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HOW TO MANAGE IMPACT OF MOTIONS ON DESIGN OF FLOATING AMINE UNIT?

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HOW TO MANAGE IMPACT OF MOTIONS ON DESIGN OF FLOATING AMINE UNIT?

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Abstract

FLNG projects combine the tightest specifications used for onshore plants with offshore constraints and floating conditions. Every effort has to be done in order to minimize the risk of weight increase deriving from the overdesign that one would implement to ensure the level of performance is met. Acid Gas Removal Unit (AGRU) and Liquefaction are two critical steps of the process that are affected by vessel movement. If this impact is not known accurately, optimization of the design will be difficult and may even involve a risk of off-spec gas being sent to the liquefied gas production unit which will then not operate properly.

In order to develop a reliable prediction tool to produce secured designs, the motion effect of an FPSO / FLNG on AGRU columns has been experimentally studied and modeled over a multitude of factors. An early model of gas-liquid maldistribution based on theoretical approach and on floating experience for other units was introduced in our proprietary simulation tool dedicated to the design of industrial amine unit.

The theoretical model has been compared with actual data obtained on 2 large diameter columns in both static tilt and under sinusoidal motion. Using a large range of operating conditions, extensive data and valuable knowledge of the impact of motions on the mass transfer efficiency and hydraulics have been acquired and used to fine tune our simulation tool.

CFD calculations on the gas-liquid flows through structured packing elements have shown that for some conditions, there is a separation of the liquid film from the packing plate, resulting in a modification of the liquid flowpath and of the gas-liquid contact, affecting the efficiency of packing bed.

In this paper, some examples are given in order to illustrate the impact of movement on tower efficiency and the need for specific process design.

1. Impact of motion on CO_2 absorption column efficiency

Acid gas absorption is a critical step in the chain of processing stages for natural gas liquefaction. Acid gases need to be removed from the natural gas down to very low levels (typical LNG specifications are: CO_2 <50 ppmv, H_2S < 4 ppmv) corresponding to the design requirement of the downstream cryogenic section. Portions of the acid gas shall never slip the Acid Gas Removal Unit (AGRU) absorber in order to avoid crystallization problems in the downstream liquefaction unit, to prevent shut down and to avoid subsequent long restart-up periods. For any project, a safe and reliable design shall be reached within an acceptable compromise between overdesign, moderate equipment number, weight, and operating costs. FLNG Projects face more sharply those constraints than any other gas development project. The motions of a hull add specific design constraints to all the units installed on the topside, and their performance can likely be affected. In order to secure those performances, the design may include additional capacity in processing

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equipment or CO_2 polishing safeguarding equipments that increases constraints on the floating structure itself. This means that the platform size increases which may jeopardize the economic feasibility of the project.

The impact of motion on the performance of AGRU columns is not well-understood. Industrial feedback for design of absorption/fractionation towers on floating platforms is still limited and does not allow for precise predictions on the actual loss of efficiency of such columns. Extrapolation from past experience on floating vessels is difficult to apply to AGRU columns due to the very different constraints than other processing units including dehydration applications or fractionation columns (Cullinane, Yeh, Grave, 2011). Meanwhile, Literature (Kobayashi et al., 1999 ; Yoshinaga et al., 1981 ; Berger et al., 1983 ; Tanner et al. 1996) indicates that the performance of packed absorbers could be decreased by up-to 60%. This performance loss is highly dependent on the system (distillation, absorption), the gas/liquid contactor (packing, tray) and the overall geometry and location of the tower on board the floating platform.

Therefore, it is critical to identify the controlling parameters and understand the impact of motion on the performance of an acid gas absorption column with amine solvents to secure and optimize the design of a floating Acid Gas Removal Unit on FPSO and FLNG vessels.

In an onshore environment, the design of acid gas absorption requires the development of accurate simulation tools to calculate the acid gas absorption rate through chemical reaction with different type of amines on given internals used within an absorption tower (Weiss et al 2014). This is not the usual approach taken for such columns, where a equivalent height type calculation is often used requiring some sort of stage efficiency to determine the overall packing height. Accurate prediction can only come from a detailed understanding of the liquid flow paths, the chemical reaction between gas-phase solute and liquid absorbent.

Figure 1 shows that the acid gas absorption rate within a tower depends on many factors such as:

- Hydraulic conditions with effective area developed by the selected internal,
- Thermodynamics and G/L equilibrium of phases,
- Mass transfer coefficient on gas side
- Mass transfer coefficient on liquid side
- Kinetics of the reaction between acid gas and amines.

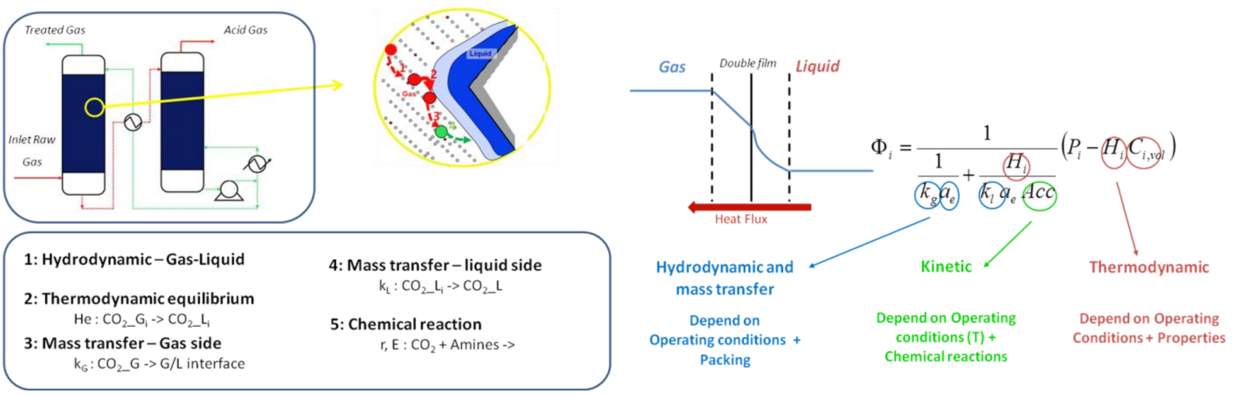


Figure 1: Mass Transfer – Principle of Reactive Absorption

The in-house proprietary simulator named Desulfo developed by TOTAL, IFP Energies Nouvelles (IFPEN) and PROSERNAT integrates State of the Art mass transfer models for the calculation of amine systems and absorption of acid gas by amine solvents. With a rate-based simulator like Desulfo, the calculation of acid gas absorption is not performed based on a theoretical stage approach including a mass transfer efficiency coefficient. Desulfo calculates the absorption of acid gas through a stage after stage approach along the column, and incorporates the type and arrangement of internals selected for the design. When the column is a packed bed, Desulfo provides a clear picture of the absorption profile within the tower, including slippage if the solvent flow is not sufficient. After each step of development based on R&D program , the simulator is tested and continuously upgraded based on the feedback recovered from the operating and design experience aggregated by Total over its 50 years experience in the field of H_2S and CO_2 removal units.

Armed with this knowledge, TOTAL, PROSERNAT and IFPEN completed an extensive review of bibliographic data available on the impact of motion on liquid/gas distribution in columns to check how motions of columns could affect the performance calculated by Desulfo. The analysis of moving environment determined that two main parameters could distort the calculation of absorption performance predicted by Desulfo. The first one is the static tilt of the column from verticality. Whatever the oscillations amplitude, whatever the period of oscillations can be, the tilt diverts the liquid from its axial route normally expected in onshore absorbers/regenerators. The distortion created by non verticality generates accumulation of liquid in some places, and drought in other places of the column section. The second key parameter is the forces of acceleration generated by the movement of hull, amplified in some places by the large distance between the upper beds of AGRU absorber and the center of rotation which can be of the order of 350 meters or higher for a ship based floating system. Radial forces imposed by accelerations make the liquid deviate from its conventional onshore distribution map normally modeled in simulator. Analysis then raises the simple question: "are the models, introduced in figures 1 and 2 determined on vertical and static systems, still valid if we want to calculate the systems under the influence of periodic oscillations and acceleration forces?"

Starting from these statements, TOTAL, PROSERNAT and IFPEN had already built an early model of liquid/gas maldistribution within an absorption column submitted to motion based on a theoretical approach. They had started an understanding of the impact of motion on column efficiency and on the distribution of liquid and gas phases in packing beds.

A floating platform will experience different motion conditions depending on vessel size and prevailing sea conditions. The movement experienced by the various pieces of equipment installed on the vessel is only defined once the hull design of the floater is developed and its location determined to give the maximum tilt angle, period of oscillations and accelerations during which the treated gas specification is to be achieved.

These parameters as well as other parameters such as liquid viscosity, height of packing, diameter of column, liquid/gas flowrate, type of packing impact on the liquid and gas distribution within the column. Changes in liquid and gas distribution will then impact on the gas pressure drop, flooding limit and, more important will impact on the acid gas absorption rate within the column.

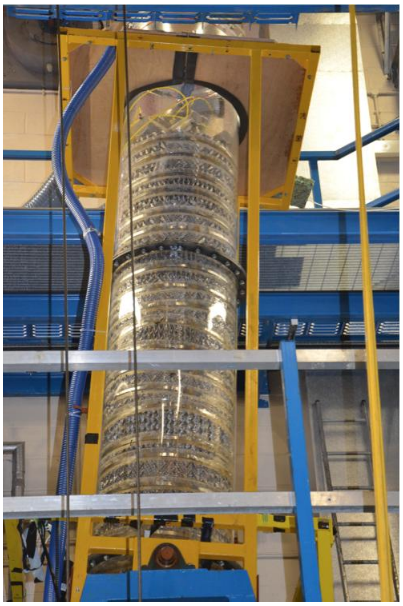
A correct understanding of the maldistribution of liquid and gas in a packing bed under motion is the key to be able to perform a predictive acid gas absorption calculation for a floating acid gas removal unit. It is also the gate to identify maldistribution effects from the loss of efficiency of packing as distortion of mass transfer model determined on static, vertical bed. TOTAL, PROSERNAT and IFPEN have now performed more than eighteen months of Research and Development program, using the tilting column facilities at Heriot-Watt University to validate and further develop a mass transfer and hydraulics model of tilted and moving column. In parallel, additional studies including CFD modeling and calculations performed at the scale of structured packing elements receiving liquid and subject to marine motions have been conducted to improve the understanding of the behavior of the liquid film.

2. Experimental strategy and set-ups

For offshore gas treating, the AGRU contactor should be designed to minimize the motion effect on the process operation. It was already demonstrated that Structured packing is more adapted to prevent liquid misdistribution than trays and random packings (Weiss et al, 2014). A metallic structured packing has hence been selected for this work.

In this study two columns are used, a 0.6m diameter and a 1m diameter column fabricated from Perspex to aid visualization of the flow patterns within the column (figures 2a and 2b). Both columns can be tilted around a point on the base of the column to a range of angles up to ±8°, either in static position or with oscillating periods from 15 to 40 seconds. Actual tests were performed over a pre-defined range of motion conditions representative of the sea states that a FLNG encounters in operating conditions. The columns used in the tests were adapted to measure either maldistribution of liquid, or fitted with a gas distributor to measure absorption performance and pressure drops.

Design of industrial packed absorption columns (Billet, 1995), is only possible with complete knowledge of capacity diagrams and mass transfer correlations. Capacity diagrams give flooding limits which are used to calculate column diameter at fixed gas and liquid flowrates. Mass transfer correlations, combined with kinetics and thermodynamics models, give packed bed height which is required to reach gas specifications. For offshore applications, the impact of platform motion on these parameters should be quantified. For capacity limits, flooding curves can be established experimentally, as there is currently no known method of prediction under tilted and oscillatory motion. For mass transfer, one approach is to combine a gas/liquid distribution model under motion to traditional mass transfer correlations (Tanner et al., 1996). In order to extrapolate the developed liquid distribution model to full industrial scale, several parameters have to be taken into account and of these the packed bed height and liquid viscosity are perhaps the two critical parameters in any offshore column design. Measurements have therefore been taken on the two columns mentioned previously, at different packing heights and liquid viscosities. Liquid and gas loads up to 120 $m^3/m^2/h$ and up to 1.2 $Pa^{0.5}$ have been applied respectively.



(a) 0.6m Column

(b) 1m Column

Figure 2: Pictures of the 0.6 and 1m inner diameter transparent columns.

For the measurement of liquid distribution, the usual gas distributor at the base of the column is replaced by a collection system to measure the flowrate from a series of points across the base of the packing. More than 200 collection points are used with the 0.6 m column (and 600 on the 1m column) in an automated system based on that used by Waldie (2003) and Tanner et al (1996). A rectangular traveler consisting of between 18 (for the 0.6m column) and 26 (for the 1m column) collection cells is positioned below the packing, with cell 1 located on the “west” side and 18 (26) on the right. Flexible hose lines carry liquid from the collection cells into pneumatically actuated collection chambers; chambers are sealed and the rise in liquid level recorded until a specific time is reached. After this time, the chambers are opened and the traveler moved to another row location. Rows are defined along the direction of tilt, between 1 to 17 for the 0.6m column and 1 to 32 for the 1m column. After scanning the entire base of the column, a mass balance is calculated to ensure consistency of the overall flowrate into and out of the column.

For mass transfer and flooding tests, the base of the column is fitted with a simple gas distributor modified to allow counter current gas flow. For flooding, the gas flowrate is slowly increased at a fixed liquid flowrate. The flooding limit corresponds to a nearly vertical slope of the pressure drop vs gas flow parameter (Spiegel and Meier, 1992), combined with visual evidence of strong liquid entrainment and accumulation at the top of the column. The loading point corresponds to the gas flowrate at which the slope of the curve becomes higher than the one measured with gas only. Below the loading point, measured pressure drop are needed to calculate the gas distribution (Tanner et al., 1996).

Mass transfer tests have been conducted with both columns at determined heights of bed by removing CO_2 from atmospheric air by contacting with diluted NaOH solution (Alix and Raynal, 2008 ; Seibert et al., 2005). These experiments intend to understand the extrapolation laws between systems of different dimensions, subject to the same motions and forces. Tests campaign has also checked the behavior of onshore correlations combined with a distribution model.

Maldistribution of liquid at the base of the packing has been studied for static inclination of the two columns and for columns under regular oscillation. The different factors investigated on liquid distribution are:

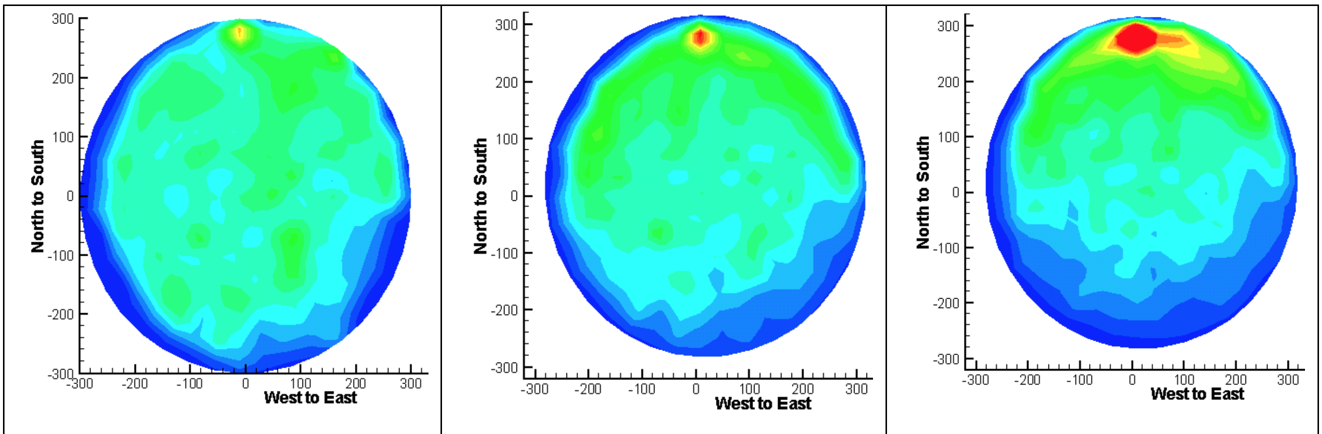
- Tilt angle: 0 to 8° max
- Diameter of column: 0.6m and 1m diameter
- Period: 0 to 40 seconds
- Liquid flowrate: liquid loads concurring in amine design, between 10 and 120 $m^3/m^2/h$. Two distributors have been used to cover the operating range for each column.
- Viscosity: figures representative of amine systems below < 10 cP
- Variable beds heights for both columns

This paper focuses on liquid distribution results at 1cP which is the first step of the study although in absorber columns, amine solutions can be 3-5cP.

3. Hydraulic maldistribution results

Static column

Figure 3 is a mapping of the liquid distribution measured with a static tilt of 5° at different heights of packing. These plots show the flux across the base of the packing, with red areas indicating a high flux and blue areas indicating a low flux. A tilt angle of 5° corresponds to some of the upper average data found in various floating production projects. Due to the design of the liquid collector, maldistribution measurements were realized without the presence of counter-current gas flowrate. However, it has been shown that liquid distribution is not changed significantly by the gas stream up to the loading point in a vertical column (Dukai and Ruckenstein, 1970; Fourati et al., 2013).



Bed height H1	Bed height H2 > bed height H1	Bed height H3 > bed height H2

Figure 3 - Liquid distribution 0.6m column for +5° static tilt

The results show that an increase in the height of the bed results in more severe maldistribution. Other studies (Fourati et al – 2013) have demonstrated that structured packing gives good distribution of liquids compared to columns filled with random packing. Under static tilt over the range of conditions used for this work, structured packing alone cannot compensate for severe inclination angles. For tall beds, a significant amount of liquid tends to accumulate close to the wall of the column and, despite wall wipers, does not redistribute back into the column. This amount of liquid is often considered to not contact gas sufficiently well, which lowers column efficiency. The study also demonstrates that dispersion of liquid by structured packing is not sufficient to ensure good liquid distribution for a tilted column as the liquid goes to one place and escape the other side. It helps and conclude that tilted columns are definitively affected by maldistribution while a vertical tower supports a natural redistribution of liquid, especially with structured packing.

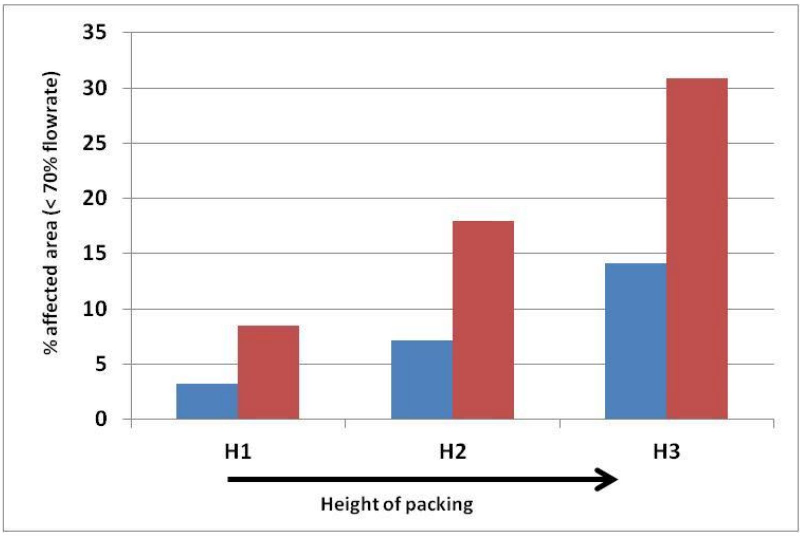


Figure 4 - Impact of static tilt for 0.6m column and two angles (3° and 5°)

Another way to quantify liquid maldistribution is to consider dry area of packing. Figure 4 presents the effect of packing height on dry area for 0.6m column with 3° and 5° static tilt. In these cases, the affected surface considered is the surface which sees less than 70% of liquid flowrate if in a vertical position. The obvious conclusion of the Figure 4 is that the higher the height of packing and the tilt angle, the higher the impact on maldistribution. From the data acquired from our tests, it is possible to quantify the maldistribution and to compare and tune with the developed model for maldistribution. The model can now be used with sufficient degree of confidence to extrapolate present results to industrial scale columns which are several meters in diameter.

Moving Column

For motion experiments, the analysis of collected data is more difficult to interpret, and the simplest method to visualize the impact of column movement is to plot the liquid flux measured against time. The difference between a static column and the one undergoing motion becomes then clear when plotting flux ratio during the motion cycles, defined as:

$$\text{Flux Ratio} = \frac{\text{Flux under motion}}{\text{Flux under static conditions}}$$

The ratio should be close to 1 in all cases if the flux is unaffected by the column inclination angle.

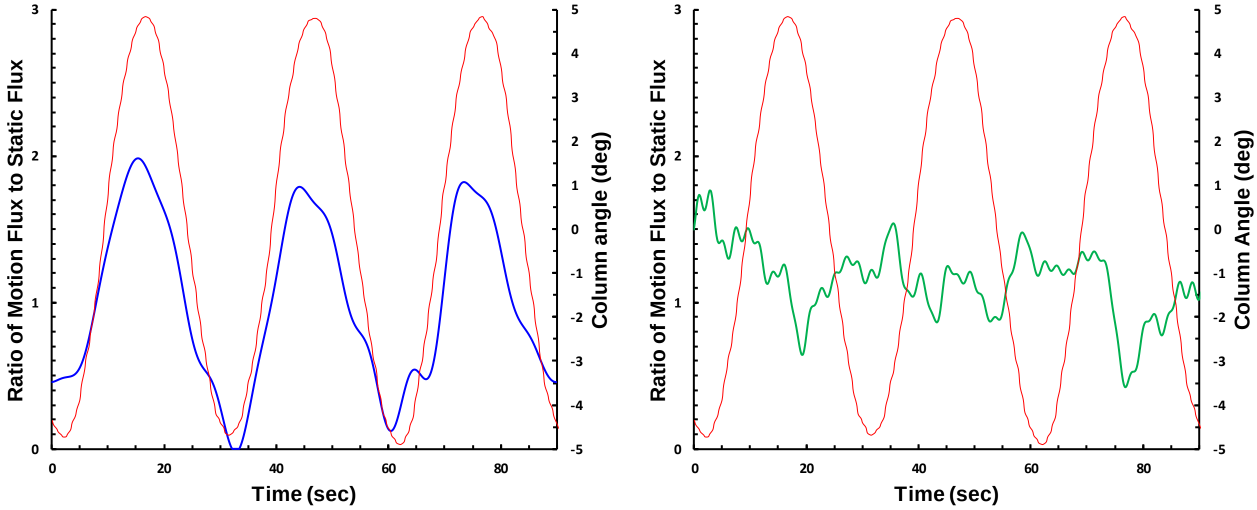


Figure 5 – a) Raw 6: 0.1 m from the column edge. b) Raw 17: near the center of the column

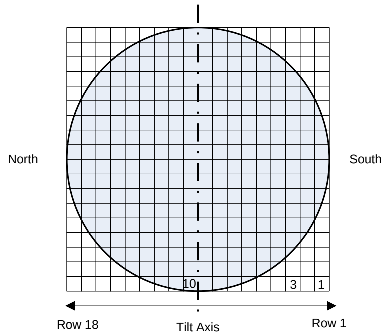


Figure 5-c) Row mapping for liquid maldistribution tests in the 0.6m column

Figure 5 is a line plot showing the sinusoidal motion in red (30 seconds period) and the liquid flux ratio measured at two positions on the base of the column (traveler locations row 6 and row 17) for the 0.6m diameter column. Under motion, the liquid flux ratio close to the column's edge varies from 2 to zero in phase with oscillating motion. Close to the center of the column (row 17), the liquid flux ratio even though varying from ±50%, is not in phase with the oscillations and its average value is equal 1. This supports what would commonly be thought to happen in that liquid moves essentially from one side of the column to the other. Once the column reaches its maximum angle of inclination, we would expect separation of the gas and liquid and a drop in mass transfer performance. As the column tilts back through vertical there would be a general gross movement of liquid across the packing. The changes in liquid film thickness, hold up on the packing would contribute to a severe distortion of parameters associated to the effective area of packing. As the column continues to tilt, situations arise where there is no liquid flowing out of the packing especially for regions close to the vessel wall (Figure 5a). The same question as above is raised here about the capability of structured packing to redistribute properly the liquid. But the test in static & tilted mode already showed that it is not the case.

These assumptions can be assessed by a direct measurement of the CO_2 content in the treated gas of an absorption column submitted to motion and compared to the one reached in static and vertical position. Such measurement has been performed at the outlet of the 1m column described above. Figure 6 is a line plot showing evolution of the CO_2 removal measured during a sinusoidal motion representative of Pitch and Roll encountered on a floating barge. The base line is also displayed for static vertical conditions (100% dotted line). Even if these measurements have been carried on under specific conditions, this figure indicates that the CO_2 content in the treated gas evolves with column motion: CO_2 removal efficiency can be decreased by a few percents, which is far enough to result in off-spec feed gas for the cryogenic loop of a FLNG.

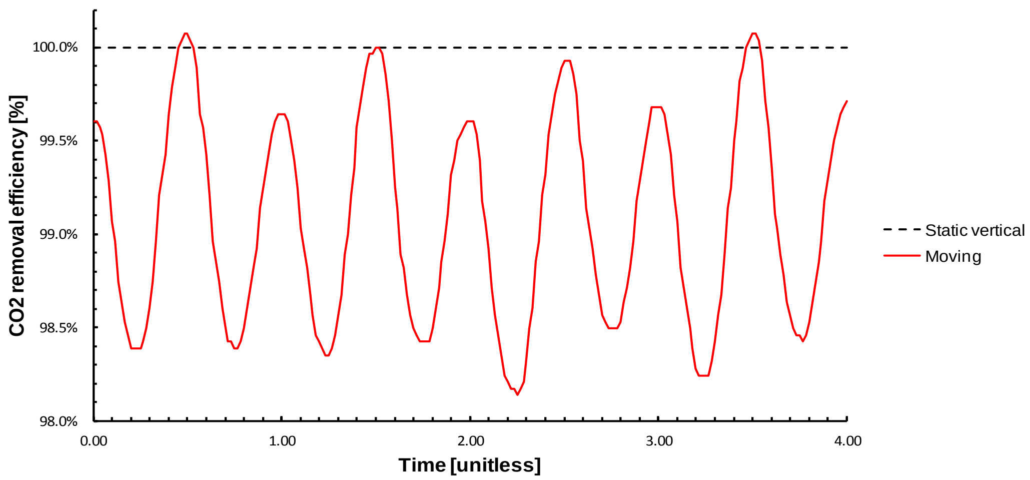


Figure 6 - Effect of motion on packing efficiency

As an example, to estimate the impact of maldistribution in industrial conditions, a simulation has been made on an absorber originally designed for an onshore application to treat 450 MMSCFD of feed gas containing 5% of CO_2 down to LNG specifications. The maldistribution of liquid and gas generated by pitch and roll of +/- 5° has been taken into account by applying different flowrates in this absorber. These flowrates have been determined using experimental maldistribution results. The corresponding CO_2 content of the treated gas calculated by our in-house simulation tool can be found in Table 1. In this example, the column is fitted with three beds of structured packing. The CO_2 content exceeds the LNG specification and rises up to 250 ppm. This simulation confirms that the hydraulic maldistribution can significantly decrease the mass transfer in the absorber, and must be taken into account to calculate and optimize the design of amine towers installed on a FLNG. Please note that the simulation presented here does not consider a degradation of the efficiency of packing in term of mass transfer parameters. The effect of motion, if taken into account at this level would further degrade the performance.

Feed Gas CO_2 content (% vol.)	Pitch & Roll (°)	Treated gas CO_2 content Considering non modified onshore design (ppmv)
5	-	50
5	± 5°	250

Table 1 - Calculation of CO_2 content at the outlet of an absorption tower submitted to Pitch and Roll of 5°

4. CFD study of liquid film flow on structured packing element subject to rolling motions

In parallel to test campaign at Heriot-Watt University, the impact of marine motion on liquid flow in structured packing at local scale is investigated using CFD. The aim of this CFD study is to check if movements of support can generate disturbances on the circulation of fluid at the surface of packing and determine if there is a risk that mass transfer coefficients ae, kl, kg could be affected by motions forces. Three-dimensional numerical simulations of gas-liquid flow on structured packing element of Mellapak 250X are performed under rolling excitation. Figure 7 shows an illustration of the calculation domain and the simulated motion.

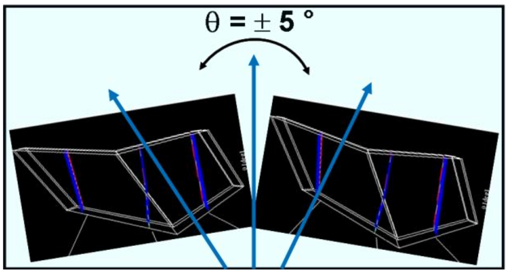


Figure 7: Schematic illustration of computational domain

The numerical approach is based on the volume of fluid (VOF) method, implemented in ANSYS Fluent 12 software. The implemented VOF method (Hirt and Nichols, 1981) consists of an Eulerian description of each phase on a fixed grid, the interface between the two phases being calculated using the transport equation of the local volume fraction of one phase. The Navier-Stokes equations are solved according to the one-fluid formulation (Haroun et al. 2014):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{U} \right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\rho \vec{U} \right) + \nabla \left(\rho \vec{U} \vec{U} \right) = -\nabla P + \rho \vec{f} + \nabla \cdot T + \vec{F} \qquad (2)$$

$$\frac{\partial}{\partial t}\alpha + U \cdot \nabla \alpha = 0 \qquad (3)$$

Where U, P, ρ, g, T, F and α are the local velocity, pressure, density, dynamic viscosity, gravity, viscous deformation tensor, capillary force and volume fraction respectively. The location of each phase is given by a scalar α (called the volume fraction). $\rho\vec{f}$ is an external force (Celebi and Akyildiz, 2002) derived from a moving coordinate system and introduced as sources terms via the User Defined Function in Fluent CFD software. These forces introduce in the calculation the effect of rolling motion and acceleration of fluids. The rolling conditions considered in this work correspond to element packing positioned in the absorber at about 50 m from the gyration center of the boat. The roll oscillation amplitude and period used are of θ=+/-5° and 15 s respectively.

The results are shown in Figures 8 a, b and c. When the rolling motion is parallel to the packing plate, calculations show that the liquid film becomes detached from the surface of packing because of the modification of the liquid flow path. Moreover, it is found that the separation of the liquid film from the packing surface occurs only when θ = -5 °.When θ=5 °, the liquid film remains indeed attached to the packing. This behavior is probably due to the variation of liquid flow path as function of the inclination of the packing. For θ= -5 °, the corrugation angle becomes more horizontal which promotes the liquid film detachment. The liquid detachment is likely to modify the mass transfer coefficients determined originally on a vertical static tower.

Other simulations were performed to investigate the effect of the heaving motion. The results are not presented here but they show that the heaving motion causes a sinusoidal variation of the liquid hold-up in the packing element.

These results show that acceleration and movements of absorber tower due to the marine motion affect the liquid flow path and the liquid hold-up in the packing bed. Thus, it confirms the need for experimental investigation on tilted and moving columns to assess the effect of motions at the scale of a complete packing bed, including the determination of mass transfer efficiency of packing bed apart from the maldistribution maps and L/G maldistribution factors.

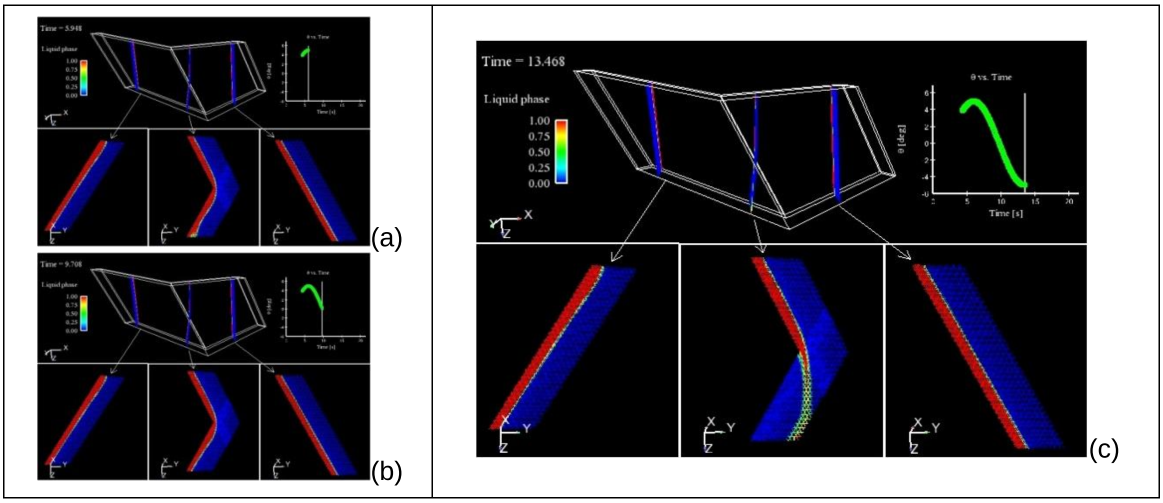


Figure 8 : Liquid film flow shape (red color) in Three-dimensional structured packing element under rolling motion.(a) : θ = 5°, (b) :θ = 0°,(c) :θ =-5°.

5. Conclusion:

To date, there is little industry experience with the design and operation of gas treating processes for floating application. The models and simulator used for the design of onshore units are not likely adapted to the design of offshore floating units, mainly because they cannot model the influence of motion on the distribution of liquid but also because both conceptual and simulation models may be not suitable to packing beds in moving environment.

From previous work, the use of structured packing is preferred for application in offshore floating columns because it features natural distribution capabilities within bed. Extensive tests on two packed columns of large diameters have given access to qualitative and quantitative effects of motion on the performance of an amine absorber on a floating vessel. For that, liquid distribution has been measured though number of collectors located just below the packed bed. CFD modeling and calculations were performed in parallel to investigate the effect of motion on liquid flow over a structured packing element.

The work presented in this paper confirms that specific design rules and models are necessary to secure the design of FPSO/FLNG AGRU since packing does not prevent liquid to distort from homogeneous distribution. It demonstrates that motion effects on liquid distribution depend on many different factors such as type of motion (permanent tilt, angle, period), and liquid load. In many cases, they are significant and increase with the bed height and the tilt angle. In addition, the movement of the column induces the detachment of the liquid film from the structured packing as demonstrated through CFD calculations. Observed effect of motion on the liquid film clearly indicates the efficiency of packing beds, through mass transfer parameters, could not be omitted from reliable models of moving absorbersAbsorption tests with CO_2 helped to evaluate the mass transfer coefficients of packing bed of towers subject to motion. The use of two different columns allows extrapolating present results to larger industrial columns which is fundamental to build a robust hydraulic and mass transfer model. The latter is highly needed if one wants to model a CO_2 absorption column for FLNG application and be able to give guarantees.

More development work now continues on oscillating columns to check an exhaustive range of parameters, representative of conditions of AGRU in FPSO or FLNG Projects, such as acceleration. Further studies also include other mass transfer tests to better assess the efficiency of a packing bed in moving conditions with influence of fluid properties.

The tuning of the packing mass transfer model implemented in Desulfo software is required to be in a position to produce the optimized designs the industry expects.

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