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Thermal regeneration of amines in vertical, inclined and oscillating CO_2 packed-bed strippers for offshore floating applications

Ion Iliuta*, Faïçal Larachi

Department of Chemical Engineering, Laval University, 1065, Avenue de la Médecine, Québec, Québec, G1 V 0A6, Canada

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ABSTRACT

CO_2-monoethanolamine desorption process performance was studied for standard vertical, static inclined, and symmetric/asymmetric oscillating packed-bed columns via a dynamic three-dimensional model which links the macroscopic volume-averaged continuity, momentum, energy and species balance equations in the liquid and gas phases with the purpose to describe the stripping packed-bed columns aboard floating production, storage and offloading platforms. CO_2 thermal desorption process is negatively impacted in static inclined and asymmetric oscillating packed-bed columns because of secondary liquid flow, generated by the buoyancy force in the radial and tangential directions, and its consequence on two-phase flow hydrodynamics and temperature fields. The continual variation of the extent of reverse secondary flow in symmetric oscillating packed-bed columns induces a symmetrical oscillatory two-phase flow follows by time-dependent waves for thermal fields and CO_2 thermal desorption performance in the vicinity of the standard vertical stripper steady-state solution. Operation with extra heat allows to obtain higher CO_2 desorption rates and avoids the deterioration of CO_2 desorption performance in static inclined and asymmetric oscillating packed-bed columns. The extra heat is considerable when the inclined and asymmetric oscillating packed-bed columns are operated at elevated reboiler heat duty in the vertical state.

1. Introduction

Chemical and petrochemical, steel, cement and aluminum production industrial processes release annually a large quantity of CO_2 into the atmosphere. CO_2 removal by chemical absorption/desorption processes with alkanolamine-based aqueous solutions (monoethanolamine – MEA, diethanolamine, diisopropanolamine, N-methyldiethanolamine, 2-amino-2-methyl-1-propanol – AMP) and blended alkanolamine-based aqueous solutions, in which the amines are regenerated to be reused, are currently massively used for CO_2 capture because of the high-level of CO_2 absorption efficiency (Kohl and Nielsen, 1997; Bougie and Iliuta, 2010; Penders-van Elk et al., 2012; Luis et al., 2012; Rambo et al., 2014). CO_2-amine absorption/desorption processes are usually carried out in countercurrent packed-bed columns whose performance is largely governed by the mass-transfer efficiency of the random/structured packings used to provide the gas-liquid contacting area (Aroonwilas et al., 2001).

CO_2 thermal desorption in stripping packed-bed columns is central to the design of CO_2-amine absorption/desorption processes. It is highly-energy intensive and responsible for the main operational cost of the process (Bougie and Iliuta, 2010). Paradoxically, there is relatively a reduced amount of information related to CO_2 desorption process in the open literature compared to the overwhelming proportion of studies on CO_2 absorption. Recently, the researchers attempted to address these gaps in published different approaches to tackle the problem of high energy consumption in CO_2 thermal desorption process by developing alternatives with amines for low regeneration cost (Bougie and Iliuta, 2010; Warudkar et al., 2013). Cullinane and Rochelle (2004) have studied the carbon dioxide absorption with aqueous potassium carbonate promoted by piperazine, a cyclic diamine with very fast reaction kinetics, and found that the activated potassium carbonate has a lower reaction heat than MEA. Bougie and Iliuta (2010) showed that solutions of hindered amines (2-amino-2-hydroxymethyl-1,3-propanediol-AHPD, 2-amino-2-methyl-1,3-propanediol-AMPD, and 2-amino-2-ethyl-1,3-propanediol-AEPD), and in particular AHPD, are more easy to regenerate as they do not form (or form very few) stable carbamates. Also, Bougie and Iliuta (2010) found that addition of a small amount of piperazine into AHPD aqueous solution allows to obtain the most appropriate solvent for CO_2 capture. Freeman et al. (2010) studied the use of concentrated aqueous piperazine as a fast reacting absorbent for CO_2 capture process. Also, CO_2 capture with ionic liquids, salts that are liquids at room temperature, have been suggested by Hasib-Ur-Rahman

* Corresponding author.
E-mail address: ion.iliuta@gch.ulaval.ca (I. Iliuta).

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Nomenclature

Notation

a	Gas-liquid interfacial area, m^2/m^3
a_s	Packing specific surface area (surface packing area/column volume), m^2/m^3
$c_{p,\alpha}$	Specific heat capacity of α-phase (α = g, ℓ), J/kgK
C_j	Concentration of species *j*, $kmol/m^3$
d_p	Effective particle diameter, m
D	Column diameter, m
$D_{j\ell}$	Molecular diffusivity coefficient of species *j* in liquid phase, m^2/s
$D_{\ell(g)}$	Liquid and gas dispersion coefficients, m^2/s
E_1	E_2 Ergun constants, –
f_e	Wetting efficiency, –
$F_{g\ell}$	Gas-liquid drag force, N/m^3
F_{gs}	Gas-solid drag force, N/m^3
$F_{\ell s}$	Liquid-solid drag force, N/m^3
g	Gravitational acceleration, m/s^2
H	Reactor height, m
H_j^α	Molar enthalpy of species *j* in α-phase, kJ/kmol
N_j	Interfacial molar flux, $kmol/m^2s$
P	Reactor pressure, Pa
P_j	Partial pressure of species *j*, Pa
P_c	Capillary pressure, Pa
r	Radial coordinate, m
R	Ideal-gas constant or reactor radius
R_j	Reaction rate of the component *j*, $kmol/m^3s$
t	Time, s
T_a	Period of angular motion
$T\alpha$	α-Phase temperature, K
T_{int}	Temperature at the gas-liquid interface
u_α	Interstitial velocity of α-fluid, m/s
$v_{s\alpha}$	α-Phase superficial velocity, m/s
x	Liquid film coordinate, m
z	Axial coordinate, m

Greek letters

α	Angle of packed-bed column inclination with respect to the horizontal plane
$\alpha_{g\ell}$	Heat transfer coefficient at the gas-liquid interface, J/m^2sK
α_{max}	Amplitude of the angular motion
ε	Packed bed porosity, –
ε_α	α-Phase holdup, –
ε_b	Porosity in the bulk region of the packed bed, –
δ_ℓ	Liquid film thickness, m
ΔH_j^{vap}	Vaporization enthalpy of species j, kJ/kmol
ΔH_r	Reaction enthalpy, kJ/Kmol
$\lambda_{\alpha,r}^{ef}$	Radial effective thermal conductivity of α-phase, J/msK
μ_α	α-Phase dynamic viscosity, kg/ms
μ_α^{ef}	α-Phase effective viscosity (combination of bulk and shear terms), kg/m s
ν_B	Stoichiometric coefficient of amine in reaction
ρ_α	α-Phase density, kg/m^3
ρ_{pb}	Packed bed density, kg/m^3
σ_ℓ	Surface tension, N/m
θ	Azimuthal coordinate, m

Subscripts/superscripts

g	Gas phase
i	Gas-liquid interface
in	Reactor inlet
ℓ	Liquid phase
ℓf	Liquid film
r	Radial direction
s	Solid phase
trans	Transfer
vap	Vaporization
z	Axial direction
w	Reactor wall

et al. (2012), Hasib-Ur-Rahman and Larachi (2012), Zhang et al. (2012), Hasib-Ur-Rahman and Larachi (2013a, 2013b), Acidi et al. (2014) and Iliuta et al. (2014).

Nowadays, the offshore gas and oil industry located in zones of deep ocean waters far of continental coasts is concerned by the integration of CO_2 removal in countercurrent random/structured packed-bed columns aboard floating production, storage and offloading (FPSO) nonstationary units. However, there are major challenges in advancing, the most prominent one being the impact of see conditions on the performance of floating countercurrent packed-bed columns for CO_2 absorption/desorption processes. The offshore environment confronted with see perturbations can initiate various ship motions which generate pressure drop and liquid holdup fluctuations, liquid maldistribution, interphase mass transfer worsening followed by significant CO_2 removal performance deviations in packed-bed columns (Kim et al., 2007; Gu and Ju, 2008; Iliuta and Larachi, 2016a). Therefore, the design of CO_2 absorption and desorption countercurrent packed-bed columns exposed to variable wind, marine currents and waves must take these effects into consideration (Pham et al., 2015; Iliuta and Larachi, 2016a, 2017) and should include valuable corrective actions (supplementary capacity, liquid redistribution, etc.) to neutralize or to avoid any performance deviation with regard to the land-based CO_2 removal units (Assima et al., 2015).

Even if CO_2 absorption performance in vertical countercurrent packed-bed columns has been extensively examined, only a small number of studies have focused on the absorption performance of packed-bed columns in inclined states with the aim to understand the behavior of CO_2 absorption process aboard FPSO nonstationary platforms. Pham et al. (2015) investigated the impact of ship inclination and motion, at small inclination angles (0–4.5°), on liquid holdup, liquid maldistribution, two-phase pressure drop and CO_2 removal efficiency (CO_2-MEA absorption process) in an isothermal countercurrent structured packed-bed column *via* a gas-liquid Eulerian computational fluid dynamics model. Iliuta and Larachi (2017) analyzed 3-D flow fields and CO_2-MEA absorption performance in standard vertical, static inclined (inclination angles from 0 to 15°) and asymmetric/symmetric oscillating countercurrent random packed-bed columns via a dynamic non-isothermal three-dimensional model which couples the macroscopic volume-averaged momentum, mass, energy and species conservation equations in the liquid and gas phases and the differential equations describing the diffusion and chemical reaction in the liquid film surrounding the gas-liquid interface. CO_2-MEA absorption process in inclined and asymmetrically oscillating packed-bed columns faces evident deviations as regards the standard vertical packed-bed column while symmetrically oscillating packed-bed columns gives oscillatory absorption performance waves, with amplitude and propagation frequency altered by the packed-bed column oscillations, in the vicinity of the steady-state solution of the standard vertical packed-bed column. The impact of static inclination on the CO_2 removal efficiency is more important than the effect of the rolling motion, when the angle of