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Non-isothermal modeling of simultaneous CO_2 and SO_2 removal in a semi-dry spouted bed reactor

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ABSTRACT

In the present study, a comprehensive non-isothermal model is developed to study the performance of a spouted bed reactor (SBR), in which CO_2 is removed at the presence of SO_2 by using NaOH solution. For this aim, the stream-tube model is applied for hydrodynamics of solid and gas phases, and then by using the conservation laws of mass and energy, the governing equations for gas and solid phases are derived and solved numerically. The effects of variation of different operating parameters and process conditions are evaluated, and by comparing the model results with the gathered experimental data, the maximum, minimum and average error are obtained. The results indicate that the CO_2 removal efficiency increases by increasing the inlet CO_2 concentration and by decreasing the inlet SO_2 concentration, ratio of superficial gas velocity to minimum spouting velocity and inlet gas temperature. Also, the modeling overall results indicate that by increasing the bed diameter and static bed height, CO_2 absorption efficiency increases.

1. Introduction

The emissions of CO_2 and SO_2 from power plants that burn fossil fuels cause changes in the global climate and form acid rain in the atmosphere, respectively, and result in serious environmental problems. CO_2 is the major atmospheric contaminant gas leading to increase of the earth temperature. Acid rain and the acidification of the environment emerged as a serious global problem during recent decades (Haghnegahdar et al., 2010; Rahimi et al., 2010). Therefore, development of new technologies to reduce or eliminate the emissions of carbon dioxide and sulfur dioxide into the environment is essential.

Carbon dioxide is usually removed by wet scrubbers, fluidized and fixed beds and spray towers. Various technologies for flue gas desulfurization FGD can be classified into three different types: wet scrubbers, semi-dry processes such as spray drying and sorbent injection, and dry processes (Ma et al., 2001; Xu et al., 2000).

Using spouting beds is a good alternative to existing processes for the removal processes of acidic gaseous pollutants from combustion gases. In this process, a slurry sorbent containing very fine absorbent particles such as soluble alkali powders (like NaOH, $Ca(OH)_2$ and $Mg(OH)_2$) is fed continuously into a spouted bed in which coarse particles are spouted with hot gas containing CO_2 and SO_2. The reaction between CO_2/SO_2 and the sorbent and the drying of the slurry take place in the bed simultaneously. Finally, the dried and reacted sorbents are entrained out of the bed and then collected in a bag filter (Ma et al., 2000; Moeini and Hatamipour, 2008; Nakazato et al., 2004).

Several investigators have already used spouted beds to remove acidic gaseous pollutants showed higher efficiency of SBR in removing gaseous pollutants than conventional processes (Haghnegahdar et al., 2010; Ma et al., 2000, 2001; Nakazato et al., 2004; Xu et al., 2000).

Mathematical modeling of spouting beds was first proposed by Mathur and Lim (1974). They defined a

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Nomenclature

a	specific surface area of solids per unit volume (m^2/m^3)
A	cross sectional area (m^2)
Ar	Archimedes number (–)
C_p	specific heat (J/kg/K)
$CO_{2,in}$	inlet CO_2 concentration (ppm)
D	Diameter (m)
E	CO_2 removal efficiency (%)
g	gravity constant (m/s^2)
G	mass flux of dry air (kg/m^2)
h	convective heat transfer coefficient ($w/m^2/s$)
H	height(m)
H_c	static bed height (cm)
H_m	maximum spoutable bed height (m)
K	streamtube numerator in annulus (–)
k_y	mass transfer coefficient of water vapor (m/s)
m	mass of water on the surface of solid particle (kg)
Na/C	molar ratio of NaOH to CO_2 (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
q	convective heat transfer (w/m^2)
$Q_{g,in}$	inlet gas flow rate (m^3/h)
r	thickness of liquid on particles (m)
r_c	flux of CO_2 consumption ($kg/m^2/s$)
r_{cs}	flux of SO_2 consumption ($kg/m^2/s$)
r_w	water evaporation flux ($kg/m^2/s$)
Re	Reynolds number (–)
S	axial mass flux of solid particles ($kg/m^2/s$)
Sc	Schmidt number (–)
Sh	Sherwood number (–)
$SO_{2,in}$	inlet SO_2 concentration (ppm)
t	Time (s)
T	Temperature (K)
U	gas velocity (m/s)
V	average axial velocity of the solid particles (m/s)
W	mass flow rate (kg/s)
X	CO_2 concentration (ppm)
y	mass fraction (ppm)
Y	mass fraction of water vapor (kg H_2O/kg dry air)
z	vertical distance from gas inlet (m)
Z	SO_2 concentration (ppm)

Subscripts

0	Reference
a	annulus region
air	dry air
c	Column
CO_2	CO_2 concentration
f	fountain region
g	gas phase
in	Inlet
k	number of stream tubes
mf	minimum fluidization
mix	gas mixture
ms	minimum spouting
out	Outlet
p	Particle
p_g	particle to gas
r	radial direction
s	spout region
SO_2	SO_2 concentration
t	total
T	terminal
v	water vapor
w	Water

Superscripts

*	saturation

Greek letters

β	porosity constant (–)
Δh_c	enthalpy of reactions between CO_2–NaOH (J/kg)
Δh_{cs}	enthalpy of reactions between SO_2–NaOH (J/kg)
ΔT	approach to saturation temperature of the bed (K)
Δz	longitudinal element (m)
ε	porosity (–)
H	enthalpy (J/kg)
λ	heat of vaporization (J/kg)
μ	viscosity (Pa s)
ρ	density (kg/m^3)

one-dimensional isothermal model considering spout and annulus regions and assuming that the gas travels in plug flow in both regions. Recently some researchers developed mathematical models to analyze the performance capability of a spouted bed in various processes (Ghalavand et al., 2010, 2012; Haghnegahdar et al., 2011; Jeng et al., 2001; Liu and Kato, 2000; Moeini and Hatamipour, 2008; Nieto et al., 2007; Niksiar et al., 2013; Olazar et al., 2005; Rahimi et al., 2010; Sanchez et al., 2000; Silva et al., 2011; Tao et al., 2010). Haghnegahdar et al. (2011) proposed a non-isothermal mathematical model for the performance of spouted bed in chemical absorption of CO_2. Their model was based on stream tubes model and mass and energy conservation equations. Besides to spout and annulus regions, their model included an additional area called "fountain". They investigated the effect of some of operating parameters such as superficial gas velocity, Ca/C ratio and static height of coarse particles bed on CO_2 absorption efficiency and then compared the predictions of their model with experimental results.

In flue gas of power plants, refineries, petrochemical and other heavy industries, both CO_2 and SO_2 gases present. These two gases react simultaneously with sorbent slurry and significantly impact to each other removal efficiency. To date no mathematical modeling has been reported to investigate the simultaneous absorption of CO_2 and SO_2 reaction in spouted bed reactors.

Hence a non-isothermal reactive absorption mathematical model is developed in the present study to analyze mass and heat transfer between the phases for CO_2 removal in presence of SO_2 from flue gas. The stream tubes hydrodynamic model (Sanchez et al., 2000) was used, and the governing equations of gas and solid phases in different areas of the spouted bed were obtained. Also the effect of operational and design parameters such as column diameter and static bed height on the performance of SBR was investigated.