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Experimental investigation of mass transfer performance in laboratory- and pilot-scale structured-packing columns under roll motion

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HIGHLIGHTS

- The relative change in the mass-transfer area due to roll motion was investigated.
- Mass transfer performance was readily worsened under high gas velocity.
- Mass-transfer area was likely reduced under low-frequency roll motion.
- Tilt could be regarded as an extreme sea state of roll motion.

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ABSTRACT

Influence of roll motion on the mass transfer performance in laboratory- and pilot-scale structured-packing columns was investigated. A six-degree-of-freedom motion parallel platform was adopted to mimic different sea states of roll motion, and the relative change in the mass-transfer area caused by roll motion was obtained using an air-NaOH system. The experimental results showed that both enhanced and deteriorative mass transfer phenomena could be induced by roll motion, which results from the combined effect involving the operating conditions, packing types and sea states. Based on these results, a nominal maximum rolling velocity was proposed. The nominal maximum rolling velocity was positively correlated with the relative change in the mass-transfer area. Furthermore, the results indicated that tilt could be regarded as an extreme sea state of roll motion.

1. Introduction

Floating liquefied-natural-gas production, storage, and offloading (FLNG) has been recently explored for offshore gas production as it is expected to be superior to traditional production approaches (Nezamian and Morgan, 2014). Since subsea natural gas can be refined and liquefied directly on FLNG plants, the costs associated with the pipeline are significantly reduced, which is beneficial for remote and marginal gas fields in the deep sea (Zhao et al., 2011a; Won et al., 2014).

The modules on the decks of FLNG plants, such as the purification and liquefaction units, are compact and highly intricate. Moreover, the devices must be adapted to the harsh marine environment where high winds, waves, and currents are commonplace. Under the combined influence of these environmental factors, complex random motion will be occurred and affect the performance of these devices on the FLNG topside.

Packing columns are a fundamental component of purification units that have been widely applied onshore for decades due to their advantages of high efficiency and low pressure drop (Aroonwilas and Tontiwachwuthikul, 2000; Aroonwilas et al., 2003; Raynal and Royon-Lebeaud, 2007). On the packing surface, the absorbent flows downward in the form of a liquid film and interacts with the natural gas to remove acidic components like CO_2 and H_2S. Compared to vertical states, the gas/liquid flow in the packing zone will be more complex in tilted and rolling states. This phenomenon can affect the working performance of the packing column and has consequently been an engineering challenge for FLNG design and application.

The liquid distribution within tilted or rolling packing columns has been previously investigated. For example, the liquid flow rate has been used to describe the liquid distribution in tilted states

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Nomenclature

Latin letters

Ae	special surface of packing, m^2
A_{roll}	rolling amplitude, °
D	diffusivity, m^2/s
d_h	hydraulic diameter of packing, m
E	enhancement factor
fe	mass-transfer area, m^2/m^3
H_A	Henry's law coefficient of component A, m^3 Pa/kmol
H_{CO2}	Henry's law coefficient for CO_2 in aqueous NaOH solution, m^3 bar/kmol
h_i	contribution from cations, anions, and gas, m^3/kmol
I	ionic strength of solution, kmol/m^3
I_i	ionic strength, kmol/m^3
K_G	overall volumetric mass transfer coefficient, kmol/m^2/s/Pa
k_G	gas phase mass transfer coefficient, kmol/m^2/s/Pa
k_L	liquid phase mass transfer coefficient, m/s
k_{OH-}	reaction rate constant, m^3/kmol/s
m	amount of CO_2 absorbed in per unit time, kmol/s
Q	liquid load, $m^3/m^2/h$
R	ideal gas constant, m^3 Pa/kmol/K
r	chemical reaction rate, kmol/m^3/s
T	absolute temperature, K
T_{roll}	rolling period, s
V	gas flow rate, m/s
V_0	nominal maximum rolling velocity, °/s
V_{roll}	rolling velocity, °/s
y	mole fraction of CO_2
y^*	equilibrium mole fraction of CO_2
z	packing height, m

Greek letters

ρ	density, kg/m^3
μ	viscosity, Pa.s

Subscripts

G	gas phase
L	liquid phase

using liquid collectors located at different positions below the column (Tanner et al., 1996). The effects of the liquid load, packing height, and packing type on the liquid distribution in tilted states were also investigated with this method, and the real-time cumulative volume of the collectors in different positions was recorded during roll motion with an amplitude of 5° and a period of 35 s (Waldie et al., 2003). The impact of tilt and roll motion on the liquid distribution in the packing column has also been discussed from a similar liquid-distribution experiment (Weiss et al., 2014).

Using gamma-ray tomography, (Fourati et al., 2012) measured the liquid distribution in a vertical column with the M250X structured packing. It was found that the liquid-spread factor of the structured packing was not affected by either the liquid or gas flow rates or by the liquid viscosity. These results indicate that the liquid dispersion phenomenon is only associated with the packing geometry. In another study using the electrical resistance tomography method, the influences of the liquid load, gas flow rate, liquid surface tension, and viscosity on the liquid maldistribution were investigated under tilt and roll motion (Son et al., 2017). The results showed that reducing either the liquid surface tension or liquid viscosity increased the liquid-maldistribution factor.

Several other simulation-based studies have also investigated the liquid flow pattern in vertical and rolling packing columns. The gas-liquid flow in a structured-packing column was discussed and the governing equations, including the porous resistance of the gas and liquid, gas-liquid momentum exchange, and dispersion forces were summarized (Fourati et al., 2013). The liquid distribution was simulated by the Fluent software package in a two-dimensional porous zone, and the liquid-spread coefficient of the M250X structured packing was found to be 0.0074 m. A three-dimensional geometric model of a column with the M500X structured packing was presented based on these governing equations (Pham et al., 2015a). The liquid hold-up and pressure drop were simulated via adjusting the Ergun coefficients from experimental data, and the mass transfer process in a monoethanolamine (MEA) – carbon dioxide (CO_2) system was modeled. Further, the effects of tilt and roll motion were simulated (Pham et al., 2015b): the results showed that both tilt and roll motion reduced CO_2 absorption. More recently, a model of the liquid-distribution mechanism for offshore conditions was proposed based on a liquid-split algorithm (Son et al., 2016). The parameters of the algorithm were adjusted according to experimental data, and the effect of the column dimensions on the liquid distribution was discussed. In these studies, the liquid distribution in tilted and rolling packing columns has been partially investigated via experimental and simulation-based approaches. However, the available literature concerning the mass transfer performance in rolling packing columns remains limited.

At present, amine-based solvent absorption has become the most mature technology for CO_2 capture. Several investigations with respect to amine-based absorbents have been recently performed. For example, (Liu et al., 2017a, 2017b) analyzed the heat and kinetics of CO_2 solubility and absorption into a 1-dimethylamino-2-propanol (1DEA2P) solution. It was found that 1DEA2P exhibited superior performance than conventional amines. (Gao et al., 2017) investigated the mass transfer performance of CO_2 absorption in blended *N,N*-diethylethanolamine (DEEA)/ethanolamine (MEA) solutions. The results showed that the liquid flow rate, liquid feed temperature, lean CO_2 load, and CO_2 partial pressure significantly influenced the mass transfer performance. In addition, the regeneration of a rich CO_2-loaded MEA solvent with two catalysts was studied (Zhang et al., 2017). In this case, the results indicated that the addition of solid acid catalysts into amine solutions could reduce the heat duty for CO_2 desorption.

Although many studies have focused on the performance of CO_2 absorption using amine-based solvents, air-NaOH systems can still be utilized to investigate the mass transfer performance of CO_2 absorption, particularly for calculating the mass-transfer area (Tsai et al., 2008, 2011; Yang et al., 2015; Wang et al., 2016). Under roll motion, the gas-liquid contact could deviate from the conditions in vertical states, resulting in a relative change in the mass-transfer area. Hence, the present study utilized an air-NaOH system to investigate the influence of roll motion on the mass transfer performance via the mass-transfer area using both laboratory- and pilot-scale structured packing columns. Under six sea states of roll motion, the effects of the liquid load, gas flow rate, and NaOH concentration were investigated. Moreover, three different types of structured packings were tested in the pilot-scale column. A nominal maximum rolling velocity was proposed in this study, and a comparison between roll motion and tilt was made.