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Full Length Article

Dynamic model of calcium looping carbonator using alternating bubbling beds with gas switching

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HIGHLIGHTS

- Dynamic model of carbonator is presented to simulate CO_2 capture.
- Configuration of alternating fluidized beds with gas switching is investigated.
- A novel scheme that enables smooth gas switching as well as energy saving is proposed.
- Parametric studies are conducted to assess key parameters.
- Experimental validation indicates acceptable reliability of model.

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ABSTRACT

Carbon capture and storage (CCS) has been globally gaining popularity as a viable greenhouse gases mitigation strategy throughout the last decade. Calcium looping (CaL) is an emerging technology to capture carbon dioxide from flue gases of fossil fueled power plants exploiting the reversible gas-solid reaction between the carbon dioxide (CO_2) and calcium oxide (CaO) to form calcium carbonate ($CaCO_3$) in a fluidized bed. In this paper, the concept of calcium looping application using alternating fluidized beds is explored as well as a proposed scheme to allow smooth gas switching between reactors using an intermediate third reactor. The latter scheme enables energy saving as well. A dynamic model of a bubbling bed carbonator, the key reactor in the capture process, is presented. The model incorporates both hydrodynamics and chemical kinetics to provide more reliable predictions. The model has been validated with experimental results obtained at combustion lab, Mansoura University, Egypt using an atmospheric fluidized bed reactor of 10.5 cm inner diameter. The key parameters have been investigated to check for system sensitivity. Bed temperature has a non-monotonic effect on CO_2 capture efficiency. Maximum CO_2 capture efficiency was found to occur around a temperature of 675 °C. Capture efficiency increases with either decreasing fluidization velocity or increasing bed particle size due to enhanced mass transfer and increased residence time. These findings almost accord with published data. Also, the average CO_2 capture efficiency was found to increase with increasing static bed height up to a certain limit. Further increase in bed height doesn't considerably affect the capture efficiency. The proposed model can be used as a design tool that would enable the optimization and commercialization of calcium looping.

1. Introduction

Global warming has many consequences including sea water level increase, agriculture and fisheries disruption, atmospheric warming, and prevalence of different diseases such as malaria. Global warming is mainly caused by anthropogenic emissions of so called greenhouse gases (mainly carbon dioxide (CO_2)). The burning of fossil fuels constitutes the major source of CO_2 emissions. Fossil fuel-based emissions of CO_2 may be originated from both stationary (e.g. power plants) and non-stationary systems (e.g. automobile). However, power generation sector is responsible for the largest amounts of CO_2 emissions [1]. Current projections for global energy demands still point to the dependence on fossil fuels to meet >85% of the world's energy needs. Therefore, the scientific community agrees that the solution for alleviating CO_2 emissions for the short- to midterm lies in a portfolio of strategies, including carbon capture and storage [2].

Carbon capture and storage, or CCS, is a chain of techniques that enables the continuous use of conventional fuels while preventing

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Nomenclature

Symbol	Description, unit
A_b	cross sectional area of bubble phase, m^2
A_e	cross sectional area of emulsion phase, m^2
Ar	Archimedes number, Dimensionless
C_b	gas molar concentration in bubble phase, mol/m^3
C_e	gas molar concentration in emulsion phase, mol/m^3
C_{CO2}	CO_2 molar concentration, mol/m^3
$C_{CO2,eq}$	CO_2 molar concentration at equilibrium, mol/m^3
$C_{CO2,in}$	CO_2 molar concentration at bed inlet, mol/m^3
$C_{CO2,out}$	CO_2 molar concentration at bed outlet, mol/m^3
d_b	bubble diameter, m
d_{bm}	mean bubble diameter along bed, m
d_p	particle diameter, m
E	reaction activation energy, J/mol
g	gravitational acceleration, m/s^2
H_{eb}	expanded (bubbling) bed height, m
H_{mf}	bed height at minimum fluidization, m
H_s	static bed height, m
K_{be}	mass interchange coefficient between bubble and emulsion phase, s^{-1}
MW	molecular weight, kg/mol
MW_s	average molecular weight of solid particles in bed (CaO + $CaCO_3$), kg/mol
N	number of calcination/carbonation cycles, Dimensionless
n	order of reaction, Dimensionless
P_{CO2}	CO_2 partial pressure, Pa
$P_{CO2,eq}$	CO_2 partial pressure at equilibrium, Pa
$Q_{gas,in}$	volumetric flow rate of inlet gas, m^3/s
R	specific reaction rate, s^{-1}
R_{CO_2}	rate of consumption of CO_2, $mol/m^3_{gas} \cdot s$
$Re_{p,mf}$	reynolds number at minimum fluidization, Dimensionless
r	grain radius at any time, m
r_0	initial grain radius, m
S	surface area of solid particles at any time, m^2/g
S_0	initial surface area of solid particles, m^2/g
T	operating temperature, K
t	time, **s**
t_{lim}	switching time, **s**
u_0	fluidization velocity, m/s
u_b	rise velocity of bubble phase, m/s
u_b^*	The effective gas velocity through the bubble phase, m/s
u_{bm}	mean rise velocity of bubble phase, m/s
u_{br}	rise velocity of single bubble, m/s
u_e	rise velocity of emulsion gas, m/s
u_{mf}	minimum fluidization velocity, m/s
V_g	volume of gas in the control volume, m^3
W_s	mass of solid particles in bed, kg
X	conversion ratio of solid sorbent, Dimensionless
X_{avg}	average conversion ratio of solid sorbent, Dimensionless
$X_{max,N}$	maximum sorbent capacity after N cycles, Dimensionless
$x_{CO_2,in}$	carbon dioxide mole fraction at bed inlet, Dimensionless
$x_{CO_2,out}$	carbon dioxide mole fraction at bed outlet, Dimensionless
z	axial distance measured from air distributor, m

Greek symbols

ε_{mf}	bed voidage fraction at minimum fluidization, Dimensionless
ρ_g	gas density, kg/m^3
ρ_s	solid particles density, kg/m^3
δ	the fraction of bed consisting of bubbles, Dimensionless
μ	dynamic viscosity, $N \cdot s/m^2$
ϕ	solid particles sphericity, Dimensionless
$\eta_{capture}$	CO_2 capture efficiency, Dimensionless

the CO_2 emissions from polluting the atmosphere. It begins with the capture of CO_2 from fossil fuel combustion or industrial processes. Next, the captured CO_2 is compressed and transported via ships or pipelines. Finally it is stored in suitable geological formations. An overview of different CCS technologies can be found in [3,4]. However, the most critical step in the CCS chain that determine the feasibility of a certain technique is the capture step [2].

One of the promising technologies that has shown some potential advantages in terms of net efficiency and cost of CO_2 avoided on both lab and pilot scale is carbon dioxide capture by absorption/regeneration process with calcium oxide, known as calcium looping as shown in Fig. 1. Both the carbonation and calcination reactions are carried out at high temperatures (600–700 °C and

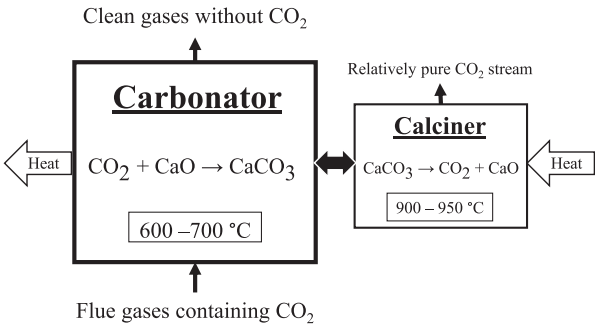

Fig. 1. Calcium looping process.

(900–950 °C respectively, allowing for efficient heat recovery in process heating or steam cycle of a power generation system. Moreover, CaL can be integrated with cement manufacturing so that a near zero-waste process can be achieved [5,6].

Hirama et al. [7] patented separation of carbon dioxide from gases containing it by contacting the gas mixture with metal based oxides (e.g. calcium oxide) to form metal carbonate. The metal oxide is then regenerated at higher temperatures in a second contacting zone where heat is supplied. The application of CaL as a post-combustion CO_2 capture process with dual fluidized bed was then proposed and applied by Shimizu et al. [8]. Since then, a lot of research has been done to further analyze and develop the process [5,9,10]. Moreover, several projects have been established to assess its feasibility on both lab and pilot scales [11–14].

Fig. 2 shows two different dual fluidized bed configurations that can be used in the calcium looping process where heat is supplied in the calciner by oxyfuel combustion. Most research works have focused on interconnected fluidized beds with solids circulation between carbonator and calciner, Fig. 2(a). However, this configuration has three main drawbacks.

First, it requires using circulating fluidized bed with relatively high inlet gas velocities which increases attrition and diminishes the possibility of reusing sorbent particles in subsequent cycles. Second, solids exiting the carbonator may include unreacted calcium oxide particles and solids exiting the calciner may include calcium carbonate particles which affects the capture efficiency. Third, plugging can occur in solid circulation lines between the two reactors. In order to solve these problems, the present work