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# Marinization of a Multiphase Packed Bed Scrubber for Offshore $CO_2$ Capture

Amir Motamed Dashliborun, Faïçal Larachi,* Seyed Mohammad Taghavi

*Laboratory of Chemical Engineering, Faculty of Science and Engineering, Laval University, Québec G1V 0A6, Québec, Canada*

**Corresponding author: Faical.Larachi@gch.ulaval.ca*

***Highlights***

- A hexapod robot with six-degree-of-freedom motions is used to emulate ship conditions.
- A structured packed column is proposed for onboard gas treatment.
- Fluid maldistribution decreases the effective interfacial area for mass transfer.
- Column tilt is responsible of efficiency drop for $CO_2$ capture.

## 1. Introduction

$CO_2$ emissions from anthropic activities are the greenhouse gases contributing to global warming and climate change [1]. The transport sector with *ca.* 23% contribution in carbon footprint is an important source of the pollution next to the power generation and industrial sectors [2]. Maritime transport is responsible for *ca.* 2.5% of global greenhouse gas emissions by emitting *ca.* 1 billion tons of $CO_2$ annually [3]. Depending on future economic and energy developments, a dramatic increase up to 250 % is predicted from shipping emissions by 2050 [4]. This is not compatible with the internationally agreed goal of keeping worldwide emissions to be at least halved from 1990 level by 2050 [4]. Accordingly, design and optimization of an environmental technology of pollution control is a way of the future for a maritime economy valorizing resources from a sustainability perspective. The installation of scrubbing units for the post-combustion capture of carbon oxides from flue gas can be contemplated for effluent treatments onboard ships. This solution is practical since in 2020 the market share of gas scrubbers is estimated at 25 % of the world's marine fleet, i.e., ~ 20,000 vessels [5]. Gas purification systems currently deployed in the maritime domain are mainly replicate on-shore processes, in which the impact of sea swells on the scrubber performances is not considered at the design stage. It is argued that atmospheric emissions from offshore vessels are subject to the same phenomenology and those on-shore studies are insufficient to restore a faithful picture. Complex sea states pose remarkable technical challenges to the operation of onboard scrubbers, which may ultimately impede meeting treatment specifications. Ship oscillations and inclinations initiated by marine swells impact the performance of gas scrubbers [6]. Therefore, in this work we develop a $CO_2$ capture scheme for onboard floating vessel installation based on the implementation of structured packed beds as a high-efficiency gas-liquid contactor. A systematic experimental study is conducted to investigate the effect of ship tilt and motions on the $CO_2$ treating performance for onboard gas scrubbers thereby filling technical and methodological gaps in the marinization of multiphase structured packed beds.

## 2. Methods

For offshore $CO_2$ treating experiments, a hexapod robotic platform with six-degree-of-freedom motions including translations (surge, sway, heave) and rotations (roll, pitch, yaw) is employed to emulate actual floating vessel conditions. The packed bed is embarked on the hexapod robot as a mock-up representative of the scrubbing unit on floating platforms (Figure 1a). Mass transfer tests are conducted through injecting a $CO_2/N_2$ gas mixture (5% v/v $CO_2$) at the bottom of the bed as flue gas simulant and introducing a 30%wt mono-ethanolamine (MEA) aqueous solution at the bed top providing a counter-current mode of operation. An infrared gas analyzer is connected to the inflowing and outflowing gas streams to measure the $CO_2$ conversion in the scrubber under different ship excitations. At the same time, on-line measurements of the pressure drop over the entire scrubber are carried out using a differential pressure transmitter. The instrumentation is positioned firmly on the hexapod platform to carry out experimental measurements in a mobile reference frame. Besides, stationary vertical (0°) and stationary tilted (5°-15°) configurations of the

packed bed were also included in this study to allow comparisons between conventional onshore and offshore configurations. Thus, we address the modeling of the scrubber on a wave simulator robot to study the impact of sea swells on the $CO_2$ capture performance.

## 3. Results & Discussion

The experimental results reveal that the $CO_2$ concentration in the exit stream for a tilted scrubber is higher than the conventional vertical configuration, indicating an efficiency drop for $CO_2$ capture with MEA in the structured packed bed as a result of column deviation from verticality (Figure 1b). This worsening of $CO_2$ absorption performance can be ascribed to liquid maldistribution caused by the gravity-driven force pulling liquid to the lower wall regions and forcing the gas phase to move toward the upper wall regions. The formation of gas-rich and liquid-rich regions through the packing decreases dramatically the effective gas-liquid contact area for the mass transfer.

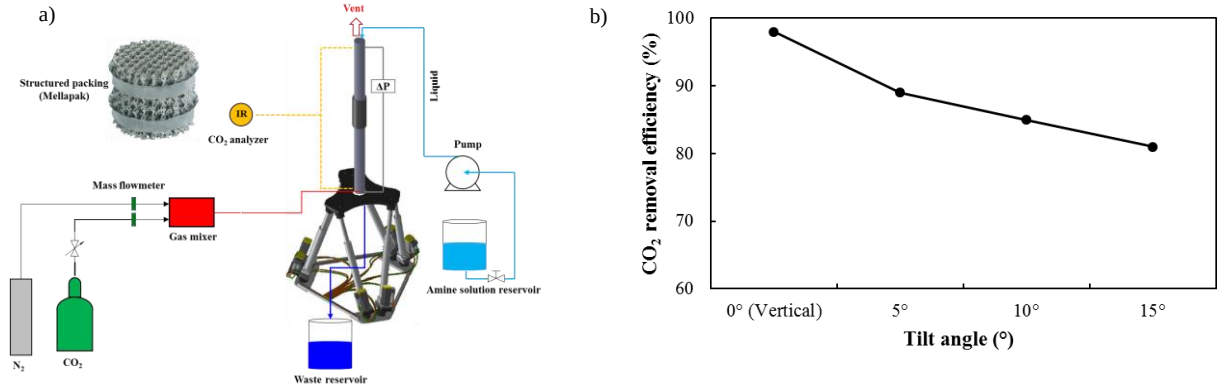


**Figure 1.** (a) Experimental setup, (b) $CO_2$ removal efficiency in structured packed bed as a function of tilt angle.

## 4. Conclusion

The $CO_2$ capture performance of the structured packed bed scrubber onboard floating vessel is assessed based on a systematic experimental study using a new state-of-the-art setup combining a hexapod robot with six-degree-of-freedom motions and an embarked packed column. We address the impact of ship oscillations and inclinations on the performance of the structured packed bed scrubber in terms of $CO_2$ capture and pressure drop. The results reveal that the scrubber performance under tilting deviates strongly from that of the conventional vertical beds. This indicates that the known characteristics of the conventional land-based packed bed scrubbers cannot be transposed on a one-to-one basis for design and scale-up of the offshore floating scrubber.

## References

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***Keywords***
$CO_2$ capture; offshore floating scrubber; ship tilt and oscillation; hexapod robot.


# Amir Motamed Dashliborun

## Personal Information

**Last Name:** Motamed Dashliborun
**First Name:** Amir
**Date of Birth:** April 14, 1987
**Address:** 2038 Boulevard Laurier, Québec, QC, Canada G1T 1B6
**Cell Phone:** (581) 681-2045
**Email:** amir.motamed-dashliborun.1@ulaval.ca & amotamed51@gmail.com
**Researchgate:** https://www.researchgate.net/profile/Amir_Motamed_Dashliborun
**Linkedin:** https://www.linkedin.com/in/amir-motamed-dashliborun-29235938/
**Google Scholar:** https://scholar.google.ca/citations?user=UTfSBo4AAAAJ&hl=en

## Education

- **Ph.D., Chemical Engineering,** Laval University, Québec, QC, Canada (**Jan 2014 – March 2018**)
  Ph.D. Thesis: Performance of Multiphase Packed Bed Scrubbers on Marine Floating Platforms: Hydrodynamics, Chemical Reaction, CFD Modeling and Simulation
- **M.Sc., Chemical Engineering,** University of Tehran, Tehran, Iran (**Sep 2010 - Sep 2012**)
  M.Sc. Thesis: Experimental Study and Modeling of Photocatalytic Oxidation of Volatile Organic Compound (VOC) by Titanium Dioxide Nano-Particles in a Fluidized Bed Reactor
- **B.Sc., Chemical Engineering,** University of Tehran, Tehran, Iran (**Sep 2006 - Sep 2010**)
  B.Sc. Thesis: Extension of Industrial Simulator Software to Simulate Non-Ideal Units in Chemical Engineering Processes

## Work Experience

**Laval University** **01/2014 – 03/2018**
**Chemical Engineering Department, Laval University, Québec, QC, Canada**
**Doctoral Research** *(Performance of multiphase packed bed scrubbers on marine floating platforms)*

- Designed the experimental setup and coordinated the construction process for "*marinization of a structured packed bed scrubber for $CO_2$ capture and $SO_2$ abatement*", in collaboration with Innovation Maritime (IM) & CO2 Solutions Inc.
- Carried out maintenance and management of laboratory equipment.
- Performed extensive setup troubleshooting to ensure stable operation.
- Designed and performed the experiments; collected, analyzed and interpreted the data.
- Investigated the effect of ship inclination, translational and rotational motions on the scrubbing performance of structured packed beds, reactants mixedness in the scrubber, their residence time, and the reaction yield.
- Proposed and explored several innovative operational strategies to reduce the fluid maldistribution stemming from sea swells in onboard packed bed scrubbers.
- Studying the optimum operating conditions and design parameters using a developed and validated computational fluid dynamics (CFD) model.
- Preparing presentations for internal meetings and international conferences as well as wrote scientific articles.

**Helmholtz-Zentrum Dresden-Rossendorf (HZDR)** **08/2015 – 11/2015**
**Institute of Fluid Dynamics, HZDR, Dresden, Germany**
**Research Fellow** *(Process intensification of multiphase packed bed systems–a part of Ph.D. research)*

- Introduced a new low-shear rotating reactor concept for process intensification of heterogeneous catalytic reactions in gas-liquid packed beds.
- Retrofitted the existing experimental setup for downflow and upflow modes of operation as well as column rotation.

- Developed MATLAB codes for the analysis of raw data obtained from WMSs and post-processing purpose.
- Planned and performed experiments.
- Investigated the effect of low-shear rotations of the column on gas-liquid flow patterns, liquid saturation, overall pressure drop, liquid axial dispersion, and mean residence time in packed beds.
- Developed a CFD model for the low-shear rotating packed bed reactor with gas-liquid cocurrent downflow mode of operation.
- Presented the findings in an international conference (ISCRE 24) and published the results in an ISI journal (AIChE J).

**University of Tehran** **10/2012 – 12/2013**
**Process Design and Simulation Research Center, Oil and Gas Centre of Excellence, University of Tehran, Tehran, Iran**
**Process Engineer** *(Oil and gas industry)*

- Evaluated feasibility of upgrading of heavy crude oils from economical and technical viewpoints for Iran's petroleum industry.
- Studied technology of RFCC, fluid coking, flexicoking, and gasification processes.
- Worked closely with plant engineers and discussed process details.
- Prepared basic and detailed technical reports.
- Educated process engineers in the framework of "Process simulation using industrial simulation software such as Aspen PLUS & Aspen HYSYS" courses.
- Prepared research proposals to acquire new funding.

**University of Tehran** **09/2010 - 09/2012**
**School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran**
**M.Sc. Research** *(Photocatalytic oxidation of VOCs using nano-particles in a Fluidized Bed Reactor)*

- Designed and fabricated an annular fluidized bed reactor, gas distributor, and cyclone.
- Purchased and installed equipment for the experimental setup & conducted preliminary tests for troubleshooting.
- Investigated experimentally and numerically the hydrodynamic behavior of the annular fluidized bed reactor using pressure fluctuation analysis and CFD simulation, respectively.
- Studied photocatalytic reaction of VOCs over $TiO_2$ nano-particles in the annular fluidized bed reactor.
- Scrutinized the influence of kinetic and hydrodynamic parameters on the reactor performance in degradation of VOCs and air treatment.
- Published the results as articles and presented the results in a national congress.

## Teaching Experience

- 01/2013-06/2013 Teaching assistant in ''*Computer aided design and simulation in gas industry*''. M.Sc. Course. Univ. of Tehran.
- 09/2012-06/2013 Teaching assistant in ''*Advanced chemical engineering mathematics*''. M.Sc. Course. Univ. of Tehran.
- 09/2012-01/2013 Teaching assistant in ''*Computer aided process simulation*''. B.Sc. Course. Univ. of Tehran.
- 01/2012-06/2012 Teaching assistant in ''*Process control in chemical engineering*''. B.Sc. Course. Univ. of Tehran.
- 01/2012-01/2013 Teaching assistant in ''*Applied mathematics in chemical engineering*''. B.Sc. Course. Univ. of Tehran.

## Activity and Membership

- **Chair** of ''***Thermodynamics and Kinetics***'' and ''***Physicochemical Separation***'' sessions in 66th Canadian Chemical Engineering Conference, October 16-19 (2016), Québec, QC, Canada
- Member of **CIC (Chemical Institute of Canada)**
- Member of **ISIPT (International Society for Industrial Process Tomography)**


- Member of **IAChE ( Iranian Association of Chemical Engineering)**
- Member of **INIC ( Iran Nanotechnology Initiative Council)**

## Honors & Awards

- Selection of the paper: "Hydrodynamics of gas-liquid cocurrent upflow in oscillating packed beds for offshore marine applications" as a key scientific article contributing to research excellence in science and engineering by **Advances in Engineering**, April 2017. https://advanceseng.com/chemical-engineering/hydrodynamics-gas-liquid-co-current-flow-oscillating-packed-beds-offshore-marine-applications/
- Research Fellow, Helmholtz-Zentrum Dresden-Rossendorf (**HZDR**), Dresden, Germany, August-November 2015.
- Ph.D. Scholarship from the Natural Sciences and Engineering Research Council of Canada (**NSERC**), the **Canada Research Chair on Sustainable Energy Processes and Materials**, and Le Réseau Québec Maritime (**RQM**), Department of Chemical Engineering, Laval University, Québec, QC, Canada , 2014-2017.
- Tuition Fee Exemption Scholarship, **Laval University**, Québec, QC, Canada, 2014-2016.
- M.Sc. thesis financial support from Iran Nanotechnology initiative council (**INIC**), University of Tehran, Iran, 2011-2012.

## Refereed Articles

1. **Amir Motamed Dashliborun**, Alexander Füssel, and Faïçal Larachi, *"Prospect of open-cell solid foams for floating-platform multiphase reactor applications - Maldistribution susceptibility and hydrodynamic behavior",* Chemical Engineering Journal, 332, 596-607, 2017.
2. **Amir Motamed Dashliborun**, Mohsen Hamidipour, and Faïçal Larachi, *"Hydrodynamics of inclined packed beds under flow modulation - CFD simulation and experimental validation",* AIChE Journal, 63, 4161-4176, 2017.
3. **Amir Motamed Dashliborun**, Faïçal Larachi, and Markus Schubert, *"Offshore floating packed bed reactors: Key challenges and potential solutions",* Chemical Engineering & Technology, in press, 2017. https://doi.org/10.1002/ceat.201700073
4. **Amir Motamed Dashliborun**, Faïçal Larachi, and Markus Schubert, *"Hydrodynamics of gas-liquid cocurrent upflow in oscillating packed beds for offshore marine applications",* Chemical Engineering Science, 170, 583-596, 2017.
5. **Amir Motamed Dashliborun**, Hans-Ulrich Harting, Markus Schubert, and Faïçal Larachi, *"Process intensification of gas-liquid downflow and upflow packed beds by a new low-shear rotating reactor concept",* AIChE Journal, 63, 283-294, 2017.
6. **Amir Motamed Dashliborun**, Faïçal Larachi, and Mohsen Hamidipour, *"Cyclic operation strategies in inclined and moving packed beds – Potential marine applications for floating systems",* AIChE Journal, 62, 4157-4172, 2016.
7. **Amir Motamed Dashliborun** and Faïçal Larachi, *"Hydrodynamics of gas-liquid cocurrent downflow in floating packed beds",* Chemical Engineering Science, 137, 665-676, 2015.
8. Gnouyaro P. Assima, **Amir Motamed-Dashliborun**, and Faïçal Larachi, *"Emulation of gas-liquid flow in packed beds for offshore floating applications using a swell simulation hexapod",* AIChE Journal, 61, 2354-2367, 2015.
9. Hamid Asadi-Saghandi, Rahmat Sotudeh-Gharebagh, **Amir Motamed Dashliborun**, Hossein Kakooei, and Mohammad Hajaghazadeh, *"Sequential-based process modelling of VOCs photodegradation in fluidized beds",* Canadian Journal of Chemical Engineering, 92 (11), 1865-1874, 2014.
10. **Amir Motamed Dashliborun**, Rahmat Sotudeh-Gharebagh, Mohammad Hajaghazadeh, and Hossein kakooei, "*Simulation of volatile organic compounds photocatalytic removal in a fluidized bed reactor*", Iranian Journal of Chemistry and Chemical Engineering (in Persian), 33 (1), 57-65, 2014.
11. **Amir Motamed Dashliborun**, Shohreh Fatemi and Ali Taheri Najafabadi, *"Hydrogen production through partial oxidation of methane in a new reactor configuration",* International Journal of Hydrogen Energy, 38, 1901-1909, 2013.

12. **Amir Motamed Dashliborun**, Rahmat Sotudeh-Gharebagh, Mohammad Hajaghazadeh, Hossein kakooei and Shahrara Afshar, "*Modeling of the photocatalytic degradation of methyl ethyl ketone in a fluidized bed reactor of nano-$Tio_2$/γ-$Al_2O_3$ particles"*, Chemical Engineering Journal, 226, 59-67, 2013.
13. Mohammad Hajaghazadeh, Hossein kakooei, **Amir Motamed Dashliborun**, Rahmat Sotudeh-Gharebagh Farideh Golbabaie, Shahrara Afshar and Abbas Rahimi Forushani, "*Photocatalytic degradation of methyl ethyl ketone by Nano $TiO_2$ in a fluidized bed reactor"*, Fresenius Environmental Bulletin, 22 (2), 435-440, 2013.
14. Mohammad Hajaghazadeh, Hossein kakooei, **Amir Motamed Dashliborun**, Rahmat Sotudeh-Gharebagh, Farideh Golbabaie, Shahrara Afshar and Abbas Rahimi Forushani, "*Photocatalytic degradation of methyl ethyl ketone in a fluidized bed reactor: A factorial design analysis"*, Fresenius Environmental Bulletin, 22 (6), 1719-1726, 2013.

## Selected Conference Presentations

1. **Amir Motamed Dashliborun**, Faïçal Larachi, and Markus Schubert, "*Hydrodynamics of gas-liquid cocurrent upflow in oscillating packed beds for offshore marine applications"*, The 13th International Conference on Gas-Liquid & Gas-Liquid-Solid Reactor Engineering (GLS 13), Brussels, Belgium, August 20 - 23 (2017).
2. **Amir Motamed Dashliborun**, Alexander Füssel, and Faïçal Larachi, "*Open-cell solid foam packed beds subject to floating platform motions: maldistribution susceptibility and hydrodynamic behavior"*, The 10th International Symposium on Catalysis in Multiphase Reactors (CAMURE-10) & the 9th International Symposium on Multifunctional Reactors (ISMR-9), Qingdao, China, July 7-10 (2017).
3. **Amir Motamed Dashliborun**, Faïçal Larachi, Mohsen Hamidipour, and Markus Schubert, "*Offshore floating packed-bed reactors: Current status, key challenges and potential solutions"*, 2016 AIChE Annual Meeting, San Francisco, USA, November 13-18 (2016).
4. **Amir Motamed Dashliborun**, Mohsen Hamidipour, and Faïçal Larachi, "*Hydrodynamics of offshore floating packed-bed reactors: Experimental studies and CFD simulations"*, The 66th Canadian Chemical Engineering Conference (CSChE2016), Québec City, Canada, October 16-19 (2016).
5. **Amir Motamed Dashliborun**, Hans-Ulrich Harting, Markus Schubert, and Faïçal Larachi, "*Process intensification of gas-liquid cocurrent downflow and upflow packed bed reactors by a new low-shear rotating tubular fixed bed concept"*, The 24rd International Symposium on Chemical Reaction Engineering (ISCRE 24), Minneapolis, USA, June 12-15 (2016).
6. **Amir Motamed Dashliborun**, Faïçal Larachi, Hans-Ulrich Harting, Markus Schubert, and Eckhard Schleicher, "*Hydrodynamics of concurrent gas-liquid flows in inclined rotating and floating packed beds"*, The 7th International Symposium on Process Tomography (ISPT 7), Dresden, Germany, September 1 - 3 (2015).
7. **Amir Motamed Dashliborun**, Gnouyaro P. Assima, and Faïçal Larachi, "*Cyclic Operation Strategies in Inclined and Moving Trickle Beds - Potential Marine Applications for Floating Systems"*, The 12th International Conference on Gas-Liquid & Gas-Liquid-Solid Reactor Engineering (GLS 12), New York, USA, June 28 - July 1 (2015).
8. Gnouyaro P. Assima, **Amir Motamed Dashliborun**, and Faïçal Larachi, "*Shaking gas-liquid flows in porous media with a notus hexapod swell simulator"*, The 23rd International Symposium on Chemical Reaction Engineering (ISCRE 23), Bangkok, Thailand, September 7-10 (2014).
9. **Amir Motamed Dashliborun**, Rahmat Sotudeh-Gharebagh, Mohammad Hajaghazadeh, Hossein kakooei and Shahrara Afshar, "*Photocatalytic oxidation of VOCs in a fluidized bed reactor"*, The 14th Iranian National Congress of Chemical Engineering (ICHEC 14), Sharif University of Technology, Tehran, Iran, October (2012).
10. **Amir Motamed Dashliborun**, Shohreh Fatemi and Ali Taheri Najafabadi, *"Improve performance of partial oxidation of methane in a fixed bed reactor with stagewise injector of Air",* The 14th Iranian National Congress of Chemical Engineering (ICHEC 14), Sharif University of Technology, Tehran, Iran, October (2012).