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Liquid distribution model based on a volume cell for a column with structured packing under permanent tilt and roll motions

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HIGHLIGHTS

- An improved liquid distribution model under offshore conditions was proposed.
- Proposed model can describe liquid distribution in a different packed column.
- Effect of packing material on liquid distribution was experimentally investigated.

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ABSTRACT

An improved liquid distribution model based on a volume cell (LDMvc) was proposed to predict the liquid load distribution in a packed column under offshore conditions. The LDMvc contained four tuning parameters. The LDMvc is an improvement of the existing intersection-based LDM since the number of model tuning parameters is reduced to four through a sophisticated flow split algorithm, and a gas flow distribution model can be associated with the LDMvc. Two experimental columns with inner diameters of 0.133 m and 0.4 m were packed with Mellapak 500X-like elements for a 1.4 m bed height and Mellapak 250X-like elements for a 4 m bed height, respectively. The 4 m bed height column was built on a sloshing machine to simulate ship movement. The liquid distribution inside the columns was measured using an electrical resistance tomography (ERT) system. The offshore conditions were a permanent tilt ranging from 2 to 6° and a roll motion with three amplitude-period pairs. The LDMvc, after tuning with the experimental data, reliably predicted the liquid load distribution in the packed columns under different tilts and roll motions.

1. Introduction

Increased attention has been given to floating liquefied natural gas (FLNG) technology to produce natural gas from stranded offshore gas wells and overcome the problem of depletion of onshore gas wells coupled with the continuing growth in the global LNG demand (Cullinane et al., 2011; Shane and Considerations, 2015; Ahmad and Floating, 2014; Weiss, 2014; Gauthier and Determine, 2016; Won, 2014). The separation columns in the FLNG plants must be designed so that the performance degradation under the ship motions is as low as possible. Among the columns with structured packing, random packing, and tray column, structured packing columns are commonly used for the offshore column application.

Although a large amount of experimental results and operational experiences have been reported for onshore packed columns (Fu, 2013; Aferka, 2011; Bishnoi and Rochelle, 2000; Rochelle, 2009; Rochelle, 2011), the hydrodynamic and mass transfer phenomena inside the packed column are difficult to predict, and the packed column design has a larger uncertainty than that of other unit operations. Studies based on mechanistic models (Nawrocki et al., 1991; Aroonwilas and Tontiwachwuthikul, 2000; Qiu et al., 2003; Brunazzin and Paglianti, 1997; Aroonwilas, 2003) and computational fluid dynamic models (Yin, 2002; Raynal and Royon-Lebeaud, 2007; Atta et al., 2007) have been conducted in addition to experiments (White, 2010; Waldie et al., 2004) to understand the liquid distribution inside the packed column.

Liquid distribution becomes uneven in packed columns on a floating platform. The liquid distribution inside a packed column loses symmetry, producing a complex shape under the ship's movement. However, very few experiments have so far been

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Nomenclature

Abbreviations

C2L	conductivity to the liquid load
ERT	electrical resistance tomography
EIDORS	electrical impedance and diffuse optical tomography reconstruction
FLNG	floating liquefied natural gas
ID	inner diameter
LDM	liquid distribution model
LCM	liquid collection method
PP	polypropylene
SS	stainless steel

Parameters and variables

L	liquid load (m^3/m^2 hr)
$\bar{L}$	average liquid load (m^3/m^2 hr)
L^{LDMvc}	liquid load calculated from the *LDMvc* (m^3/m^2 hr)
N	number of the discretized intervals along the tilt axis
M_f	maldistribution factor
b	coefficient of proportionality in Eq. (3)
c	adjustable parameters in Eq. (2)
f	perforation factor (–)
f_w	wall flow factor (are consistent with the experimental liquid distribution data measured in packed columns with different)
f_{wt}	additional wall tilt factor (are consistent with the experimental liquid distribution data measured in packed columns with different)
q	liquid flow rate

Greek letters

Θ	adjustable parameter vector to be estimated
α	split factor within the packing path streams
θ	permanent tilt angle (degrees)

Sub- and superscripts

B	backward
F	forward
T	tilt alignment condition
V	vertical alignment condition
even	even packing
odd	odd packing
pp	polypropylene
ss	stainless steel
tot	total
w	wall
wt	wall with tilt alignment

reported, mostly using the liquid collection method (LCM) and not looking inside the column. Recently, Son et al. (Son, 2017) developed a method to measure the liquid load distribution inside a structured packing column using ERT (electrical resistance tomography) and reported measured liquid distribution in a packed column with an inner diameter of 0.4 m under different tilts and roll motions.

The packing pattern of a structured packing bed is regular and repetitive. Therefore, the formation and division of liquid rivulets over the packing surface can be described. Nawrocki et al. (Nawrocki et al., 1991) was the first to propose a systematic liquid distribution model (LDM) based on this idea. They considered that a liquid rivulet was split into two downward rivulets at an intersection created by the contact of two corrugated sheets of structured packing. By applying a mechanistic liquid split algorithm at each intersection, the liquid rivulet distribution could be obtained over the three-dimensional region. Aroonwilas and Tontiwachwuthikul (Aroonwilas and Tontiwachwuthikul, 2000; Aroonwilas, 2003) improved Nawrocki et al.'s model (Nawrocki et al., 1991) by introducing more split paths, and Qiu et al. (Qiu et al., 2003) added wall and perforation flows to the previous models. Recently, Son et al. (Son et al., 2016) improved the existing models and applied their LDM to a column under offshore conditions. They fit their LDM to the offshore flow distribution data obtained by Waldie et al. (Waldie et al., 2004) under different tilt conditions. Using the tuned LDM, they computed inferred liquid distributions inside the column under various tilt angles and roll motions.

In this study, an improved liquid distribution model based on a volume cell (LDMvc) was proposed for improving the prediction of the liquid distribution in a structured packing column under offshore conditions. Unlike the intersection-based LDM, the LDMvc divides the entire volume of a packed bed into repeated regular volume cells formed by two opposing corrugate sheets and assumes that the liquid flow from an upper layer volume cell is split into the connected volume cells in the lower layer. The LDMvc has only four tuning parameters by a flow split algorithm and provides a convenient platform for a gas flow distribution model to be developed. Two experimental columns with inner diameters (IDs) of 0.133 m and 0.4 m, packed with Mellapak 500X-like elements for 1.4 m and Mellapak 250X-like elements for 4 m, respectively, were built on a sloshing machine (for the 0.4-m ID column) that simulated ship movements. The liquid distribution inside the columns was measured using electrical resistance tomography (ERT). The offshore conditions were set as a permanent tilt ranging from 2° to 6° and a roll motion with three amplitude-period pairs. The experimental data were collected by varying the liquid load, tilt angle, and roll motion conditions of both columns and were used for model tuning and validation.

2. Model description

2.1. Liquid distribution model based on the intersections (LDMi)

Current LDMs for structured packings were developed based on the assumption that the liquid streams flowing over the packing surface were collected and redistributed at the corrugated packing intersections (Nawrocki et al., 1991; Aroonwilas and Tontiwachwuthikul, 2000; Qiu et al., 2003; Aroonwilas, 2003). A network of intersections can be constructed for a packed bed using the bed dimensions, packing method, and packing geometry, such as the crimp height and channel base. A liquid split algorithm was proposed as an essential part of the LDM. If the number and positions of the intersections in a 3D coordinate are established, the adjacent intersections of any arbitrary intersection can be identified. Then, the possible flow paths of the liquid from the upper to lower intersections can be defined. Fig. 1 shows two representative liquid split algorithms of the LDM in the literature (Aroonwilas and Tontiwachwuthikul, 2000; Qiu et al., 2003). Fig. 1(a) shows the split paths proposed by Aroonwilas and Tontiwachwuthikul, and Fig. 1(b) shows an LDM proposed by Qiu et al. in a 2D plane. (Son et al., 2016) presented an LDM for offshore liquid distribution by adding a vertical downward flow from an intersection and a split algorithm between the column wall and an adjacent interac-