Applied Energy 190 (2017) 1068–1080

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Mass transfer and energy consumption for CO_2 absorption by ammonia solution in bubble column

Fengming Chu, Lijun Yang *, Xiaoze Du, Yongping Yang

Key Laboratory of Condition Monitoring and Control for Power Plant Equipments of Ministry of Education, School of Energy Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

HIGHLIGHTS

- Both the CO_2 capture and ammonia escape in the BCR are investigated.
- Influences of the BCR geometries and operating conditions are obtained.
- Increased orifice size can enhance CO_2 mass transfer and restrain ammonia escape.
- Consumed energy increases with increasing operating pressure, orifice number, size.
- Recommended height-to-diameter ratio is 5.76 for energy consumption and CO_2 removal.

ARTICLE INFO

Article history:
Received 17 September 2016
Received in revised form 11 January 2017
Accepted 14 January 2017
Available online 23 January 2017

Keywords:
Carbon dioxide capture
Ammonia escape
Mass transfer
Energy consumption
Bubble column

ABSTRACT

The CO_2 absorption in the bubble column using ammonia solution has been proved a viable approach for the post-combustion CO_2 capture, so it is of benefit to the energy saving of CO_2 absorption and the bubble column design to clarify the impacts of the geometry and running parameters on the mass transfer and energy consumption of CO_2 capture. Based on the representative elementary volume method, a computational model of both the CO_2 capture and ammonia slip was developed and validated by the experimental data, by which the hydrodynamic characteristics, mass transfer performances and energy consumption in CO_2 capture process were investigated. The results show that at the same inlet velocity of CO_2, the higher height-to-diameter ratio of the column can improve the mass transfer performances of both the CO_2 capture and ammonia escape. What's more, the energy consumption decreases with the reduced orifice number on the bottom of column, and increases as the orifice size increases. An optimal height-to-diameter ratio of 5.76 is recommended when taking both the energy consumption and CO_2 removal efficiency into consideration. This work can provide the viable guidance and suggestions of the better mass transfer performance and energy saving for the industrial application of CO_2 capture, as well as the inhibition of ammonia escape.

1. Introduction

The climate change has become a serious environmental issue all over the world, which is mainly caused by the emission of greenhouse gases (GHGs). Carbon dioxide (CO_2) is regarded as one of the most important GHGs [1]. As the excessive consumption of coal, the annual emission from the coal-fired power plants occupies nearly 35% of the CO_2 emission in the world [2]. The anthropogenic CO_2 emission accounts for 80% of the total GHGs and makes a significant contribution to the global climate change [3,4]. The carbon capture and storage (CCS) is an essential measure against the CO_2 discharge from the coal-fired power plants and other related industries, whereas with the tremendous energy consumption.

Various approaches have been proposed to deal with the CO_2 emission, including physical adsorption, chemical absorption, membrane separation, cryogenic methods, biological fixation, photocatalytic reduction and O_2/CO_2 combustion [5–11]. Among these methods, the chemical absorption is regarded as an alternative and potential choice with the high efficiency and mature technology [12]. Due to the higher absorption capacity than the monoethanolamine (MEA) at the same operating temperature and pressure, the aqueous ammonia is basically applied to the chemical absorption [13–17]. Farid et al. [17] studied the aqueous ammonia absorption in comparison with aqueous amine, finding that the aqueous

* Corresponding author.
E-mail address: yanglj@ncepu.edu.cn (L. Yang).

http://dx.doi.org/10.1016/j.apenergy.2017.01.027
0306-2619/

Nomenclature

C_{CO2_G}	CO_2 mass concentration in gas phase, dimensionless
$C_{\mathbf{HCO_3^-}\_L}$	NH_4HCO_3 mass concentration in liquid phase, dimensionless
C_{NH3_G}	NH_3 mass concentration in gas phase, dimensionless
C_{NH3_L}	NH_3 mass concentration in liquid phase, dimensionless
$D_{G,CO2}$	molecular diffusivity of CO_2 in gas phase, m^2/s
$D_{G,NH3}$	molecular diffusivity of NH_3 in gas phase, m^2/s
$D_{L,\mathbf{HCO_3^-}}$	molecular diffusivity of NH_4HCO_3 in liquid phase, m^2/s
$D_{L,NH3}$	molecular diffusivity of NH_3 in liquid phase, m^2/s
E	enhancement factor, dimensionless
F_G	momentum source term of gas phase, N/m^3
F_L	momentum source term of liquid phase, N/m^3
g	gravitational acceleration, m/s^2
G_F	gas flow rate, kmol/s
$G_{CO2,in}$	CO_2 gas molar flow rate, kmol/s
G_{N2}	N_2 molar flow rate, kmol/s
H_{CO2}	Henry's constant of CO_2, kPa m^3/kmol
$K_G^{CO_2}A$	volumetric overall mass transfer coefficient of CO_2 absorption, kmol/(L s kPa)
$K_G^{NH_3}A$	volumetric overall mass transfer coefficient of ammonia escape, kmol/(L s kPa)
$k_{G,NH3}$	gas phase mass transfer coefficient of NH_3, m/s
$k_{L,CO2}$	liquid phase mass transfer coefficient, m/s
$k_{L,NH3}$	liquid phase mass transfer coefficient of NH_3, m/s
$p_{CO2,i}$	partial pressure of CO_2 in main gas, kPa
p_{in}	inlet pressure of compressor, kPa
p_{NH3}	partial pressure of NH_3 in main gas, kPa
$p_{NH3,i}$	partial pressure of NH_3 at the interface, kPa
p_{out}	outlet pressure of compressor, kPa
Q_L	volumetric flow rate of gas phase, m^3/s
R_{CO2}	mean chemical reaction rate of CO_2 absorption in BCR, kmol/s/L
S_{CO2_G}	source term of CO_2 mass fraction equation, $kg/m^2/s$
$S_{\mathbf{HCO_3^-}}$	source term of NH_4HCO_3 mass fraction equation in liquid phase, $kg/m^2/s$
S_G	source term of the continuity equation for gas phase, $kg/m^3/s$
S_L	source term of the continuity equation for liquid phase, $kg/m^3/s$
S_{NH3}	source term of the NH_3 mass fraction equation in liquid phase, $kg/m^3/s$
S_{NH3_Esc}	source term of the NH_3 mass fraction equation in gas phase, $kg/m^3/s$
t	time, s
u_G	averaged velocity vector of gas phase, m/s
u_L	averaged velocity vector of liquid phase, m/s
V_L	volume of the solvent in BCR, L
W	total energy consumption, dimensionless
W_C	energy consumption of compressor, kW
W_f	energy consumption of fan, kW
$X_{CO2,i}$	CO_2 concentration at the interface, $kmol/m^3$
$X_{CO2,L}$	CO_2 concentration in liquid phase, $kmol/m^3$
X_{NH3}	NH_3 concentration in liquid phase, $kmol/m^3$
$X_{NH3,i}$	NH_3 concentration at the interface, $kmol/m^3$
Y^{CO2}	molar ratio of CO_2 to N_2, dimensionless
y_1, y_2	CO_2 mole ratio in gas phase entering and leaving BCR, dimensionless
$y_{NH3,out}$	NH_3 mole ratio in gas phase at outlet of BCR, dimensionless
$y_{N2,out}$	N_2 mole ratio in gas phase at outlet of BCR, dimensionless
Y_{out}	NH_3 to N_2 mole ratio in the gas phase at the outlet of the BCR, dimensionless
z	number of compression stage, $z = 1$

Greek symbols

α_G	volume fraction of gas phase, dimensionless
α_L	volume fraction of liquid phase, dimensionless
δ_G	thicknesses of gas film, m
δ_L	thicknesses of liquid film, m
ε	gas hold up, dimensionless
η	CO_2 removal efficiency, dimensionless
η_c	efficiency of compressor, $\eta_c = 0.85$
η_p	efficiency of fan, $\eta_p = 0.8$
μ_G	viscosity of gas phase, Pa s
μ_L	viscosity of liquid phase, Pa s
ρ_G	density of gas phase, kg/m^3
ρ_L	density of liquid phase, kg/m^3

ammonia requires a much lower energy for regeneration. Moreover, SO_2 can be simultaneously absorbed by the aqueous ammonia [18]. Yu et al. [19] and Li et al. [20] confirmed the technical feasibility of the CO_2 capture by aqueous ammonia solution based on the pilot plant trials. Han et al. [21] concluded that the waste heat recovery system can supply the energy for the regeneration of absorbent solution. Bonalumi and Giuffrida [22] proposed the integration of CO_2 capture at three different levels, showing that the specific primary energy consumption for the 90% of CO_2 avoided was as low as 2.3 MJ/($kgCO_2$). Though the CO_2 removal by ammonia is treated as the most viable technology in practical engineering thanks to its high removal efficiency and adequate adaptability [23], it suffers the ammonia escape disadvantage, which leads to the ammonia loss and secondary atmosphere pollution [24]. Moreover, the absorbing and ammonia escape processes are affected by the reaction conditions and reactor configuration, so should be further investigated.

The conventional gas and liquid reactors have been investigated for several decades. Especially, the packed tower and bubble column have been successfully applied to the post-combustion CO_2 capture in pilot and industrial scales [25]. The packed column is good at the lower pressure drop [26], but inferior to the bubbling reactor in mass transfer performance [27]. Thanks to its high heat and mass transfer rates and low operation and maintenance costs, the bubble column reactor (BCR) has been widely used in chemical and power engineering [28]. However, the fundamental studies of CO_2 capture in bubble column reactors mainly focused on the CO_2 removal efficiency or the ammonia escape inhibition, and the mass transfer of ammonia escape process as well as CO_2 absorbing process was rarely involved. Although the geometry of BCR is relatively simple, it is difficult to predict the mass transfer and energy consumption inside the BCR due to the complex multiphase hydrodynamics and reaction mechanism. The mass transfer performance and energy consumption are influenced significantly by the operating conditions, gas and liquid properties and the configuration of BCR. Bai and Yeh [13,29] studied the CO_2 capture by ammonia in BCR, finding that the removal efficiency can reach 95%. Zhao et al. [4] experimentally investigated the influence of BCR geometry on the CO_2 capture efficiency, pointing out that the height-to-diameter ratio plays an important role in CO_2 capture. Zhang et al. [30] investigated the ammonia escape in a super-gravity bed with disks, finding that the outlet molar fraction of ammonia arrived at 1.3–3.6%. Ma et al. [27] studied the impacts of mass transfer of ammonia escaping, and obtained the volumetric mass