Marinization of a Multiphase Packed Bed Scrubber for Offshore CO₂ Capture

Amir Motamed Dashliborun, Faïcal Larachi,* Seyed Mohammad Taghavi

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

*Corresponding author: Faical.Larachi@rch.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 CO₂ capture.

1. Introduction

CO₂ 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 CO₂ 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 CO₂ 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 CO₂ treating performance for onboard gas scrubbers thereby filling technical and methodological gaps in the marinization of multiphase structured packed beds.

2. Methods

For offshore CO₂ 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 CO₂/N₂ gas mixture (5% v/v CO₂) 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 CO₂ 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 CO₂ capture performance.

3. Results & Discussion
The experimental results reveal that the CO₂ concentration in the exit stream for a tilted scrubber is higher than the conventional vertical configuration, indicating an efficiency drop for CO₂ capture with MEA in the structured packed bed as a result of column deviation from verticality (Figure 1b). This worsening of CO₂ 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](image.png)

**Figure 1.** (a) Experimental setup, (b) CO₂ removal efficiency in structured packed bed as a function of tilt angle.

4. Conclusion
The CO₂ 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 CO₂ 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

Keywords
CO₂ 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)
• M.Sc., Chemical Engineering, University of Tehran, Tehran, Iran (Sep 2010 - Sep 2012)
• 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 CO₂ capture and SO₂ 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 TiO₂ 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
- 09/2012-06/2013 Teaching assistant in “Advanced chemical engineering mathematics”. M.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 ISIP (International Society for Industrial Process Tomography)
Member of IAChE (Iranian Association of Chemical Engineering)
Member of INIC (Iran Nanotechnology Initiative Council)

Honors & Awards
- 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.

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