

# Capacitance wire mesh imaging of bubbly flows for offshore treatment applications



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## ABSTRACT

The impact of ship motion on bubbly flow was emulated using a swell simulator to expose flow structure changes emerging in bubble columns relevant to offshore floating applications. Roll, roll+pitch, yaw, heave and sway were implemented at various frequencies and changes in bubbly flow resulting from the imposed motions were monitored for the first time by means of a dual capacitance wire mesh sensor to measure local gas holdup and velocity. Visualizations of the two-phase flow revealed that roll, roll+pitch, and high-frequency sway were the most impactful in terms of bubble zigzag and swirl, and bubble-clustering and segregation due to vessel dynamic inclinations. As a consequence of these motions, lateral migration of bubbles and their clustering enhanced liquid recirculation and local streamwise gas velocity. Compared to static vertical bubble column, bubbly flow pattern was barely altered by yaw and low-frequency sway except the heave displacements which tended to slowdown the bubble rise.

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## 1. Introduction

Three main types of multiphase reactors, namely, trickle beds, ebullated (or gas–liquid–solid fluidized) beds and (slurry) bubble columns, are commonly used in chemical, biochemical, petrochemical, and wastewater treatment operations [1]. Bubble columns imposed themselves as the simplest among them by being auspicious in accomplishing various processes such as petroleum residues conversion, hydrotreating, Fischer–Tropsch synthesis, coal liquefaction, hydrogenation, wastewater treatment [2–5] and so forth. Bubble columns as multiphase reactors are perceived to be particularly useful in fuel processing and gas treatment applications with regard to offshore oil and gas fields in deeper water and areas far off continental shores on account of an increasing scarcity of land-based hydrocarbon reserves [6]. Remoteness of oil and gas production sites is matter-of-factly imposing technology shifts in order to meet with specific offshore exploitation constraints [7]. Among the systems envisioned as viable options for deep-water/offshore fields, floating production storage and off-loading (FPSO) units are gaining momentum among industry players as they allow integration on the same floating systems of extraction, production and storage operations. Basically, FPSO units allow extracted hydrocarbons to be treated and refined on-site by means of onboard multiphase reactors [8].

Implementation of efficient (slurry) bubble columns requires good gas–liquid contacting whereby often gas flows as a discontinuous phase rising in the form of bubbles through a continuous liquid or slurry phase. From a practical viewpoint, the dispersed phase and corresponding rise velocity, by being sensitive to buoyancy, could be strongly impacted by the sea swells that ceaselessly assault FPSO units. To the best of the authors' knowledge, despite the growing significance of petroleum FPSO applications and potential on-board installation of multiphase reactors, investigations on flow dynamics of floating bubble columns is a virgin field of research. There are a few studies in the literature, which exclusively tackled hydrodynamic issues arising from static inclined bubble columns [9,10]. So far, only floating packed beds and fluidized beds received somewhat more coverage. Indeed, inclined configurations are increasingly studied in terms of flow behavior and phase maldistribution in packed and fluidized beds [11–17]. Other studies were interested on emulating fluidized beds under rolling motion with relevance to marine use [18–24], though disregarding the impact of other ship-motion degrees of freedom such as surge, sway and heave (translations), and pitch and yaw (rotations).

For the sake of providing additional knowledge in this emerging area of multiphase flows and reactors, the present study's object of scrutiny consisted of a liquid-batch bubble column operated in the homogeneous bubble flow regime and embarked on a hexapod ship motion simulator, which was submitted to a variety of motion regimes. Single sinusoidal excitations of roll,

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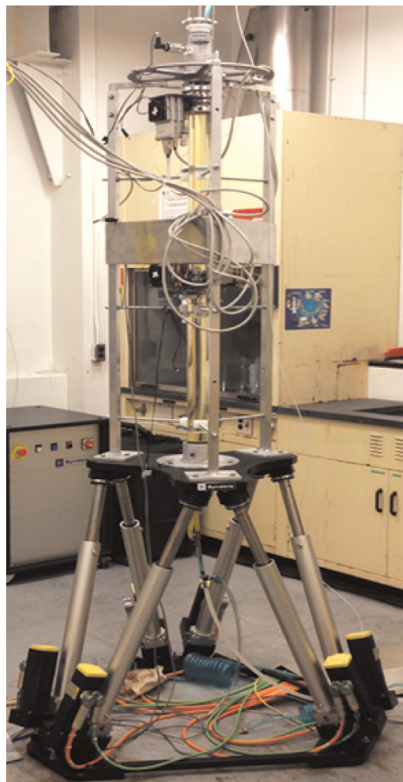
sway, heave, yaw and coupled sinusoidal excitations of roll+pitch were tested and a dual capacitance wire-mesh sensor inserted in the bubble column was employed to measure on-line the local void fraction and axial gas velocity. This wire mesh sensor technique, tested for the first time on a moving bubble column, enabled measurements in two-phase flows by sensing at high frequency and with millimeter spatial resolutions the local electrical capacitance in the vessel cross-wise planes. Post-processing algorithms thence enabled retrieving, after suitable calibration, the local void fractions, phase distributions, and with dual sensors, velocity hydrodynamic information. As a general tendency of the assessed column programmed motions, preliminary tests indicate a reduction of gas phase mean residence chiefly attributed to bubble upper-wall clustering and segregation foreshowing degradation of gas–liquid contacting of bubble columns onboard FPSO units.

## 2. Experimental

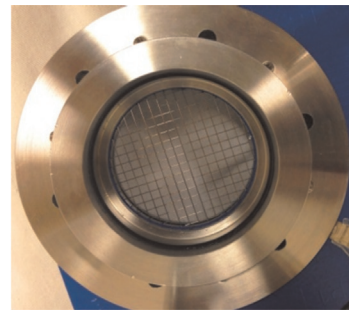
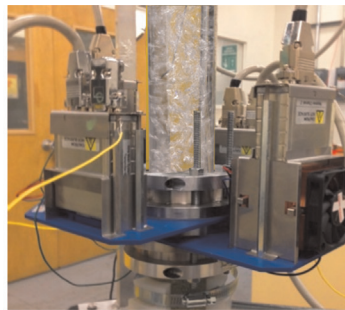
The moving bubble column assembly illustrated in Fig. 1 consisted of (1) a 5.7 cm inner-diameter and 170 cm high Plexiglas column equipped with (2) a flange-connectible dual  $16 \times 16$  capacitance wire-mesh sensor (HZDR-Innovation GmbH, Dresden, Germany) to collect gas voidage, gas velocity and flow pattern information, while the whole of which was firmly upheld on (3) a 6-degree-of-freedom hexapod platform simulator (Symétrie, Nîmes, France) to emulate ship motion conditions.

Wire-mesh sensors belong to the realm of flow imaging techniques. Despite their intrusive character, they allow investigation of multiphase flows at high temporal resolutions. In addition, with their millimeter spatial resolution, they outperform their non-invasive direct rival techniques such as electrical capacitance

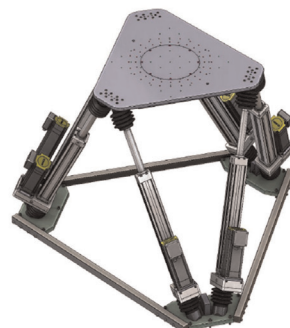
tomography [12]. Being electrical-field based, wire-mesh capacitance sensors enable measurement of the medium electrical permittivity in confinements between two planes of wire electrodes stretched through the flow cross-section [25–28]. In dual capacitance wire mesh sensors such as the one employed in this study, the two wire mesh modules were 12 mm apart (as illustrated from photo on the left of item (2) in Fig. 1 by the two blue plates) and were located 70 cm from the gas inlet (Fig. 1). Each wire-mesh sensor consisted of two orthogonally-arranged (upstream and downstream) planes, 1.5 mm afar, each made of 16 parallel stainless steel wires 0.4 mm in diameter. The upstream and downstream wire planes were, respectively, excited in transmission and reception modes. Such arrangement provided a spatially-resolved cross-sectional matrix of permittivity data composed of 148 full-square core pixels of  $3.57 \times 3.57 \text{ mm}^2$  each and 40 peripheral area-reduced wall pixels for which only areal fractions inscribed within the flow region of interest were accounted for. The measuring technique gave access to a local multiphase mixture permittivity at each touchless nodal (cross-point) voxel stemming for the perpendicularly meeting transmission and reception wires (Fig. 1). To permit signal disambiguation of the excited nodal voxels, the sensor electronics briefly excited but one transmitting wire during a few  $\mu\text{s}$  with a high-frequency AC voltage while keeping all the other transmitting wires disabled at ground potential by means of a set of analog switches. The resulting AC currents established between the activated transmitter electrode and the receiving wire electrodes of the downstream plane were converted into proportional dc voltages detected in parallel by means of sensing blocks which include trans-impedance amplifiers, logarithmic demodulators and voltage amplifiers. The measured dc output voltages were related to the fluid electrical permittivity in the control volume surrounding each two-wire junction. A micro-controller was in charge of the analog switches and ADC timing.



(1)



(2) Capacitance wire mesh sensor (CWMS)



(3) Motion simulator hexapod

**Fig. 1.** Layout and components of the hexapod/wire-mesh sensor/bubble Plexiglas column assembly (1), capacitance wire-mesh sensor (2), and ship motion simulator (hexapod) (3). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

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