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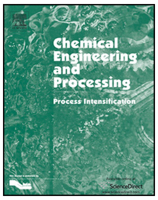

Simulation of carbon dioxide absorption by monoethanolamine solution in wetted-wire column

Sanaz Abouali Galledari[a], Reza Alizadeh[b,*], Esmaeil Fatehifar[b], Ebrahim Soroush[a]

[a] *Sahand University of Technology, Tabriz, Iran*
[b] *Institute of Environmental Engineering and Sustainable Development, Chemical Engineering Faculty, Sahand University of Technology, Tabriz, Iran*

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ABSTRACT

This study is an attempt to investigate the chemical absorption of CO_2 in aqueous mono-ethanolamine (MEA) solution in a multi-wire column. A rate-based process model based on the fast reaction for the CO_2–MEA system was employed for modelling of mass transfer and chemical reaction inside the column. As the gas phase mass transfer resistance is not negligible comparing to the liquid phase mass transfer resistance, unlike previous models, gas side mass transfer resistance has also been considered in the model. In addition, the heat effects associated with the absorption and chemical reaction are included through energy balances in the gas and liquid phases. A computer program (MATLAB code) was developed to simulate CO_2 absorption into aqueous solution of mono-ethanolamine in a multi-wire column. The model is capable of predicting essential information, such as overall mass transfer coefficient, gas absorption rate and efficiency of the column. The modelling results were compared with available experimental data conducted in columns that equipped with both single wire and multiple wires and good agreement was achieved. Thereby it was concluded that the developed model is capable to predict the chemical gas absorption performance of both multi-wire and one-wire gas–liquid contactors.

1. Introduction

In the present decades, global warming and climate change seems to become the most important environmental issues. The increase in the concentration of greenhouse gases (GHGs) is attributed to be the cause of these phenomena. More than 85% of world's commercial energy is provided by fossil fuels [1] and they may continue to be the major energy resources for at least the next 20 years. This means the emission of GHGs remains as a very important issue in the decades ahead. Since carbon dioxide accounts for nearly 77% of total GHGs emission [2], it plays an important role in global warming. In this manner, reducing the carbon dioxide emissions seems to be a priority. Among various industrial CO_2 removal methods, absorbing carbon dioxide with amines become prevalent and mature in the past decades [3–5]. Mono-ethanolamine (MEA) is the one most commonly used alkanolamines due to advantages like low cost, low viscosity, high boiling point and solubility in water [6,7].

CO_2 separation by alkanolamine in packed columns is a very common method in chemical and petroleum industries [8] and the most preferred one for carbon dioxide removal from power plant flue gases [9,10], however, absorption with the use of packed columns is known to suffer from operational problems such as liquid channeling, flooding and more importantly large gas-side pressure drop. In fact, because of the packing geometry, a large drag exerts on the gas flow which results in gas phase pressure-drop. Nevertheless, CO_2 absorption from flue gases is in need of a gas–liquid contact device, which is able to remove carbon dioxide efficiently at high rates without imposing a high gas phase pressure-loss. It will be crucial from energy saving prospect to have a contact device which is not in need of flue-gas compression process for balancing the hydrodynamic pressure drop inside contactor [11,12].

This means a contactor is needed, which have the advantages of packed-bed columns (high surface area for gas–liquid contact, long residence time, and proper mixing of liquid phase) but impose a small pressure-drop on the gas phase. In recent years, wetted-wire columns are suggested for replacement of conventional contacting devices like spray, wetted-wall, and packed-bed columns in processing flue gases [11–13]. Inside of these vertical columns, multiple wires are vertically hung in a way that a liquid absorbent

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* Corresponding author. Fax: +98 4133444355.
E-mail address: r.alizadeh@sut.ac.ir (R. Alizadeh).

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Nomenclature

A_d	Liquid bead surface area, m^2
a	Gas–liquid interfacial area per unit volume of contactor, m^2/m^3
c_{CO_2}	Mass of CO_2 absorbed in unit volume of liquid absorbent, g/m^3
$c_{CO_2,s}$	Mass-based physical solubility of CO_2 in liquid absorbent, g/m^3
$c_{CO_2,sat}$	Mass-based overall solubility of CO_2 in liquid absorbent, g/m^3
C_{MEA}	Molar concentration of MEA, mol/m^3
C_P	Specific heat capacity, J/mol K
$D_{CO_2,l}$	Diffusion coefficient for CO_2 diffusion in liquid phase, m^2/s
$D_{N_2O,l}$	Diffusion coefficient for N_2O diffusion in liquid phase, m^2/s
$D_{N_2O,w}$, $D_{CO_2,w}$	Diffusivity of N_2O and CO_2 in water, respectively, m^2/s
$D_{CO_2,g}$	Diffusion coefficient for CO_2 diffusion in gas phase, m^2/s
d	Inner diameter of column, m
d_n	Inside diameter of nozzle, m
d_{d1}	Axial length of liquid bead, m
d_{d2}	Maximum diameter of liquid bead, m
d_f	Diameter of cylindrical liquid film, m
d'_f	Diameter of liquid film when total liquid flow distributed annular-film-shaped, m
d_w	Wire diameter, m
d_d	Diameter of liquid bead assumed to be spherical (approximated by $\left(d_{d1}d_{d2}^2\right)^{1/3}$), m
d_s	Equivalent diameter for wires, m
G	Molar flow rate of gas phase, mol/m^2 s
h	Height of column, m
$He_{CO_2,l}$	Henry's constant for CO_2 in MEA solution, mol/m^3 Pa
$He_{N_2O,l}$	Henry's constant for N_2O in MEA solution, mol/m^3 Pa
$He_{N_2O,MEA}$	Henry's constant for N_2O in pure MEA liquid, mol/m^3 Pa
$He_{N_2O,w}$, $He_{CO_2,w}$	Henry's constant for N_2O and CO_2 in water, respectively, mol/m^3 Pa
H_R	Heat of reaction, J/mol
H_S	Heat of solution, J/mol
h_g	Heat transfer coefficient in gas phase, J/s K m^2
K_G	Overall mass transfer coefficient based on the gas phase, mol/m^2 s
k_g	Gas phase mass transfer coefficient, m/s
k_l	Liquid phase mass transfer coefficient, m/s
k	Second-order reaction rate constant, m^3/mol s
k'	First-order reaction rate constant, 1/s
L	Molar flow rate of liquid phase, mol/m^2 s
L_d	Axial interval between successive beads, m
M	Molar mass, g/mol
N_{CO_2}	Molar flux of CO_2 across the gas–liquid boundary, mol/m^2 s
N	Number of wires
P_t	Total pressure, Pa
Pr	Prandtl number
Q_l	Total volume flow rate of liquid absorbent, m^3/s
Q_i	Volume flow rate of liquid over each wire, m^3/s
r	Rate of chemical reaction, mol/m^3 s
R_{CO_2}	Rate of gas absorption, g/s
S_f	Cross-sectional area of film, m^2
T	Absolute temperature, K
U_d	Fall velocity of bead, m/s
U_g	Mean gas velocity in column, m/s
V_d	Bead volume, m^3
v	Superficial velocity, m/s
X_{MEA}	Mole ratio of MEA in liquid phase
y_{CO_2}	Mole fraction of CO_2 in gas balk
$y^*_{CO_2}$	Mole fraction of CO_2 in equilibrium with liquid bulk concentration
Y_{CO_2}	Mole ratio of CO_2 in gas phase
z	Axial direction, m

Greek letters

τ	Contact time, s
ρ	Molar density, mol/m^3
μ	Dynamic viscosity, g/m s
ε	Volume fraction void
ν	Kinematic viscosity, m^2/s
ϕ_{MEA}, ϕ_w	Volume fraction of MEA and water in aqueous MEA solutions, respectively, dimensionless
$\Re$	Excess Henry's quantity, mol/m^3 Pa

Superscripts and subscripts

g	Gas phase
l	Liquid phase
I	Inert gas
i	Interface
w	Water
in, 0	Condition of liquid absorbent before contact with gas flow
out	Condition of liquid absorbent after contact with gas flow

flows down the wire, while it is in touch with the countercurrent gas stream [11–13]. Fig. 1 shows the cropped view and the side view of a wetted-wire column [14].

The desired on-wire flow pattern in wetted-wire columns is called “string-of-beads.” In this liquid flow pattern, tear drop-shaped liquid beads aligned on a wiresheathed by annular thin films, which flow down at much lower velocity at regular intervals. The velocity difference between film flow velocity and beads fall velocity, result in the continuous mass displacement between the beads and film that provide an excellent mixing for the absorbent and reduce its diffusive resistance [11–13]. Fig. 2 shows liquid flow pattern of string-of-beads on one wire [11].

The idea of using vertical wires instead of conventional device for gas–liquid contactors was first introduced by Hattori et al. [15]. They proposed wetted-wire columns which could be used in thermal energy recovery from hot gases due to the string-of-beads regime features such as long gas–liquid contact time and small pressure-drop in the gas stream. Chinju et al. [13] noticed the significant velocity difference between the beads and the film causes a considerable mixing in liquid phase, which is very important for interphase mass transfer where major diffusional resistance lies in the liquid phase. Based on this idea they suggested that string-of-beads regime is more suited for