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Effect of tilt on mass transfer and hydrodynamic performance in a packing column

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ABSTRACT

To investigate the working performance of packing columns used in offshore floating production, CO_2-absorption and hydrodynamic experiments were performed in a tilted laboratory-scale packing column. A six-degree-of-freedom motion parallel platform was adopted to mimic different tilted states (3°–12°). Using a CO_2–NaOH system, the effects of the liquid flow rate (6–24 $m^3/m^{2/}h$), NaOH concentration (0.5–2 mol/L), gas flow rate (4.1–8.0 m^3/h) and CO_2 molar fraction at the inlet (4.0–7.5%) on the CO_2 absorption performance were investigated under normal pressure and temperature conditions. Liquid hold-up and pressure drop were measured using a water–air system. Three different types of packing were tested to compare their anti-tilt performance. The experimental results showed that tilt significantly reduced the mass transfer performance of Pall Ring 10 mm; however, the reductions in the performance of Sulzer BX500 and BY500 were minor. Further, both liquid holdup and pressure drop of three packings were reduced by tilt.

1. Introduction

Natural gas is a clean-energy source, and its demand is increasing around the world. With the gas resources on land exhausting, it is necessary to exploit offshore gas fields. In traditional offshore gas production, the natural gas collected from the sea bed is transported to a terminal on land for further pretreatment and liquefaction via subsea pipelines, which are difficult and uneconomical to be install [1].

Recently, a concept called floating liquid-natural-gas production storage and offloading (FLNG) has been proposed, which can be used to process and liquefy the natural gas into liquefied natural gas (LNG) on the deck. Therefore, FLNG has become a most promising equipment for offshore gas production, especially for remote and marginal gas fields in the deep sea [2,3]. However, in contrast to the LNG plants on land, many devices in FLNG are not kept in a steady vertical state, which may diminish their performance.

Packing columns have been widely used onshore for decades as key devices in natural gas purification units. They are designed to effectively absorb the CO_2 and H_2S found in natural gas [4–6]. Many studies have investigated CO_2 absorption in vertical packing columns on land. Aroonwilas et al. [7–10] studied the effects of operating parameters on CO_2 absorption performance in structured-packing columns, including the liquid load, initial liquid distribution and liquid temperature with several solvents (AMP, NaOH and MEA). The results showed that liquid load had a significant impact on CO_2 absorption performance, but the quality of initial liquid distribution affected the performance slightly when structured packings were used. Further, a mechanistic model based on the liquid distribution in the packing zone was proposed to predict the mass transfer performance. With aqueous ammonia solution, Zeng et al. [11,12] investigated the overall absorption rate and volumetric overall mass transfer coefficient in a random packing column. Various operating parameters were studied, including the liquid flow rate, gas flow rate, CO_2 concentration at the inlet and aqueous ammonia concentration. It was found that both the overall absorption rate and overall volumetric mass transfer increased with the aqueous ammonia concentration increasing. Similarly, Li et al. [13] investigated CO_2 absorption using an aqueous ammonia solution in a structured packing column and obtained the same conclusions, i.e., a high liquid load and aqueous ammonia concentration resulted in an improved overall volumetric mass transfer.

Gao et al. [14] investigated the effects of several operating parameters on CO_2 absorption performance with an MEA-methanol hybrid solvent using three types of packings, namely Sulzer BX500, Mellapak 500Y and Pall Rings 16 mm. The experimental results showed that the Sulzer BX500 performed the best among these packings. Zhao et al. [15] studied the CO_2 absorption performance with a K_2CO_3 solution using three other types of packing; the results showed that the SMR 13 mm packing provided a superior mass transfer performance than Pall Rings 13 mm and Mellapak 700Y. Tsai et al. [16,17] measured the effects of liquid load, gas flow rate, liquid surface tension, liquid

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Nomenclatures

Latin Letters

Ae	Effective area, m^2/m^3
D	Diffusivity, m^2/s
$D_{CO2,L}$	Diffusivity of CO_2 in solution, m^2/s
d_h	Hydraulic diameter of packing, m
E	Enhancement factor
G_B	Inert gas flow rate, $kmol/m^2/h$
H_A	Henry's law coefficient of component A, $m^3 \cdot pa/kmol$
H_{CO2}	the henry's law coefficient for CO_2, m^3 bar/kmol
Ha	*Hatta* number
h_i	Value of contribution for cations, anions and gases, $m^3/kmol$
I	Ionic strength of solution, $kmol/m^3$
I_i	Ionic strength, $kmol/m^3$
K_G	Overall mass transfer coefficient, $kmol/m^2/h/pa$
K_GAe	Overall volumetric mass transfer coefficient, $kmol/m^3/h/pa$
k_{OH^-}	Reaction rate constant, $m^3/kmol/s$
k_G	Gas phase mass transfer coefficient, $kmol/m^2/h/pa$
k_L	Liquid phase mass transfer coefficient, m/h
m	Amount of CO_2 absorbed in per unit time, kmol/h
N_A	Absorption rate of component A into a solution, $kmol/m^2/h$
P	Total pressure, pa
S	Cross area of column, m^2
T	Temperature, K
u	Velocity, m/s
V	Total volume of the packing, m^3
Y	Molar ratio of CO_2
y_A	Mole fraction of A in the gas
y^*	Equilibrium molar fraction of A in the liquid
Z	Height of the column, m

Greek letters

Φ	Overall absorption rate, $kmol/m^3/h$
φ	Reduction in the value of Φ
ρ	Density, kg/m^3
μ	Viscosity, Pa s

Subscript

G	Gas phase
L	Liquid phase

viscosity and the packing type on the mass-transfer area in a CO_2–NaOH system. The experimental results showed that liquid load and packing sizes had the strongest effects on the effective area and a reduction in surface tension could improve the effective area. In addition, gas flow rate, liquid viscosity and packing corrugation angle had little influence on the mass-transfer area. Yang et al. [18] designed a series of structured packings with different geometrical parameters to research the effect of the packing geometry on the mass-transfer area. The results revealed that a geometry parameter with a corrugated angle of 30° and an addendum angle of 75° gave the best mass transfer performance among their structured packings tested.

Although the CO_2 absorption performance in vertical packing columns has been widely investigated, only a few studies have focused on the absorption performance of packing columns in tilted states, which are regraded as an even more extreme state than roll motions of floating plants [19,20]. Hence, this study utilises a six-degree-of-freedom (6-DOF) motion parallel platform to investigate the effects of several operating parameters on the mass transfer performance of a tilted packing column using a CO_2–NaOH system.

Further, several studies have recently investigated the hydrodynamic performance of tilted packed beds. Using an electrical-capacitance tomographic imaging technique, Assima et al. [21] observed the liquid distribution in an tilted packed bed and studied the effect of the obliquity of packed beds on liquid drainage. Two textural flow regimes, i.e., film and droplet flows were found to be associated with the gravity, capillary and viscous forces. The results of this study show that an tilted packed bed could provide a better performance in terms of the drainage rate. Using plastic Raschig rings, Wongkia et al. [22] investigated the hydrodynamics of gas-liquid flow in an tilted packed bed. The results revealed that the pressure drop and liquid saturation were decreased in tilted states. The flooding capacity of tilted columns was higher than that of vertical columns, which indicated a prospective applications of such columns in catalytic processes. Son et al. [23] measured the liquid distribution in a structured packing column with tilt and roll motion using an electrical-resistance tomography method. The results showed that liquid maldistribution was enhanced with the decrease in liquid surface tension and liquid viscosity. In present study, except the investigation on the mass transfer performance in a tilt packing column, the liquid hold-up and pressure drop were also measured. Three types of packing, including random and structured packings, were tested to compared their mass transfer and hydrodynamic performance in tilt.

2. Theory

2.1. Overall volumetric mass transfer coefficient and overall absorption rate

In CO_2-NaOH systems, the dominant chemical reaction is:

$$CO_2(aq) + 2OH^- \rightarrow CO_3^{2-} + H_2O \tag{1}$$

Based on the two-film theory, the absorption rate of component A into a solution, N_A, can be expressed as:

$$N_A = K_G P (y_A - y^*) \tag{2}$$

where K_G is the overall mass transfer coefficient, P represents the total pressure, y_A is the mole fraction of A in the gas and y^* is the equilibrium molar fraction of A in the liquid at equilibrium.

Based on the mass balance, the variation in the number of CO_2 molecules in any height element along packing columns can be represented as:

$$dm = G_B S dY = N_A AeSdz = K_G P (y - y^*) AeSdz \tag{3}$$

$$\frac{G_B}{P}\frac{dY}{dz} = (K_G A_e)(y - y^*) \tag{4}$$

where G_B is the inert gas flow rate, m is the amount of CO_2 absorbed in per unit time, S is the cross area of columns and Y is the molar ratio of the CO_2 component. There is a relationship between Y and y as:

Table 1
Contributions of anions, cations and gases to Henry's constant for CO_2.

h_+	h_-	h_g (CO_2)
$Na+$ 0.091	$OH-$ 0.066	0.2 °C −0.007
	CO_3^{2-} 0.021	15 °C −0.010
		25 °C −0.019
		40 °C −0.026
		50 °C −0.029
		60 °C −0.016