, steam generation consumes a lot of energy, thus the cost of CLC to capture CO_2 is increased. In this regard, in a real CLC plant for power generation, the hot off-gas of the fuel reactor, mainly containing CO_2 after steam condensation, has been suggested as an option to be partly recycled to the fuel reactor to participate in the solid fuels' gasification reaction to reduce the total amount of steam in the system (Cuadrat et al., 2011; Adánez et al., 2014).

1.2. Oxygen carrier

The oxygen carrier is significant for fulfilling the CLC process and providing a reaction scheme to balance the endothermic gasification reactions (Song et al., 2013b). Up to 2016, more than 900 different materials based on iron, nickel, copper, manganese, as well as other mixed oxides and low-cost materials, have been investigated as potential oxygen carrier materials for CLC using solid fuels. Oxygen carrier with high chemical reactivity in the circulating reduction and oxidation processes is needed. In order to mitigate surface sintering, metal oxide can be synthetically manufactured by using an inert high-temperature material such as SiO_2, Al_2O_3 or Y-stabilized ZrO_2 (YSA) as support material. The reactivity, durability and lifetime of oxygen carrier can be improved significantly as well (Zafar et al., 2006; Corbella et al., 2006; Adánez et al., 2012). In CLC industrial application, the manufacture cost of oxygen carrier is certainly another very important consideration. Fluidized-bed granulation and spray drying are two suitable and promising technologies in the fields of chemical engineering for particles' production in industry scale. Many sorts of oxygen carriers have been tested in a wide scale from micro-batch

Table 1
Units for CLC of solid fuels using interconnected fluidized beds.

Centre & Location	Unit (kWth)	AR	FR	Ref.
Chalmers, Sweden	10	CFB, H (2 m), ID (0.15 m/0.08 m)	BFB, H (0.5 m), CS (0.08 m × 0.225 m)	Berguerand and Lyngfelt (2008)
SEU, China	10	CFB, H (2 m), ID (0.05 m)	SB, H (1.5 m), CS (0.23 m × 0.04 m)	Shen et al. (2008, 2009a)
SEU, China	1	CFB, H (1.6 m), ID (0.02 m)	SB, H (1.0 m), CS (0.05 m × 0.03 m)	Shen et al. (2010)
CSIC, Spain	0.5-1.5	BFB, BH (0.1 m), ID (0.08 m)	BFB, BH (0.2 m), ID (0.05 m)	Cuadrat et al. (2011), Abad et al. (2012)
Alstom Power	3000	CFB	CFB	Abdulally et al. (2012, 2014)
IFP-Lyon, France	10	BFB-BFB, H (1 m), ID (0.1 m)	BFB, H (1 m), ID (0.13 m)	Sozinho et al. (2012)
TU Hamburg, Germany	25	CFB, H (8 m), ID (0.1 m)	BFB, H (4 m), ID (0.25 m)	Thon et al. (2012)
Chalmers, Sweden	100	CFB, H (4 m), ID (0.4 m/0.154 m)	CFB, H (5 m), ID (0.154 m)	Markström and Lyngfelt (2012)
TU Darmstadt, Germany	1000	CFB, H (8.66 m), ID (0.59 m)	CFB, H (11.35 m), ID (0.4 m)	Orth et al. (2012)
University of Stuttgart, Germany	10-50	CFB, H (12 m), ID (0.07 m)	BFB, H (3.5 m), ID (0.15 m)	Mayer et al. (2012)
SEU, China	50	CFB, H (2 m), ID (0.276 m)	CFB, H (8.5 m), ID (0.08 m)	Xiao et al. (2012)
CSIC, Spain	50	CFB, H (4.80 m), ID (0.3 m/0.102 m)	CFB, H (4.15 m), ID (0.102 m/0.081 m)	Adánez et al. (2014)
HUST, China	5	CFB, H (0.55 m), ID (0.045 m)	CFB, H (1 m), ID (0.055 m)	Ma et al. (2015)
HUST, China	50	CFB, H (0.55 m/3.37 m), ID (0.40 m/0.10 m)	BFB, H (0.75 m/3.20 m), ID (0.35 m/0.06 m)	Ma et al. (2016)
VTT, Finland	20	CFB, H (8 m), ID (0.10 m/0.15 m)	BFB, H (2.5 m), ID (0.32 m/0.42 m)	Pikkarainen et al. (2016)
SEU, China	5	CFB, H (2.7 m), ID (0.03 m)	SB-BFB, H (1 m/0.25 m), CS (0.1 m × 0.05 m)	Yan et al. (2017)
JCOAL, Japan	100	CFB	CFB	Lin and Saito (2016)
University of Utah, USA	225	CFB	CFB	Lighty et al. (2012)

BFB – bubble fluidized bed, CFB – circulating fluidized bed, SB – spouted bed, MB –moving bed, H – height, BH – bed height, ID – inner diameter, CS – cross section.