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Modelling, simulation and analysis of intensified regenerator for solvent based carbon capture using rotating packed bed technology

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HIGHLIGHTS

- New first principle model for RPB stripper/regenerator developed and implemented in Aspen Plus®.
- Steady state model validation for RPB regenerator performed using experimental data from literature.
- Analysis of the impact of rotational speed and reboiler temperature on regeneration efficiency and regeneration energy.
- Study over wide range of MEA concentrations (32.6 wt%, 50 wt% and 60 wt%).
- 9.69 times size reduction between RPB regenerator and regenerator using packed bed under same conditions.

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ABSTRACT

Intensified regenerator/stripper using rotating packed bed (RPB) for regeneration of rich-MEA solvent in post-combustion CO_2 capture with chemical absorption process was studied through modelling and simulation in this paper. This is the first systematic study of RPB regenerator through modelling as there is no such publication in the open literature. Correlations for liquid and gas mass transfer coefficients, heat transfer coefficient, liquid hold-up, interfacial area and pressure drop which are suitable for RPB regenerator were written in visual FORTRAN as subroutines and then dynamically linked with Aspen Plus® rate-based model to replace the default mass and heat transfer correlations in the Aspen Plus®. The model now represents intensified regenerator/stripper. Model validation shows good agreement between model predictions and experimental data from literature. Process analyses were performed to investigate the effect of rotor speed on the regeneration efficiency and regeneration energy (including motor power). The rotor speed was varied from 200 to 1200 rpm, which was selected to cover the validation range of rotor speed. Impact of reboiler temperature on the rate of CO_2 stripping was also investigated. Effect of rich-MEA flow rate on regeneration energy and regeneration efficiency was studied. All the process analyses were done for wide range of MEA concentration (32.6 wt%, 50 wt% and 60 wt%). Comparative study between regenerator using packed column and intensified regenerator using RPB was performed and the study shows a size reduction of 9.691 times. This study indicates that RPB process has great potential in thermal regeneration application.

1. Introduction

1.1. Background

Environmental concern has posed many questions as to the impact of greenhouse gas to those changes currently noticed in world climate and the future dangers that will be expected if mitigation measures are not put in place. Combustion of coal and petroleum accounts for the majority of the anthropogenic CO_2 emissions. Petroleum is mostly used as a transportation fuel for vehicles while coal is used mostly for electricity generation, for instance about 85.5% of coal is used for electricity generation in 2011 in the UK [1]. Albo et al. [2] stated that among the greenhouse gases, CO_2 contributes to more than 60% of global warming. Statistics from World Metrological Organisation (WMO) showed the amount of CO_2 in the atmosphere reached 393.1 ppm in 2012. The WMO report also showed that the amount of CO_2 in the atmosphere has increased on average by 2 ppm per year for the past 10 years. Recent report by CO2-Earth [3] shows that as at 8 April

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2017 CO_2 atmospheric concentration stood at 407.78 ppm, this increased atmospheric concentration of CO_2 affects the radiative balance of the earth surface [4].

In order to meet the set target of 50% emission reduction by 2050 as compared to the level of 1990 as proposed by Intergovernmental panel on climate change (IPCC) [5], carbon capture and storage (CCS) is an important option for that target to be achieved. The International Energy Agency (IEA) [6] identifies CCS as a significant and low-cost option in fighting climate change. The most matured CO_2 capture technology is post-combustion CO_2 capture (PCC) based on chemical absorption as reported in Mac Dowell et al. [7] which is also believed to be a low-risk technology and promising near-term option for large-scale CO_2 capture.

PCC for coal-fired power plants using conventional packed columns has been reported by many authors. Dugas [8] carried out pilot plant study of PCC in the context of fossil fuel-fired power plants. Lawal et al. [9–11] carried out dynamic modelling and process analysis of CO_2 absorption for PCC in coal-fired power plants. In all these studies, one of the identified challenges to the commercial roll-out of the technology has been the high capital and operating costs which has an unavoidable impact on electricity cost. Systematic study of aqueous monoethanolamine (MEA)-based CO_2 capture process looking at the techno-economic assessment of the MEA process and its improvements was reported by Li et al. [12]. Oh et al. [13] study energy minimization of MEA-based CO_2 capture process it was found that Flue gas splitting gives a significant reduction of energy consumption. Solvent performance comparison for a large scale pulverized coal power plant was reported by Sharifzadeh et al. [14]. Hanak et al. [15] reported efficiency improvements for the coal-fired power plant retrofit with CO_2 capture plant using chilled ammonia process showing efficiency penalty reduced to 8.7% Also Zhao et al. [16] using mixed solvent for 650 MW power plant reported that the net power efficiency penalty was reduced from 9.13% to 7.66%. Approaches such as heat integration, inter-cooling among others could reduce the operating cost slightly. However, they limit the plant flexibility and will make operation and control more difficult [17]. Process intensification (PI) has the potential to meet this challenge [18–20].

Study of intensified absorber was reported in Joel et al. [21,22] and Agarwal et al. [23]. Joel et al. [21] reported 12 times volume reduction for absorber if using RPB technology as compared to packed column. Results from Agarwal et al. [23] indicated 7 times volume reduction when using RPB as compared to conventional packed column. The study by Joel et al. [21] uses aqueous MEA solvent while Agarwal et al. [23] uses diethanolamine (DEA) as solvent. This is the main reason for the differences in size reduction since faster reaction rate means shorter residence time and slower reaction rate means longer residence time required for the same capture rate. Jassim et al. [24] and Cheng et al. [25] reported experimental studies on intensified regenerator using RPB. Zhao et al. [26] study the mass transfer performance of CO_2 capture in rotating packed bed and Chamchan et al. [27] compared RPB and PB absorber in pilot plant.

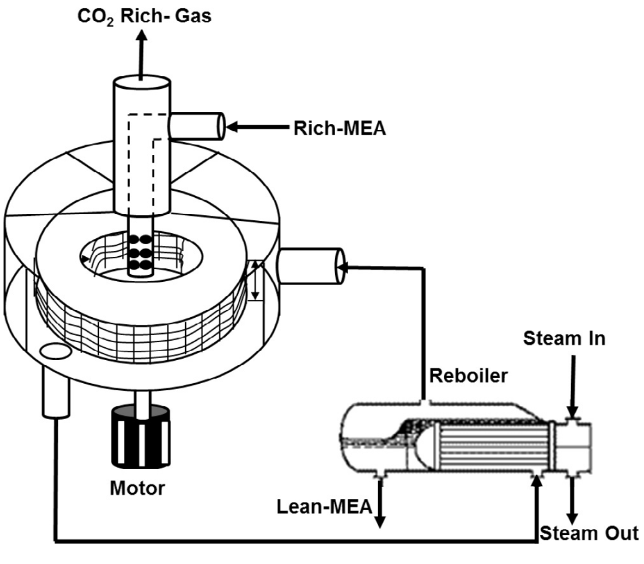

Fig. 1. Schematic diagram of an RPB regenerator.

Fig. 1 is a typical process flow diagram of an intensified regenerator using RPB for solvent regeneration. The flowsheet was used by Jassim et al. [24] and Cheng et al. [25] for experimental study. One of the operational benefits of using RPB is its ability to be operated at higher gas and/or liquid flow rates owing to the low tendency of flooding compared to that in the conventional packed bed [28]. Another benefit of using RPB is its better self-cleaning, avoidance of blocking in the system, and being unaffected by a moderate disturbance in its orientation [29].

Nomenclature

a	effective interfacial area (m^2/m^3)
a_i	activity of species *i* in a solution
a_t	total specific surface area of packing (m^2/m^3)
a_w	wetted area per unit volume (m^2/m^3)
a'_p	parameter for Chen et al. [24] and Chen et al. [25] correlations for liquid and gas film mass transfer coefficients (=3000 m^2/m^3)
c	width of wire mesh packing opening (mm)
C_i^l	concentration of component *i*
Cp_i	heat capacity for component *i*
d	wire diameter of wire mesh packing (mm)
D	column diameter (m)
D_G	diffusivity of gas (m^2/s)
D_L	diffusivity of liquid (m^2/s)
E_j	activation energy (kJ/mol)
d_p	packing size (m)
G	volumetric gas flow rate (m^3/s)
G^m	Gas molar flowrate (kmol/s)
g_c	gravitational acceleration or acceleration due to centrifugal field (m^2/s)
g_o	characteristic acceleration value (100 m^2/s)
H	height of packing (m)
h_G	gas phase specific molar enthalpy (J/kmol)
h_L	liquid phase specific molar enthalpy (J/kmol)
$h_{g/l}$	interfacial heat transfer coefficient (W/m^2 K)
ΔH_r	heat of desorption of CO_2 (J/kmol)
ΔH_{vap}	heat of vaporisation of H_2O (J/kmol)
k_G	gas film mass transfer coefficient (m/s)
K_G^a	overall mass transfer coefficient (1/s)
k_j^o	pre-exponential factor ($kmol/m^3$ s)
k_L	liquid film mass transfer coefficient (m/s)
L	liquid mass flowrate per tangential area ($kg/m^2/s$)
L^m	liquid molar flowrate (kmol/s)
MEA	monoethanolamine
N_i	molar fluxes for component *i* ($kmol/m^2$ s)
P_{motor}	motor power (kilowatts)
Q_L	volumetric flow rate of liquid (m^3/s)
r	radial position (m)
R_c	ideal gas constant (J $kmol^{-1}$ K^{-1})
r_j	reaction rate for reaction *j*
rxn_i	reaction rate of component *i*, ($kmol/m^3/s$)