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

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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.

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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.

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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 CO₂ and H₂S 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 optimize 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.
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 0.4 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...
ERT sensor configuration and conditions.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of electrodes in a plane</td>
<td>16</td>
</tr>
<tr>
<td>Measurement protocol</td>
<td>Adjacent measurement strategy</td>
</tr>
<tr>
<td>Installed configuration of electrodes</td>
<td>Circular</td>
</tr>
<tr>
<td>Injected current (mA)</td>
<td>12.7</td>
</tr>
<tr>
<td>Electode size (width x height in m)</td>
<td>0.040 x 0.055</td>
</tr>
</tbody>
</table>

The packed column is filled with a large portion of non-conductive gas and at most 10–15% of conductive liquid. Therefore, to appropriately apply ERT to measure the liquid distribution in a packed column, a distinctive method should be used. In this study, EIDORS and a proprietary conductivity-to-liquid load (C2L) function with ERT were applied. EIDORS is an open source software suite for 3D image reconstruction in electrical impedance tomography and diffuse optical tomography (Adler and Lionheart, 2006). EIDORS can deliver a highly accurate conductivity tomogram with a reconstruction algorithm that is quite advanced compared with the IT+ reconstruction software, and the C2L function is able to map the conductivity tomogram to a corresponding liquid load distribution through an optimization procedure. Details of EIDORS and the C2L function are described in a later section.

2.2. Experimental apparatus

Fig. 2 shows the experimental packed column system. The column has an inner diameter of 0.4 m and a total height of 6.5 m with a bed height of 4 m composed of twenty TSP-250X (similar to Mellapak 250X) packing elements measuring 0.2 m in height supplied by TPT Pacific, Korea. Eleven of the packing elements consist of polypropylene (PP), whereas the remaining nine are 316-stainless steel (SS). What we desire was to obtain operation data with all metal packing, which is the industrial practice in most cases. The mixed use of PP and SS packings was inevitable choice since ERT cannot be used with metal packing because the high conductivity of metal interferes with the voltage measurement. PP packing elements were located in the ERT spool sections according to the manufacturer’s guidance. At the cross-section where two packing elements are touched, the liquid accumulation can be slightly higher than other cross-sections (Brunazzi et al., 2001; Aferka and et al., 2011).

Four ERT spools were placed as indicated in Fig. 2. The height center of all electrodes, where the 2D tomogram is computed by EIDORS, is located 2.5 cm above the position where two PP packing elements are touched. Geometry data for TSP 250X and Mellapak 250X are compared in Table 2 based on Fig. 3.

Table 3 lists the experimental conditions. The offshore condition was reflected in terms of the permanent tilt at three different angles and roll motions at four degree/period combinations. The liquid load and gas factor were varied over three and five different values, respectively.

The viscosity and surface tension of water were modified using a viscosity enhancer (Polyox® WSR-N750, Dow), a surfactant (Tergitol® Type NP-7.5), and an anti-foaming agent (XIAMETER® ACP-3183). To measure the surface tension of water after adding anti-foamer and/or surfactant, the Du Noüy ring method (static) was employed.

Table 4 shows the amounts of the additives and the resulting values of viscosity and surface tension. Because the target process to be investigated for our study is the AGRU, these

![Fig. 1. (a) ERT spool with multiple electrodes and adjacent measurement strategy, (b) 2D conductivity tomogram created by the ERT system.](image-url)
values coarsely cover the properties of the activated-MDEA solution (Paul and Mandal, 2006a; Paul and Mandal, 2006b), which is one of the most widely adopted solvents in the AGRU for natural gas treatment. Solutions with modified properties were designated using simple code names listed in the Description column of Table 4.

### 3. Data processing method

#### 3.1. EIDORS

The 3D electrostatic field inside the bed created by the current injection is described by an elliptic partial differential equation (PDE). EIDORS searches for a 3D conductivity distribution by solving the forward and inverse problems in a back-and-forth manner.

The forward problem consists of solving the elliptic PDE with a known conductivity distribution and injected current and yields the boundary voltage values at the periphery of the space under consideration where the electrodes are installed. Conversely, the inverse problem consists of finding the conductivity distribution using the boundary voltage measurements and the injected current. Because the problem is generally nonlinear and ill posed, regularization and iterative methods are used in the solution. In this study, the forward problem was solved using the finite

---

**Table 2**

Packing geometry of TSP-250X and Mellapak 250X.

<table>
<thead>
<tr>
<th></th>
<th>TSP250X (SS)</th>
<th>TSP250X (PP)</th>
<th>Mellapak 250X (SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel side (mm)</td>
<td>19</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>Channel base (mm)</td>
<td>30</td>
<td>36</td>
<td>25</td>
</tr>
<tr>
<td>Crimp height (mm)</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Corrugation angle (°)</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Parameter sources</td>
<td>Measured</td>
<td>Measured</td>
<td>Suess and Spiegel (1992)</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Schematic diagram of the experimental packed column.

**Fig. 3.** Packing geometry of a corrugated sheet.
element method (FEM) with 3D mesh elements for the bed, as shown in Fig. 6, and the inverse problem was handled using the Gauss-Newton method. The reconstructed 2D conductivity tomogram of a cross-section at an ERT plane was obtained as a discretized circle with 332 equal-area pixels of which the spatial resolution is $0.0195 \text{ mm}^2$. Additional details on the reconstruction algorithm and EIDORS can be found elsewhere (Adler and Lionheart, 2006; Polydorides, 2002; Grychtol and Adler, 2013; Polydorides and Lionheart, 2002).

EIDORS is more rigorous than the linear back-projection algorithm in IT2+, which includes linear approximations, and can offer more accurate results. In Fig. 6, meshes were allotted densely around the ERT planes and coarsely in the mid-regions between the ERT planes because the electric current can flow within a ±20 cm region around an ERT plane. Virtually no electric current flows outside this region.

Reconstruction of the conductivity tomogram is based on a linearized model and is performed using the difference of the voltage measurement between the reference and operational states. Choice of the reference state can be arbitrary, but accuracy of the

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Table 3: Main experimental conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Mean liquid load ($m^3/m^2/h$)</td>
<td>14, 32, 50</td>
</tr>
<tr>
<td>Gas factor ($Pa^{a/b}$)</td>
<td>0, 1, 2, 3, 3.45</td>
</tr>
<tr>
<td>Permanent tilt ($\theta$, degrees)</td>
<td>0, 2, 4, 6</td>
</tr>
<tr>
<td>Roll motion (D, degree/period)</td>
<td>4/15 (D1), 4/30 (D2), 8/15 (D3), 8/30 (D4)</td>
</tr>
<tr>
<td>Viscosity ($\nu$, cP)$^a$</td>
<td>1 ($V_1$, 5 ($V_5$), 10 ($V_{10}$)</td>
</tr>
<tr>
<td>Surface tension ($S$, mN/m)$^a$</td>
<td>38 ($S_{38}$), 50 ($S_{50}$), 72 ($S_{72}$)</td>
</tr>
<tr>
<td>Liquid distribution measurement positions (packed height from the top (H), m)</td>
<td>0.2, 1.3, 2.5, 3.7</td>
</tr>
</tbody>
</table>

Table 4: Amounts of additives and true values of viscosity and surface tension tested in the experiments.

<table>
<thead>
<tr>
<th>Description</th>
<th>Amounts of additives</th>
<th>Viscosity at 28 °C (cP)</th>
<th>Surface tension at 28 °C (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W ($V_1$, $S_{70}$)</td>
<td>–</td>
<td>0.86</td>
<td>72</td>
</tr>
<tr>
<td>S50</td>
<td>Anti-foamer 100 ppmv</td>
<td>0.84</td>
<td>49.8</td>
</tr>
<tr>
<td>S38</td>
<td>Anti-foamer 100 ppmv</td>
<td>0.84</td>
<td>38</td>
</tr>
<tr>
<td>V5</td>
<td>Viscosity enhancer 0.70 wt.%</td>
<td>4.92</td>
<td>50.7</td>
</tr>
<tr>
<td>V10</td>
<td>Viscosity enhancer 0.98 wt.%</td>
<td>10.8</td>
<td>50.2</td>
</tr>
</tbody>
</table>

Column operating temperature and pressure: 28 °C and 1 bara.

More accurate values are presented in Table 4.

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Fig. 4. Pictures of employed (a) plastic and (b) metal packing elements with wall wipers.

Fig. 5. (a) Picture and (b) sketch of the liquid distributor with drip points and dimensions.

(a) (b)
linearized model is enhanced by reducing the difference between the two states. In this study, the state corresponding to liquid load of 14 m$^3$/m$^2$ h of water under the vertical condition was taken as the reference state for tomogram reconstruction for all other conditions including liquid load, property-modified water, tilt, and rolling. For analysis of the case for the liquid load of 14 m$^3$/m$^2$ h under the vertical condition, a wet packing state with no liquid flow, which can be attained by stopping the liquid flow after normal operation, was taken as the reference state.

The reconstructed conductivity through the procedure above is in fact the conductivity difference between measured and reference states. Conversion of this value to absolute flow rate is carried out using the C2L function described in the subsequent section.

3.2. Conductivity to liquid load (C2L) transformation

It is difficult to theoretically relate the conductivity tomogram to a liquid load distribution because the local conductivity of the bed is affected by many factors such as liquid conductivity, liquid holdup, and 3D geometry of the liquid flow at the concerned location. To cope with this problem, the relationship between the measured conductivity and liquid load was established empirically and is referred to as the C2L function. To construct the C2L function, liquid load values under various conditions including tilt were plotted against the corresponding EIDORS conductivities in Fig. 7(a). Liquid load data in Fig. 7(a) are the values measured in each section of the sump using the LCM. The x-axis label of Fig. 7, Local EIDORS conductivity, refers to the averaged value of conductivity

![Fig. 6. Meshing of the FEM in EIDORS for the experimental packed column.](image)

![Fig. 7. (a) Empirical relationship between the EIDORS conductivity and liquid load (LCM experimental data), (b) normalized plots of the data in (a), and (c) proposed C2L function with two adjustable parameters, $(L_m, \alpha)$.](image)
this, respectively, at position $L_m$ and $L_a$.

In this section of the sump. The liquid load increases exponentially with maximum conductivity and the corresponding maximum liquid load was 50 m$^3$/m$^2$ h, and there was no gas flow. The 2D distribution was obtained with a resolution of 20 pixels, and the MDF $M_f(y)$, which indicates the degree of non-uniformity of the liquid load distribution as a single value, was calculated as follows:

$$M_f(y) = \frac{1}{\Delta y} \frac{1}{A} \sum_{x=0}^{A-1} \left[ \frac{L_x}{L_{y}} - 1 \right]$$

where $L_x$ and $A_x$ denote the index and area, respectively, of the pixel over the cross-section of the bed; $A$ and $L$ are the cross-sectional area and the average liquid load over the cross-section, respectively.

In summary, the block diagram of data processing for ERT-EIDORS method is shown in Fig. 8. The first step is to experimentally measure the boundary voltage using ERT (step A). After obtaining the boundary voltage measurements, the voltage data are reconstructed to a conductivity tomogram through EIDORS (step B). Finally, the 2D conductivity tomogram is processed to a 2D liquid load distribution using the C2L function with estimated parameters such that the estimated total liquid load is equal to the experimental total liquid load (step C).

4. Results and discussion

4.1. ERT-EIDORS validation results

Validation experiments for the reliability of the ERT-EIDORS method were performed by comparing the estimated liquid loads using the ERT-EIDORS-C2L with the values measured using the LCM. After averaging over the area of each liquid collection sector, estimates of the liquid load distribution over the lowest ERT plane were compared with the values measured using the LCM. The experiments were performed for 36 conditions, as shown in Table 5. Four measurements were collected from each experimental run, and hence a total of 144 data points were obtained and compared in the parity plot, as shown in Fig. 9.

The average relative error with respect to the measured values was calculated as 7.2%. The relative error is considered to be small enough to establish the validity and reliability of the ERT-EIDORS method.

4.2. Liquid distribution under permanent tilt condition

4.2.1. Effects of packed height on liquid distribution in the vertical and 2° tilt cases

Figs. 10 and 11 show the effects of the packed height on the liquid load distribution in the vertical column (Fig. 10) and in a tilted column with a tilt angle of 2° (Fig. 11). In both cases, the inlet liquid load was 50 m$^3$/m$^2$ h, and there was no gas flow. The 2D distribution was obtained with a resolution of $20 \times 20$ pixels, and the averaged 1D distribution was obtained by averaging the liquid load along the x-axis at each y-point considering that tilt direction is the y-axis. Finally, the MDF $M_f(k)$, which indicates the degree of non-uniformity of the liquid load distribution as a single value, was calculated as follows (Aroonwilas and Tontiwachwuthikul, 2000):

$$M_f(k) = \frac{1}{\Delta y} \frac{1}{A} \sum_{x=0}^{A-1} \left[ \frac{L_x}{L_{y}} - 1 \right]$$

Table 5

<table>
<thead>
<tr>
<th>Label</th>
<th>Liquid properties</th>
<th>Tilt angle (°)</th>
<th>Total liquid load (m$^3$/m$^2$h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 W</td>
<td>0, 2, 4</td>
<td>14, 50</td>
<td></td>
</tr>
<tr>
<td>2 W</td>
<td>0</td>
<td>10 (2), 20, 30 (2), 40, 50 (2), 60, 70 (2)</td>
<td></td>
</tr>
<tr>
<td>3 S50</td>
<td>0</td>
<td>20, 30, 40, 50, 60, 70</td>
<td></td>
</tr>
<tr>
<td>4 S38</td>
<td>0</td>
<td>20, 30 (2), 40, 50 (2), 60, 70 (2)</td>
<td></td>
</tr>
<tr>
<td>5 V5</td>
<td>0</td>
<td>10, 30, 50, 70</td>
<td></td>
</tr>
</tbody>
</table>

(): number of repetition.
Fig. 10. Liquid distribution for water measured at different packed heights in the vertical column under a liquid load of 50 m³/m² h and zero gas factor. (a) 2D liquid load distribution, (b) averaged 1D liquid load distribution along the tilt axis (y-axis), and (c) MDF at four packed heights.

Fig. 11. Liquid distribution for water measured at four packed heights under permanent tilt, liquid load of 50 m³/m² h, zero gas factor = 0, and tilt angle of 2°. (a) 2D liquid load distribution, (b) averaged 1D liquid load distribution along the tilt axis (y-axis), and (c) MDF at four packed heights.
where \( L(i,j,k) \) is the local liquid load measured at \( x = i, y = j, \) and \( z = k, \) and \( L_{\text{mean}}(k) \) is the average liquid load at a given axial position. In this study, \( N = 20 \) or equivalently, the 2D distribution was represented using \( 20 \times 20 \) pixels (332 non-zero pixels).

It is observed from Fig. 10 that a non-negligible liquid load maldistribution occurs even in the vertical column. Particularly, the 2D distribution at \( H = 0.2 \) m appears slightly inclined compared with the other three. After averaging over the \( x \)-axis, the 1D distribution has a linearly inclined profile initially at \( H = 0.2 \) m but shows similar concave profiles at the other three axial positions. Interestingly, the liquid load in the central region is higher than that in the wall region, which means that the natural tendency
for the wall flow to increase in the packed column is effectively suppressed by the wall wiper of the structure packing. In Fig. 10 (c), the MDFs calculated at all four heights are shown. On the whole, the liquid distribution tends to be more uniform as it moves further downward along the structured packing in the vertical condition. Note that reproducibility of the detailed distributions is not high in this type of experiment, and presenting the result as a simple lumped factor is quite useful.

Fig. 11 summarizes the results for the column with a $2^\circ$ tilt angle considered in this study. The slant of the liquid load distribution along the tilt axis ($y$-axis) is intensified with the increase in $H$ from the top to the bottom. At $H = 0.2$ m, the 1D distribution in Fig. 11(b) appears somewhat asymmetric to the reverse direction of the acting tilt motion. As $H$ increases, however, the maldistribution became severer as can be anticipated. At $H = 3.7$ m, liquid flow channeling became highly intense such that the liquid load near $y = 1$ was more than 4 times larger than that near $y = 21$. This result shows that even a tilt angle $2^\circ$ is detrimental to the liquid distribution. MDF in Fig. 11 (c) shows the sharp slope with respect to $H$. It is interesting to note that the slope is gradually increased from $H = 0.2$ m to $H = 3.7$ m, revealing that the effect of the packed height on liquid distribution becomes stronger as the packed height increases.
followed by the sinusoid at $H = 1.3$ m, and so forth. The acceleration force under the roll motion is proportional to the distance from the center of gravity of the FPSO plant to the measurement point. Hence the liquid load at the highest measurement point exhibits the fastest response, followed by the next highest, and so forth.

Fig. 13(b) shows the MDFs calculated at four packed heights. Similar to the liquid load behavior observed in Fig. 13(a), these values also oscillate with respect to the measured time. The maximum value of the MDF at $H = 3.7$ m reaches approximately 0.8, whereas that under permanent tilt at $6^\circ$ is approximately 1.1. Recalling that the amplitude of the roll motion is $8^\circ$, this result signifies that the maldistribution is attenuated by the roll motion. To quantify the extent of maldistribution under the roll motion condition, the time-averaged MDF at cyclic steady state was also calculated, plotted, and compared with the tilt cases in Fig. 14(b). As under the tilt condition, the time-averaged MDF increases with increasing packed height. However, compared with the results under the tilt $6^\circ$ conditions, the time-averaged MDFs are all smaller. From these results, it is concluded that the attenuation effect of roll motion on liquid distribution is obvious.

4.4. Effects of gas factor

The effects of the gas factor on the liquid distribution at different packed heights and permanent tilt angles are presented in Fig. 15. The liquid load was fixed at 50 m$^3$/m$^2$ h. As shown in Fig. 15(a), the MDF at $H = 0.2$ m has small and nearly constant values regardless of the magnitude of the gas factor and tilt angle. At $H = 1.3$ m, the MDF at the gas factor of $3.5$ Pa$^{1/2}$ exhibits larger values at all tilt angles than the MDF at other values of the gas factor. At $H = 2.5$ m, $3$ Pa$^{1/2}$ together with $3.5$ Pa$^{1/2}$ produces larger MDF values, whereas the gas factors of $1$ and $2$ Pa$^{1/2}$ yield MDF values similar to those under a zero gas factor. Finally, at $H = 3.7$ m, the MDFs at all gas factors deviate from those at a zero gas factor.

To understand the effects of the gas factor on the liquid distribution under tilt conditions, the pressure drop depending on the gas factor and liquid load is plotted in Fig. 16, whereas the liquid load is fixed at 50 m$^3$/m$^2$ h. The pressure drop was measured only across the entire bed and not locally. In the vertical case, the loading occurs at gas factors between $3$ and $3.5$ Pa$^{1/2}$. In the tilt case, the pressure drop decreases as the tilt angle increases. The latter behavior is caused by increased channeling of gas flow and liquid flow, which is severer along the packed height from the top, as demonstrated in Fig. 11. At a high gas factor in a tilt case, the loading might occur in an upper region of the bed while flow channeling occurs in a bottom region of the bed.

![Fig. 16](image16.png)  
Fig. 16. Pressure drop measured in the experimental packed column at a liquid load of 50 m$^3$/m$^2$ h and water case under different gas factors and tilt angles.

![Fig. 17](image17.png)  
Fig. 17. Effects of (a) surface tension ($S72$, $S50$, and $S38$ with viscosity fixed at 0.84 cP) and (b) viscosity ($V1$, $V5$, and $V10$ with surface tension fixed at 50 mN/m) on the liquid distribution under a liquid load of 50 m$^3$/m$^2$ h and zero gas factor.
Based on the above observations, large MDFs at a gas factor of 3.5 Pa$^{1/2}$ in the vertical case are due to liquid loading. However, large MDFs under large tilt angles are primarily caused by channeling. Flow channeling is the dominant cause of the LMD in the lower region of the bed, but the LMD in the upper region of the bed can be attributed to liquid loading especially at large gas factors.

4.5. Effects of liquid properties

The effects of the surface tension and viscosity on the liquid distribution are summarized in Figs. 17(a) and 15(b), respectively. Detailed values of the properties used in the experiments are given in Table 4.

Waldie et al. (2004) reported a detrimental effect of surface tension on the liquid distribution under the permanent tilt condition. As shown in Fig. 17(a), reduction in the surface tension from 72 to 50 mN/m results in considerable increase in the MDF. This effect is intensified as the tilt angle increases and the bed height is decreased. At a tilt angle of 6°, the MDF at $H = 3.7$ m for SS0 is approximately 2.5 times larger than that for SS2 (water). When the surface tension was further reduced from 50 to 38 mN/m, however, the liquid distribution was somewhat improved, although it was still worse than for SS2. This observation was repeated in a series of verification experiments. Thus far, the reason for this non-linear behavior is still obscure.

The effect of the viscosity on the LMD under the permanent tilt condition is presented in Fig. 17(b). As anticipated from the viscosity property, the LMD is more intense as the liquid viscosity is decreased, but the relationship appears quite nonlinear. Except at certain points, the MDF for V5 has values similar to that for V1 regardless of the tilt angle and H. However, the MDF is significantly reduced for V10. This nonlinear behavior is quite noticeable as the nonlinear effect of the surface tension. We still do not understand the reason for this observation.

Many studies on understanding flow phenomenon in a packed column (McGlamery, 1988; Nicolaiewsky and Fair, 1999; Shetty and Cerro, 1995, 1997, 1998) have been performed using an approximation to a simple system such as an inclined plate. From these studies, it was concluded that the surface tension enhances the spreading capability of liquid, and the viscosity makes the spreading and thickness of liquid flow decrease and increase, respectively.

5. Conclusions

In this paper, the liquid distribution in a packed column with the inner diameter of 0.4 m and the packed height of 4 m under offshore conditions was investigated using the ERT-EIDORS method combined with the C2L function. The experimental packed column has the inner diameter of 0.4 m and the packed height of 4 m and is packed with twenty TSP-250X, which is similar to Mel-lapak 250X. The ERT-EIDORS method enables us to simultaneously measure the 2D conductivity tomogram in a packed column at multiple axial positions. The conductivity tomogram was converted to a 2D liquid load distribution using the C2L function. As the offshore conditions, the permanent tilt angle was varied from 0 to 6°, and the roll motion at four different conditions was considered. The average liquid load and the gas factor were varied from 14 to 50 m$^3$/m$^2$ h and from 0 to 3.5 Pa$^{0.5}$, respectively. To investigate the effect of liquid properties, experiments with other liquid properties in which the surface tension and viscosity were modified ranged from 72 to 38 mN/m and from 1 to 10 cP, respectively, were performed. Quantitative analysis for the considered effect was suggested in terms of the MDF.

The LMD was aggravated under the permanent tilt condition as the liquid flows downward and the tilt angle increases. Even at a tilt angle of 2°, three times more liquid flows through the inclined zone of the cross-section in the bottom section of the bed than in the top section of the bed (Fig. 11(a)). The LMD was affected more strongly by the tilt at low liquid load (14 m$^3$/m$^2$ h). However, the MDF obtained at a liquid load of 32 m$^3$/m$^2$ h was quite similar to that at 50 m$^3$/m$^2$ h.

Increments in both amplitude and period of the roll motion degrade the LMD, as can be inferred. The roll motion affects the LMD weakly compared with the permanent tilt of an angle that is the same as the maximum angle of the roll motion. This result is due to the mixing effect created by the motion. Roll motions with an amplitude angle of 8° and periods of 15 s and 30 s yielded values of the MDF similar to those produced by permanent tilts of 6° and 4°.

The LMD under tilt conditions causes gas flow maldistribution, which again exacerbates the liquid distribution. The LMD was observed to intensify as the gas factor is increased and the liquid flows downward. At a high gas factor, liquid loading can occur, which additionally increases the LMD, especially in the top section of the bed.

The effects of liquid properties such as surface tension and viscosity were also investigated for three different values of the surface tension and viscosity, respectively. Overall, a reduction in the surface tension was observed to increase the LMD. However, a nonlinear effect was observed, and the order of MDFs from largest to smallest was 50, 38, and 72 mN/m (see Table 4). We could not discover the reason for this phenomenon.

An increase in the viscosity reduced the LMD. However, the effect was obvious only when the viscosity is larger than 5 cP. The MDF values for 10 cP liquid were less than a half of those of the 1 and 5 cP liquids, whereas the latter two yielded similar values of the MDF. We have no appropriate explanation for this phenomenon either.

It should be noticed that the experimental results in this paper were obtained in a bed composed of mixed PP and SS packing elements. Column behaviors with pure SS or PP packing, if needed, have to be inferred from these results.

References


Tsai, R.E. et al., 2011. A dimensionless model for predicting the mass-transfer area of structured packing. AIChE J. 57 (5), 1173–1184.


Weiss, C. et al., 2014. How waves can significantly impact performance of amine unit installed on a FLNG? In: Offshore Technology Conference,


