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Marinization of Mass Transfer Columns for FLNG Applications

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Still today, there is limited information available about the predictive impact of column motion on the fluid dynamics and mass transfer efficiency of industrial-sized marinized columns. Raschig and UOP started a new approach in 2010 to evaluate the performance of random and structured packings during column motion. In a moving pilot plant, columns containing different random and structured packings have been investigated for a wide range of liquid loads with varied constant column tilt and different column motion frequencies. This paper compares the performance of random and structured packings used with different column tilts and motions and will provide information on when to apply one of these product lines.

1. Introduction

In research concerning packed-column mass transfer efficiency under floating conditions, some papers do conclude that structured packings may have more tolerance to motion than random packings, s. Hoerner et al. (1982a), Hoerner et al. (1982b), Berger et al. (1983). Unfortunately, the related published data do not provide clear experimental proof for this, as the data are too scattered. Other papers have referred to this conclusion and have limited studies to only structured packing performance when the column is under motion. A very valuable literature overview was published by Cullinane et al. in 2011.

Because of the above-described uncertainties, Raschig and UOP set up a new pilot plant to study the performance of various structured and random packings under identical column motion conditions The experimental test results have been validated by UOP in terms of Computational Fluid Dynamics (CFD) modeling. On the basis of this CFD modeling, gas and liquid flow performance can be predicted at any elevated position within mass transfer columns under combined heave, sway, surge, list, trim, roll, yaw and pitch conditions on a floating vessel, s. Figure 1. Based on these results, a “Floating Column Model” was developed to predict the packing performance under constant column tilt and motion frequency conditions.

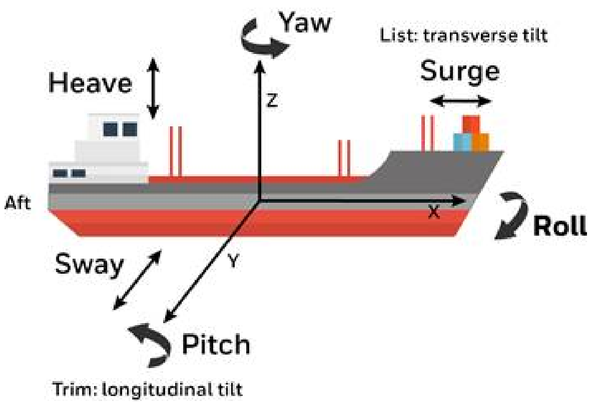

Figure 1: Nomenclature for moving vessels

2. Experimental Setup for Fluid Dynamics Studies

The experimental test facility erected at Raschig Ludwigshafen to study the effect of column tilt and motion on packing performance had a column diameter of 450 mm and a maximum packing height of 1600 mm, which resulted in a maximum height-to-diameter ratio of H/D = 5.3. In the experiment, water was distributed onto the top of the column under ambient conditions. The liquid load was varied from 40 m^3/m^2h to 150 m^3/m^2h. Four different constant tilt positions (1 deg., 2 deg., 5 deg. and 10 deg.) were tested, and three periods of column motion (6 sec., 12 sec. and 30 sec.) were investigated at mentioned four maximum inclinations. The liquid distribution quality in terms of the maldistribution factor M_V was measured in a liquid collector with 35 chambers. For each test, the maldistribution factor as defined by Eq. (1) was calculated.

$$M_V = \frac{1}{n}\sum_{i=1}^{i=n}\frac{\left(L_i^{vol} - L_{mean}^{vol}\right)^2}{\left(L_{mean}^{vol}\right)^2} \tag{1}$$

The experiments started with the test column in the vertical position, s. Figure 2. The maldistribution factor was used because this parameter was also used by Stikkelmann (1989a) and Stikkelmann et al. (1989b) to report the maldistribution of liquid inside the packing.

The liquid distributor was a closed-pan type designed to ensure enough liquid head pressure inside the pan. Consequently, the maldistribution factor M_V at the distributor elevation was zero. At a packing height of 1.6 m below the top of the bed, for example, a maldistribution factor of M_V = 28% was measured for Raschig Super-Ring No. 2 (RSR #2.0). This maldistribution factor is called natural maldistribution, as it is naturally generated in any random or structured packing by the liquid flowing downward through the packed bed. Table 1 shows an overview of the maldistribution factors measured in Raschig's test facility and by Stikkelmann at vertical column position. Good agreement can be seen between both experimental studies, s. Schultes (2000).

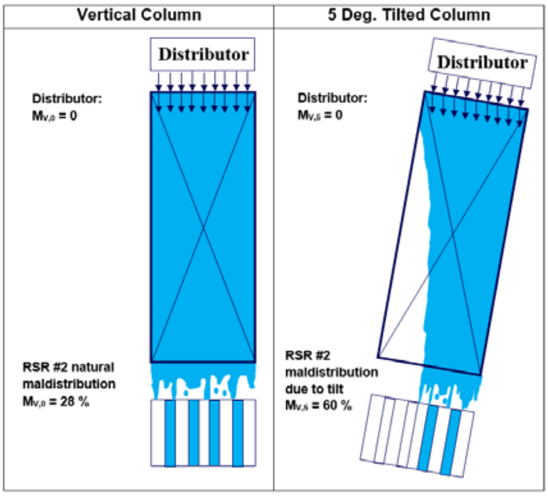

Figure 2: Sketch of the vertical and tilted test column at Raschig in Ludwigshafen

After testing with the column in vertical orientation, the performance of the tilted column was studied, s. Figure 2. In a tilted column, the liquid tends to follow gravity, and the vertical flow generates a cone-shaped area where fluid flow dries out. The distributor helps to wet the column cross-section area at the top end, but after a certain flow length, the liquid starts to under-wet the column wall and the packing volume next to it. On the other side of the column, liquid collects at the column wall and begins moving downward as a collective wall flow. The maldistribution factor M_V was measured under all 4 constant tilt conditions.

Table 1: Maldistribution factors measured at vertical column position in Raschig's test and by Stikkelmann (1989a) and Stikkelmann et al. (1989b)

Packing	Material	Maldistribution Factor	Data Base
25 mm Pall-Ring	Metal	0.81/1.1	Stikkelmann/Author
50 mm Pall-Ring	Metal	0.5	Author
25 mm IMTP-Ring	Metal	0.57	Stikkelmann
Raschig Super-Ring No. 2	Metal	0.28	Author
Mellapak 250 Y	Metal	0.21	Stikkelmann

For a 5-degree constant tilt, for example, a maldistribution factor of 0 % was measured just below the distributor and of 60 % at the bottom of the 1.6 m tall bed with RSR # 2.0. For further evaluation, a reference change was made from the maldistribution factor to standard deviation C_V as defined by Eqn. (2). For a high number of sample points, the standard deviation approximates the square root of the maldistribution factor.

$$C_V = \left[\frac{\sum \left(\frac{L_i^{vol} - L_{mean}^{vol}}{L_{mean}^{vol}} \right)^2}{n-1} \right]^{1/2} \tag{2}$$

After testing the tilted columns, the system was set under motion, and the standard deviation factor C_V was measured. The results are shown in Figure 3 as the ratio of standard deviation C_V measured under tilt and motion related to the standard deviation for 0-degree tilt $C_{V,0}$. As seen in Figure 3, under a constant column tilt of 5 degrees compared to the vertical position, the standard structured packing SP 250Y generated an increase in standard deviation of 310% at 40 m^3/m^2h. Raschig Super-Pak 250Y performed with an increase of 210% and Raschig Super-Ring #2.0 with an increase of 170%. With a constant column tilt of 10 degrees, the column standard deviation increased by 555% for the standard structured packing 250Y (SP 250Y), by 485% for Raschig Super-Pak 250Y (RSP 250Y) and by 395% for RSR #2.0 at 40 m^3/m^2h. An increase in liquid load resulted in a slight reduction of standard deviations.

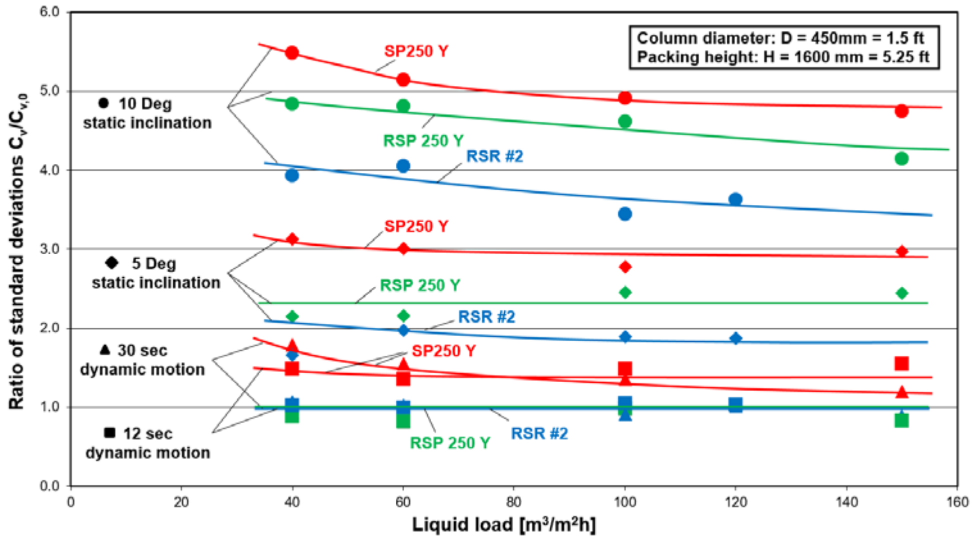

Figure 3: Ratios of standard deviations $C_V/C_{V,0}$ for various packings, with different liquid loads and for columns under constant tilt or under motion.

As soon as the column started to move back and forth, the increase in standard deviation compared to that of the vertical position was reduced significantly. For a maximum tilt of 5 degrees and a slow-motion sequence of 30 seconds, the increase in standard deviation dropped to 170% for the standard structured packing SP 250Y, to 145% for RSP 250Y and to 0% for RSR #2.0 at 40 m^3/m^2h. For a maximum tilt of 5 degrees and a fast motion sequence of 12 seconds, the standard deviation for RSP 250Y and RSR #2.0 was the same as in the vertical column. Only the standard structured packing SP 250Y retained an increase in standard deviation of app. 150%. The tested standard structured packing SP 250Y had holes in the corrugated sheets to allow liquid and gas to pass through, but the test verified that the transmission of liquid through the holes became very limited. It became obvious that if the sheets of the standard structured packing were in perpendicular orientation to the rotation axis of the column, liquid could easily flow downward by gravity along the sheets toward the low column side. Every second layer was rotated by 90 degrees, however, and as a consequence, every second layer was hindering the liquid from following gravitational flow, which resulted in an increase in standard deviation C_V measured at the bottom of the packing. Because RSP 250Y is a grid-type structured packing and RSR #2.0 is a very open random packing, the liquid flow through these packings always followed the gravitational force in the column under motion. This resulted in less under-wetted column volume and led to lower standard deviations at the bottom of the packing.

3. Mass Transfer Studies for Columns under Motion

In 1992, Baker et al. published mass transfer performance data for 3 different random packings and for one structured packing. The authors tested the packing efficiency behavior for oxygen absorption into water under constant column tilt and under column motion. Figure 4 (left part) shows the deterioration of mass transfer efficiency under various tilted column positions for 25 mm Pall-Rings and Mellapak 250Y. The highest number of transfer units was seen for both packings in the vertical column position. If the column was set in a tilted position, the mass transfer was reduced. The higher the column tilt, the lesser was the number of transfer units measured for both packings.
Figure 4 (right part) shows the performance improvement when the column was set under motion. A constant column tilt of 3 degrees corresponds to 0 Hz of motion frequency and was the baseline of packing performance for these tests. As seen in Figure 4, the worst mass transfer efficiency was given at 3-degree constant tilt for all 3 different packings. As soon as the column started to move, the mass transfer efficiency improved. Both random packings achieved performance equivalent to that in the vertical column as soon as the motion frequency exceeded 0.05 Hz, equal to 20 seconds of motion. The Mellapak 250Y could not recover in terms of mass transfer efficiency because even under fast motion conditions, a reduced efficiency was recognized. This is in line with Raschig's hydrodynamic test results.

4. CFD Modeling of Columns under Motion

To apply these test results to an industrial column design for floating vessels, a Computational Fluid Dynamics (CFD)-based floating column model was elaborated. In the CFD study, the packing was characterized as porous media and the liquid flow was modeled from the forces liquid undergoes: gravity, gas-liquid interaction, liquid-packing interaction, inertia force originated from the ocean wave, etc.

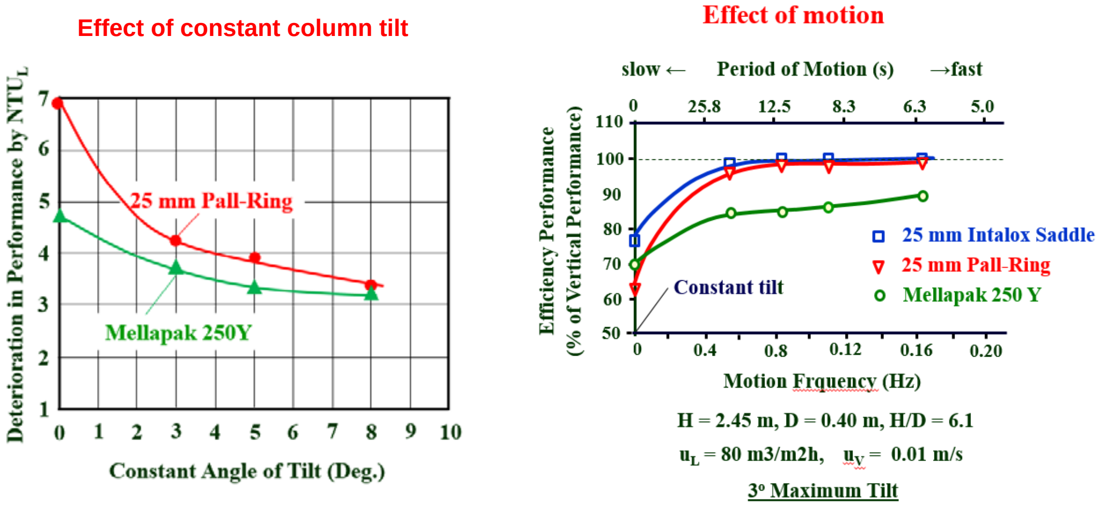

Figure 4: Deterioration of mass transfer performance in terms of number of transfer units under various tilted column positions and under motion for 25 mm Intalox Saddle, 25 mm Pall-Ring and Mellapak 250Y; experimental data acc. Baker et al. (1992).

Figure 5 shows the liquid mass flux rates under column motion conditions and the calculated relative standard deviations based on CFD studies for RSR #2.0 with a specific liquid flow rate of 60 m^3/m^2h. Under a fast column motion of 12 seconds and with 10-degree maximum tilt, the increase in standard deviation was calculated to be 126% (upper left part of Figure 5). If the column motion slows down to 30 seconds, the increase in standard deviation rose to 140% (upper right part of Figure 5). If the maximum angle of tilt drops down to 4-degree, a fast motion of 12 seconds did not yield any increase in standard deviation (lower left part of Figure 5). However, if the motion was slowed down to 30 seconds with a maximum tilt of 4-degree, the standard deviation increased slightly to 106% (right lower part of Figure 5).

5. Floating Column Model

The ability to simulate the liquid flow performance in a column under motion at any position on a vessel allows the development of a "Floating Column Model" for use in a process simulator. Published mass transfer data from Baker et al. (1992) for oxygen absorption into different packings was used to compare the calculated results. The data in Figure 6 (left hand) are the same as in Figure 4 (left hand), but the lines in Figure 6 are the result of the “Floating Column Model”. Figure 7 show the results of the column under motion tested at the Harriot-Watt University and predicted by the “Floating Column Model”. A good fit between experimental and predicted data can be seen. The larger the maximum tilt is under motion conditions, the more severe the column performance reduction is for any packing. Large maximum tilt angles under motion lead to the high motion frequencies required to recover the column performance. Random packings can recover from their loss in efficiency if the motion of frequency is high enough. For structured packings, a constant loss in efficiency must be considered in the design of a mass transfer column, even under high frequency of motion conditions.

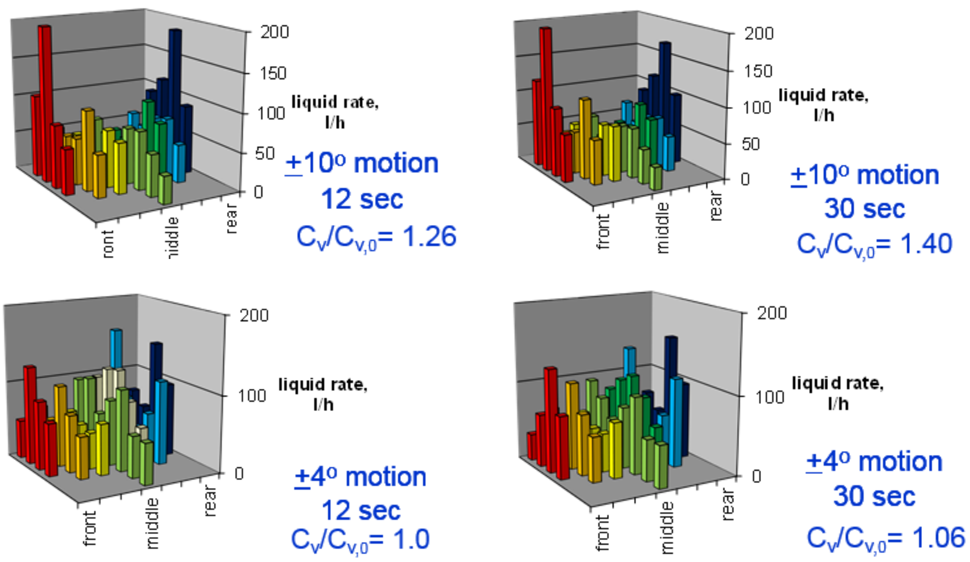

Figure 5: Liquid mass flux tested under column motion conditions and simulated by CFD modeling. Upper left side: 10-deg. maximum tilt and fast motion; upper right side: 10-deg. maximum tilt and slow motion; lower left side: 4-deg. maximum tilt and fast motion; lower right side: 4-deg. maximum tilt and slow motion. Packing: RSR #2.0, D = 0.45 m, H = 1.6 m, liquid load = 60 m^3/m^2h.

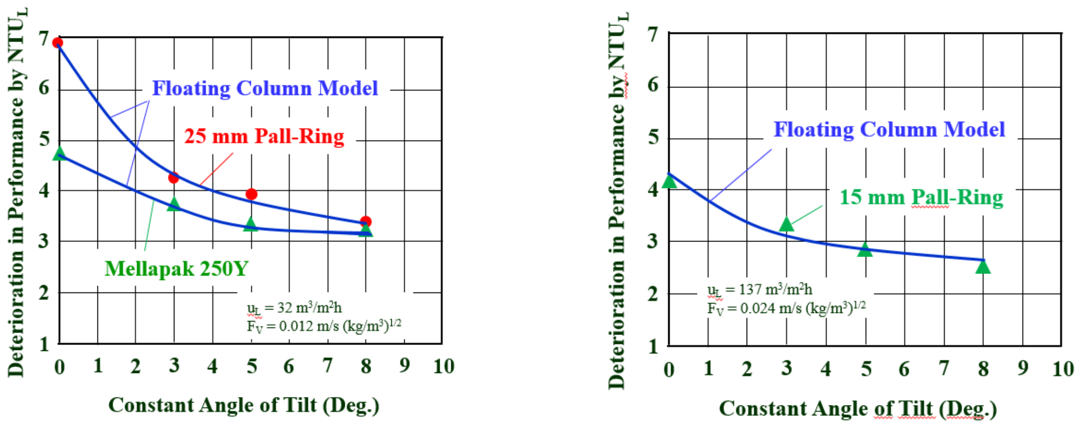

Figure 6: Predicted deterioration in performance of mass transfer columns under different constant column tilt positions.

6. Conclusions

Previously, it was concluded that only structured packings could be used for column tower designs used under moving conditions. Based on the presented research results, it becomes obvious that random packings can also be selected for use in columns under moving conditions on a vessel. The selection of packing should be based on performance advantages. As demonstrated in this article, random packings show less hydraulic maldistribution and loss in efficiency under floating conditions.

Consequently, random packings can be used on floating vessels in applications where they have shown proven advantages in land-based designs. The loss in efficiency for any type of packing depends on the column frequency of motion and the degree of column tilt. It is also related to the column position on a floating vessel. The presented "Floating Column Model" allows the prediction of packing efficiency, pressure drop and packing capacity for any random or structured packing on floating vessels. New optimized column designs are possible based on this model.

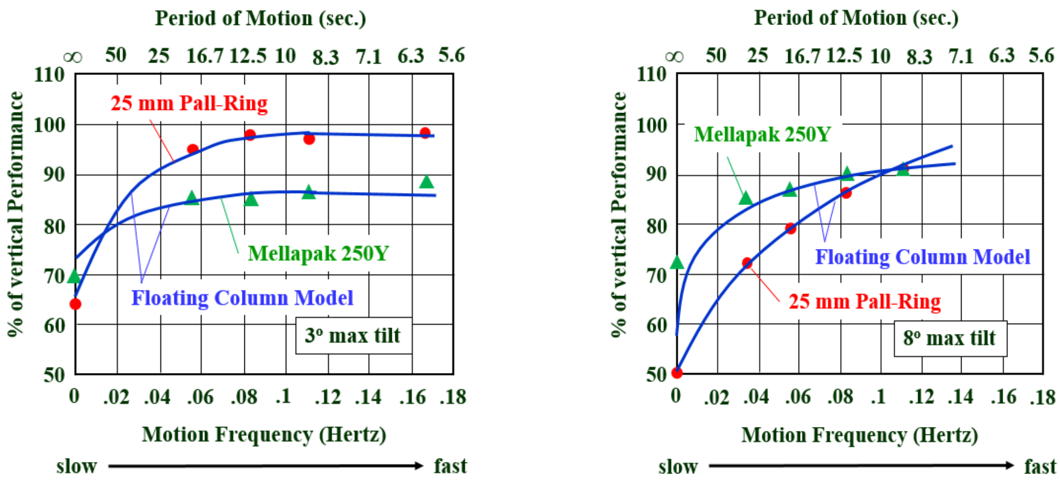

Figure 7: Predicted improvement in performance of mass transfer columns under different frequencies of column motion; experimental data acc. Baker et al. (1992)

Nomenclature

D	m	Diameter	N	Number of data points
C_V		Standard deviation	NTU	Number of transfer units
H	m	Height	**Indices**	
L_i^{vol}	m^3/h	Volumetric liquid rate at location i	L	Liquid
L_{mean}^{vol}	m^3/h	Mean volumetric liquid rate	V	Volume
M_V		Maldistribution factor	X	Angle value

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