Chemical Engineering Science 166 (2017) 168–180

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Experimental investigation of liquid distribution in a packed column with structured packing under permanent tilt and roll motions using electrical resistance tomography

Yongho Son [a], Gwagin Kim [a], Sangyoon Lee [a], Huiyong Kim [a], Kwangjoon Min [b,c], Kwang Soon Lee [a,*]

[a] Department of Chemical & Biomolecular Engineering, Sogang University, 35, Baekbeom-ro, Mapo-gu, Seoul 121-742, Republic of Korea
[b] Plant Basic Engineering Team, GS Engineering & Construction, 33, Jong-ro, Jongno-gu, Seoul 110-130, Republic of Korea
[c] Department of Chemical Engineering, Hanyang University, Wangsimni-ro 222, Seongdong-gu, Seoul 133-791, Republic of Korea

HIGHLIGHTS

- Liquid distributions in a packed column under including permanent tilts and roll motions, gas factor, and liquid properties were measured using ERT-EIDORS method.
- Resulting liquid maldistributions were quantified and compared using the maldistribution factor.

ARTICLE INFO

Article history:
Received 14 January 2017
Received in revised form 15 March 2017
Accepted 17 March 2017
Available online 19 March 2017

Keywords:
Liquid distribution
Electrical Resistance Tomography (ERT)
EIDORS
Offshore conditions
Absorption column
Structured packing
FPSO
Maldistribution

ABSTRACT

Liquid distribution in a pilot-scale packed column under offshore conditions was experimentally measured and investigated. An experimental column with an inner diameter of 0.4 m and a packed height of 4 m was built on a sloshing machine that can simulate offshore conditions. A method of electrical resistance tomography combined with electrical impedance and diffuse optical tomography reconstruction software (ERT-EIDORS) was proposed and used to simultaneously measure the liquid distribution at multiple axial positions in the packed column. Validation experiments for the reliability of the ERT-EIDORS method were conducted first. Then the effects of the liquid load, gas factor, and liquid properties on the liquid distribution were investigated under various offshore conditions using the proposed method. For offshore conditions, three permanent tilt angles and four roll motions were considered. The results are presented in terms of the maldistribution factor in most cases and also the 3D plot for selected demonstration cases.

1. Introduction

An FPSO (floating production storage and offloading) plant is a floating production system that receives crude oil from a subsea reservoir, produces various oil products, and stores those products until they are offloaded onto a tanker. FPSO plants are preferred for small offshore oil reservoirs, which are otherwise not economical to develop because they are mobile, easy to install, and do not require pipeline infrastructure. A related floating unit is the FLNG (floating liquefied natural gas) plant dedicated to natural gas production and processing. Many separation columns are contained in an FLNG plant, including the acid gas removal unit (AGRU) that separates CO_2 and H_2S from well gas or product gas. Although various types of separation columns have been designed and used on onshore natural gas processing platforms for a long time, their use in offshore conditions introduces new challenges caused by the ship motions of the FLNG, such as permanent tilt and roll motions. The ship motions acting on the separation columns deteriorate the separation performance (Kobayashi et al., 1999) and must be considered in the early stages of design. The ship motions prohibit the use of tray columns and allow only packed columns with mostly structured packing to minimize the offshore effect on a column. However, even in a packed column, LMD (liquid maldistribution) caused by the ship motions is unavoidable, and a firm understanding of the maldistribution phenomenon and its consequences is required for design of an offshore column.

* Corresponding author.
E-mail address: kslee@sogang.ac.kr (K.S. Lee).

http://dx.doi.org/10.1016/j.ces.2017.03.044
0009-2509/© 2017 Published by Elsevier Ltd.

Nomenclature

Abbreviations

AGRU	Acid Gas Removal Unit
C2L	Conductivity To Liquid load
DAS	Data Acquisition System
ERT	Electrical Resistance Tomography
EIDORS	Electrical Impedance and Diffuse Optical tomography ReconStruction
FEM	Finite Element Method
FLNG	Floating Liquefied Natural Gas
FPSO	Floating Production Storage Offloading
LCM	Liquid Collection Method
LMD	Liquid MalDistribution
MDF	MalDistribution Factor
PDE	Partial Differential Equation
PP	PolyPropylene
SS	Stainless Steel

Parameters and variables

ΔA_i	area of pixel i
C	EIDORS conductivity (mS/cm)
C_m	maximum conductivity (mS/cm)
H/D	packed height from the column top over column diameter
L_m	maximum liquid load (m^3/m^2 h)
M_f	MDF
N	number of total pixels
Q	total volumetric flow rate (m^3/h)
$Q(i,j,k)$	local liquid load measured at $x = i$, $y = j$, and $z = k$ (m^3/m^2 h)
$Q_{mean}(k)$	average liquid load at a given axial position ($z = k$)
S	liquid surface tension (mN/m)
T	temperature (°C)
V	liquid viscosity (cp)
W	water

Greek letters

α	tuning factor in C2L function
θ	permanent tilt angle (degrees)

Limited published studies are available on the liquid distribution inside a packed column under offshore conditions. Tanner et al. (1996) performed experiments in a column using random packing with a diameter of 0.4 m and a bed height of 2.5 m to measure the liquid distributions under offshore conditions. These researchers measured the liquid distributions at three different packed heights (0.6, 1.3, and 2.5 m) under two tilt angles (3° and 5°) with no gas flow. Waldie et al. (2004) conducted experiments in a column using structured packing with a diameter of 1 m and a bed height of 4 m. A tilt of 4° was considered as the offshore condition, and the effect of surface tension on the liquid distribution was investigated as well. White et al. (2010) measured the liquid distribution under three different offshore conditions (tilt of 1° and 4° and roll motion with a period of 35 s and an amplitude of 3°). Unlike the other studies, the effects of the type of structured packing were reported. Weiss et al. (2014) conducted experiments in two columns with inner diameters of 0.6 m and 1 m and measured the liquid distribution under tilt of 3° and 5° and roll motion with a period of 30 s and an amplitude of 3°.

All of the studies reviewed above used the liquid collection method (LCM) in which the liquid load distribution across the cross-section is directly measured below the bed bottom using multiple divided sumps. Although the LCM has historically been used, this method poses experimental difficulties and suffers from certain limitations. The effect of the bed height can be explored only by replacing the column with a new one with a different bed height, and the resolution of the distribution measurement is limited.

Existing studies have not adequately investigated how liquid properties such as surface tension and viscosity affect the liquid distribution under offshore conditions. To the best of our knowledge, the effects of viscosity have not been reported in the literature, although a few studies have reported on the effects of surface tension. The influence of gas flow on the liquid load distribution under offshore conditions has not been reported either. It can be inferred that gas flow channeling becomes severer in a packed column under offshore conditions, and this gas flow channeling distorts the liquid distribution to a greater extent than in the case with no gas flow.

In this study, a comprehensive experimental study on the liquid distribution in a packed column was performed under offshore conditions using electrical resistance tomography (ERT). The experiments were performed in a pilot-scale packed column with an inner diameter of 0.4 m and a bed height of 4 m. To noninvasively measure and effectively estimate the liquid flow distribution inside the column, a method of ERT with electrical impedance and diffuse optical tomography reconstruction software (ERT-EIDORS) was applied. To demonstrate the reliability of the ERT-EIDORS method for measuring liquid distribution in a packed column, validation experiments were conducted, and the results were presented. Using the experimentally measured liquid distribution, the effects of the liquid load, gas factor, and liquid properties (including viscosity and surface tension) on the liquid distribution under various offshore conditions were discussed and quantified using the maldistribution factor (MDF).

2. Experimental section

2.1. Electrical resistance tomography with EIDORS (ERT-EIDORS)

The ERT system used in this research is a model P2+ from ITS Ltd., UK, which consists of ERT spools, a data acquisition system (DAS), and reconstruction software known as IT2+. Fig. 1(a) shows an ERT spool around which 16 electrodes are installed. Current injection is applied to an adjacent pair of electrodes, and the induced voltages are measured at the remaining electrodes according to a predetermined protocol, which is known as an adjacent measurement strategy. Table 1 describes details of the ERT sensor configuration and conditions. This information is required for tomogram reconstruction.

The IT2+ software embedded in the P2+ offers a two-dimensional (2D) conductivity tomogram, as shown in Fig. 1(b), using a reconstruction algorithm based on linear back-projection from the boundary voltage measurements (Wu et al., 2005; Tapp et al., 2003; Dickin and Wang, 1996; Yang and Peng, 2002). However, the 2D tomogram does not correctly represent the true 2D conductivity distribution because the electric current flows through the liquid distributed over a 3D space in the column, and the electrostatic field is generated accordingly. The resulting 2D tomogram is unavoidably affected by the 3D liquid distribution.(Lionheart, 1999; Vauhkonen et al., 1999) ERT has been used primarily in applications in which a conductive continuous phase is mixed with a non-conductive secondary phase. However, a