Integration of calcium looping technology in combined cycle power plants using co-gasification of torrefied biomass and coal blends

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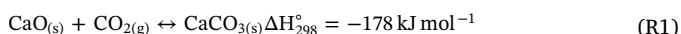
ABSTRACT

To comprehensively understand the impact of calcium looping (CaL) technology on a co-gasification of torrefied biomass and coal power plant, two kinds of proposed configurations (pre- and post-CaL), including a co-gasification system, a CaL system, and a combined heat and power system, are studied and compared with each other in the present work. In the CaL process, the kinetic modeling of the carbonation reaction and CaO sorption-enhanced water gas shift (SE-WGS) reaction are developed in a fast fluidized bed reactor (carbonator) to predict the performance of hydrogen production and CO_2 capture. The influences of torrefied biomass blending ratios (BRs) and CaO to fuel mass flow rate ratios (CaO/F) on various performance indicators such as hydrogen enhancement factor, hydrogen thermal efficiency (HTE), CO_2 capture efficiency, specific CO_2 emissions, and overall system efficiency are evaluated. A comparison of pre- and post-CaL schemes reveals that the SE-WGS reaction has a markedly profound effect on the former, causing the hydrogen production and HTE to be higher than those in the latter, whereas the latter is much more conducive to CO_2 capture and specific CO_2 emissions. Under optimal operating conditions (BR = 40 wt%, CaO/F = 3.5), the values of CO_2 capture efficiency and overall system efficiency of both schemes are higher than 90% and 50%, respectively. Overall, the pre-CaL case is suitable to design as a highly efficient co-generation of hydrogen production and electricity plant with low CO_2 emissions, whereas the post-CaL case is recommended for a co-gasification power plant with nearly zero CO_2 emissions.
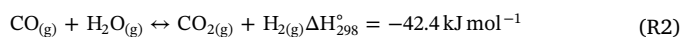
1. Introduction

Carbon capture technologies are currently being widely developed to reduce CO_2 emissions from power plants and industrial sectors. In recent years, several carbon capture approaches have become available to capture CO_2 from flue gases. In general, they can be classified into pre-combustion, post-combustion, and oxy-fuel combustion capture types [1]. In addition to the above conventional methods, various chemical looping technologies are now being investigated for integration into power plants, one of which is the calcium looping (CaL) carbon capture process, which utilizes solid CaO particles to carry out sorption and desorption cycles for the purpose of capturing and concentrating CO_2. A schematic illustration of the CaL process is shown in Fig. 1, which contains a carbonator and a calciner. The major reactions occurring in the CaL process are given as follows [2,3]:
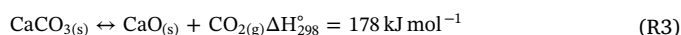
Carbonation reaction:

$$CaO_{(s)} + CO_{2(g)} \leftrightarrow CaCO_{3(s)} \Delta H^\circ_{298} = -178 \, \text{kJ mol}^{-1} \tag{R1}$$

CaO sorption-enhanced water gas shift reaction:

$$CO_{(g)} + H_2O_{(g)} \leftrightarrow CO_{2(g)} + H_{2(g)} \Delta H^\circ_{298} = -42.4 \, \text{kJ mol}^{-1} \tag{R2}$$

Calcination reaction:

$$CaCO_{3(s)} \leftrightarrow CaO_{(s)} + CO_{2(g)} \Delta H^\circ_{298} = 178 \, \text{kJ mol}^{-1} \tag{R3}$$

In the carbonator, emitted CO_2 in an exhaust gas produced from a power plant is reacted with solid CaO sorbents to form $CaCO_3$ through an exothermic carbonation reaction (R1) at around 650 °C. Furthermore, if the flue gas contains syngas (H_2 and CO), H_2O, and CO_2, according to Le Chatelier's principle, a water gas shift reaction (R2) also occurs due to the removal of CO_2 from carbonation, which is the so-called CaO sorption-enhanced water gas shift reaction (SE-WGS). Therefore, syngas can be converted into a hydrogen-rich product gas through the CaO SE-WGS reaction with simultaneous in situ CO_2 removal. In the calciner, the endothermic calcination (R3) of $CaCO_3$ takes place at around 900 °C to decompose concentrated CO_2 and regenerate

Nomenclature

A	cross sectional area of fluidized bed (cm^2)
Ar	Archimedes number (–)
C_A	concentration of reactant gas (mol L^{-1})
$C_{b,i}$	concentration of reactant i in the bubble phase (mol L^{-1})
$C_{c,i}$	concentration of reactant i in the cloud phase (mol L^{-1})
$C_{e,i}$	concentration of reactant i in the emulsion phase (mol L^{-1})
u_{mf}	minimum fluidize velocity (cm s^{-1})
ϕ	particle sphericity
d_p	particle diameter (cm)
d_p^*	dimensionless particle dimeter
h	height of fluidized bed (cm)
g	gravity (980 cm s^{-2})
ρ_s	density of particle (kg m^{-3})
ρ_g	density of reactant gas (kg m^{-3})
ε_{mf}	porosity of the fixed bed at minimum fluidization
ε_b	local bubble volume fraction
u	gas velocity (cm s^{-1})
μ	viscosity of reactant gas (kg m^{-1}s^{-1})
u_T	terminal velocity (cm s^{-1})
k_{elu}	elutriation velocity (cm s^{-1})
k_{cat}	intrinsic rate constant (s^{-1})
$k_{b,i}$	rate constant of reactant i in bubble phase (s^{-1})
$k_{c,i}$	rate constant of reactant i in cloud phase (s^{-1})
$k_{e,i}$	rate constant of reactant i in emulsion phase (s^{-1})

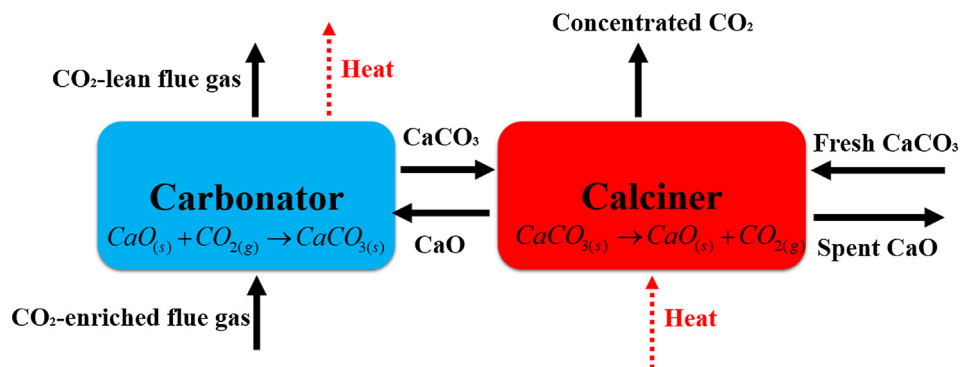|	
Re_p	Reynolds number (–)
ν_f	kinematic viscosity of the gas (cm^2 s^{-1})
f_b	volume fraction of solids in bubble phase
f_c	volume fraction of solids in cloud phase
f_d	volume fraction of solids in dense region
f_e	volume fraction of solids in emulsion phase
f_l	volume fraction of solids in lean region
f_e	volume fraction of solids for the exit location
f_{core}	volume fraction of solids in the core region
f_{wall}	volume fraction of solids sliding down the wall
W_d	weight of catalyst in dense region (kg)
W_l	weight of catalyst in lean region (kg)
W_T	total weight of catalyst (kg)
H_d	height of dense region (cm)
H_l	height of lean region (cm)
H_T	total height of fluidized bed (cm)
$R_{b,i}$	reaction rate of reactant i in bubble phase (mol kg^{-1} s^{-1})
$R_{c,i}$	reaction rate of reactant i in cloud phase (mol kg^{-1} s^{-1})
$R_{e,i}$	reaction rate of reactant i in emulsion phase (mol kg^{-1} s^{-1})
K_{bc}	volume rate of gas exchange coefficients between bubble and cloud phases per unit bubble volume (s^{-1})
K_{ce}	volume rate of gas exchange coefficients between cloud and emulsion phases per unit bubble volume (s^{-1})
η_d	contact efficiency in the dense region
η_l	contact efficiency in the lean region

Fig. 1. Schematic illursation of the calcium looping technology.

CaO particles. Based on the reversible carbonation and calcination cycles of the CaL process, its advantages include the following [2–5]: (1) a high concentration of CO$_2$ is obtained without using solvents, and there are lower energy and cost penalties when compared to MEA- or MDEA-based process; (2) the natural sorbents used for CaL process are low cost and widely available; (3) the excess waste heat produced from the carbonator can be recovered for electricity generation, leading to higher system energy efficiency, and (4) the waste spent from the CaL process can be reutilized and integrated into the cement industry.

Reviewing recent studies concerning the applications of CaL technology, many researchers have studied the process integration of the CaL process in a coal gasification combined cycle power plant. For example, Cormos and Cormos [6] evaluated a coal integrated gasification combined cycle (IGCC) power plant with the CaL process in both pre- and post-combustion configurations. They concluded that the net efficiency of their designed systems was in the range of 34–37% with a carbon capture rate greater than 95%, and the pre-combustion configuration had higher energy plenty when compared to that of the post-combustion one. Zhu et al. [7] simulated a coal IGCC system with the CaL process using the Aspen Plus simulator and pointed out that higher energy and exergy efficiencies are obtained in the CaL based IGCC system compared to those of a physical absorption-based system. In addition, they also found that the CaL based system is more economical than the physical absorption-based technology. Hu and Ahn [8]