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Experimental Investigation on Plume Enlargement and Fountain Effect Due to Gas Blowout nn Seawater

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The present paper focuses on experimental tests performed in an experimental outdoor basin with three gases (air, CO_2 and methane) in order to characterize the consequences of underwater gas release. Water elevation (fountain effect) and surface velocity where measured for various mass flow. Results for maximum water elevation clearly show a strong influence of gas flow rate with an increase of water elevation with decrease of gas density. Results obtained for current velocity with air and methane release show an increase of water velocity with gas flow rate. On the contrary, for CO_2 release water velocities are lower due to solubilization process of CO_2 in water column involving decrease of gas momentum.

1. Introduction

Due to the increasing of demand for gas and oil, deep-ocean drilling has increased drastically and most oil companies extend drilling to abyssal areas. Extraction in these deep areas involves industrial hazards to people and equipment in the case of wellhead or a broken riser which may involve a loss of buoyancy due to blowout; a toxic zone linked to the gas cloud at the sea surface or an explosion or a fire related to the gas cloud (Johansen & Cooper, 2003; Fingas, 2017). The underwater releases of natural gas, resulting from accidents in offshore drilling or broken gas pipelines, are currently the major danger for ships and offshore structures. A total of 320 accidents are reported by Sintef (Holand, 1983) between 1970 and 1995 in the various areas in the world (Gulf of Mexico, the Outer Continental Shelf and the North Sea). The last worst environmental disaster was the Deepwater Horizon drilling accident that occurred on 20 April 2010. The four million barrels of oil that were released into the Gulf of Mexico involved important environmental impact and strong consequences on human activities (Pereira, 2015 and Thibaut, 2016). Those potential hazard make it mandatory to know when, how, where and in which quantities the gas will reach the surface of the ocean. Various investigation on the dynamics breakup of drops and bubbles in both turbulent flows and quiescent conditions exist (Hinze, 1955; Grace et al., 1978; Friedl 1998; Martinez-Bazan et al. 1999; Frield & Fannelop, 2000; Eastwood et al., 2004; Solsvik et al., 2016), but there are few experimental studies focusing on the gas impact at sea surface. Or, in the case of underwater gas leak, the risk of loss of buoyancy of a structure corresponds to its depression due to a decrease in densities in the plume and can be extended to the phenomenon of loss of stability. Indeed, the effort due to the speed of the water driven by the bubbles, directed upwards, is much higher than the loss of buoyancy. The total effort applied by the plume is directed upwards. The loss of stability therefore represents a greater risk than the loss of buoyancy identified initially.

2. Experimental setup

Experimental tests presented in the present paper have been performed in the Cedre outdoor basin. This test device is mainly used to deploy and test response means during training course. Basin is extended over 1900 m² and it is filled with seawater with salinity of 21 psu and its water depth can be modified between 2 m to 3 m. A homemade floating cell was deployed in the middle of basin to avoid the boundary effects (Figure 1) to fix

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the sensors. A 10 mm internal diameter nozzle was located at the center of the floating structure at 2.45m of depth. Three different gas were used to analyze the fate of gases at the water surface, compressed air, CO2 and methane. Air was used as non-hazardous, low soluble gas and to calibrate the experimental device. Carbon dioxide was used as a soluble gas and methane, which is a major component of natural gas, was used as slightly soluble product. Physico-chemical properties of air, CO_2 and methane are listed in Table 1 for atmospheric pressure and ambient temperature. A Gas mass flow regulator SLA5853 Series of Brooks Instrument was used to measure and control the gas mass flow rate during the test. Different flow rates were manually adjusted from 25 l/min to 400 l/min. To control the release conditions, temperature and pressure are respectively measured inside injection pipe before flow regulator with thermocouple K while pressure transducer between 0-40 bar with an accuracy of 5% of full scale.

Table 1: Fluid physical properties for air, CO2 and methane at atmospheric pressure and ambient temperature (NIST Webbook of physical properties of fluid systems)

Chemical	Air	Carbon Dioxide	Methane
CAS number	132259-10-0	124-38-9	74-82-8
Molecular weight (g/mol)	28.96	44.01	16.04
Density at 25°C [$kg.m^{-3}$]	1.292	1.83	0.66
Henry's law constant at 25°C ($atm.m^3/mol$)	/	0.0152	0.6576
Hydrosolubility in fresh water at 25°C [mg/L]	/	1475	22
Hydrosolubility in fresh water at 25°C [mmol/L]	/	33.5	1.4
Interfaciale tension at 25°C [N/m]	/	0.055	0.071
Dynamic viscosity at 25°C [Pa.s]	$1.849\ 10^{-5}$	$1.49\ 10^{-5}$	$1.12\ 10^{-5}$

Mass flow measure corresponds to normal value (Patm, 0°C) at the vertical of gas injection device located at 2.45 m depth. The water elevation was measured with 7 handmade capacitive sensors (Figure 3) connected to an electronic module which make the probe capacity conversion into period. This module is then connected to an electronic integrator to convert the periods into voltage (± 10V) and acquisition is performed with National Instrument 9205 acquisition cards with a frequency of 10 000 Hz. In the present investigation, first probe (P1) was located at the vertical of fountain effect and others at different radial distance as mentioned on Figure 2.

Figure 1: Illustration of the experimental floating cell; b) capacitive probe for water elevation measurements

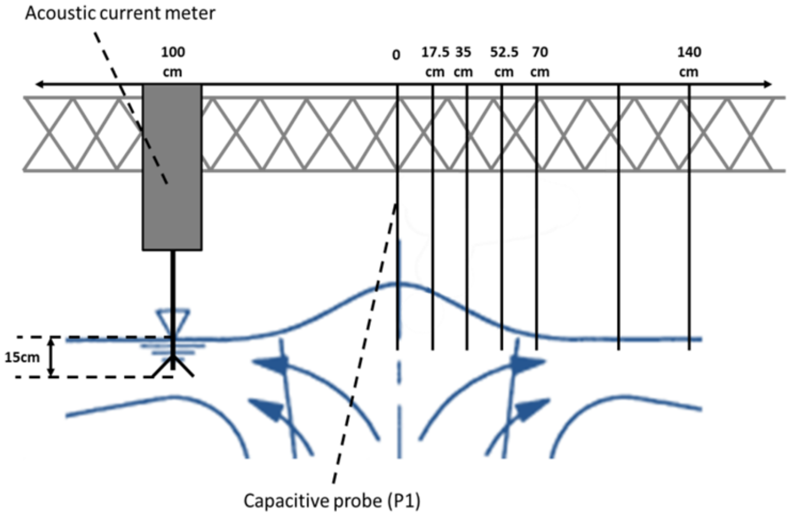

Figure 2: Illustration of location of capacitive probes to measure water elevation and acoustic current meter

A 3D acoustic velocimeter (Vector – Nortek) was immerged at 15 cm below the sea surface and at 1m of fountain effect to measure the horizontal surface current average velocity (Figure 4). The measurement range is between 0.01 and 7 m/s, accuracy is ± 0.5% of measured value and sampling rate was configured at 8Hz. The system uses the Doppler effect to measure current velocity by transmitting short pairs of sound pulses, listening to their echoes and measuring the change in pitch or frequency of the returned sound. It transmits through a central beam and receives through three beams. The Vector uses three receivers, all focused on the same volume, it obtains three velocity components from this volume. It noticed that if air bubbles are inside the transmit transducer; this can induced an error in measurement.

Figure 3: Illustration of handmade capacitive probe for water elevation measurements

Figure 4: 3D acoustic velocimeter (Vector – Nortek) for horizontal surface current average velocity

3. Results analysis

Figure 5 shows a typical result for water elevation measured by capacitive probe during a test carried out with methane and a mass flow rate of at 1.43g.s^{-1}. These data correspond to the variation of the voltage related to the variation of the water height measured by the electronic module linked to the capacitive probe. The fluctuations observed on the first part of the curve (red dashed area) represent the wave at water surface due to the wind. The second part of the curve (green dashed area) represents the rise of the water due to methane release. It can be noted that after the blowout test, the level of the water measured by the capacitive probe returns to its original level. The measurement of the mean elevation of the water level is done by subtracting the average elevation calculated on the green area from the average elevation calculated on the red zone. The purple circle represents the maximum elevation value recorded during the test.

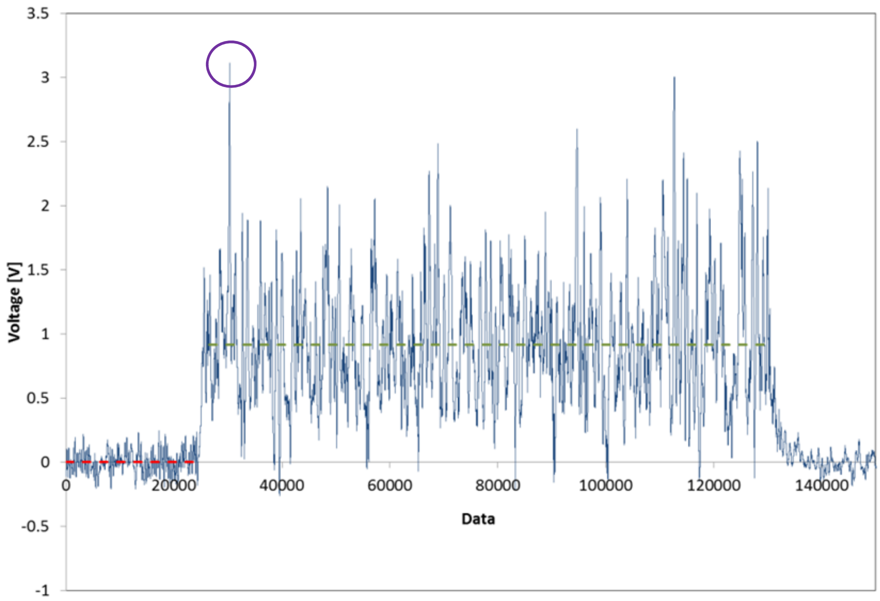

Figure 5: Illustration of typical measurement signal for water elevation parameter (CH_4, 1.43 $g.s^{-1}$))

Concerning current velocities measurements, the Figure 6 shows raw data for the XYZ module of water velocity measured with the 3D current meter during a methane release of 10.02 g.s-1. The red dashed area represents the velocity due to the wind at the water surface and the blue dashed area represents the variations in the velocity of the surface current associated with the methane release. The calculation of the average velocity is then obtained by the average calculation of the modulus for the 3 components of the velocity.

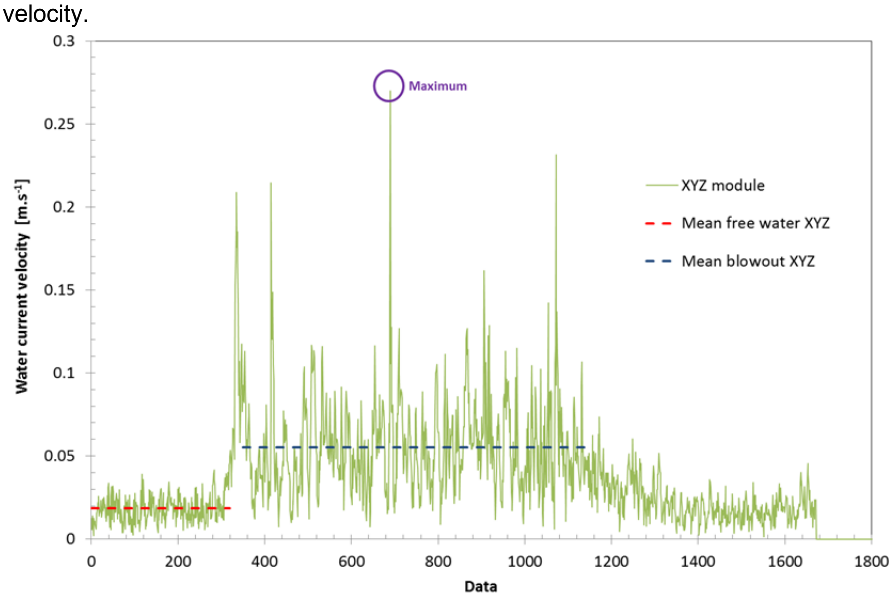

Figure 6: Illustration of typical signal for velocity modulus of water current (CH_4, 10.02 $g.s^{-1}$)

Figure 7 presents a comparison of water elevation regarding to the gas mass flow rate for the different tested fluids. For a given mass flow rate, results clearly show that maximum water elevation obtained with methane are greater than air data which are higher than those obtained for CO_2. These remarks can be easily explicated by the difference between fluids density. Methane density is lower than air and CO_2, so for a given mass released in water, methane volume will be two times larger than for the air and approximatively three times larger than for the CO_2. The momentum quantity will be greater and water elevation at the surface will be higher. Water velocity measurements clearly show an increase of water surface velocity with gas flow rate (Figure 8). The increase of gas flow rate involves the increase of gas momentum and then an increase of entrained water in the zone of pure plume. At the surface, the rising water is deflected outward in a radial flow yielding to an increase of the water surface velocity. The comparison of current velocity at water surface between the different tested fluids shows that for same gas mass flow rate, same trends are observed for air and methane data and differences for CO_2 results. This may be due to solubilization process of CO_2 in the water column involving decrease of bubbles and then decrease of entrained water.

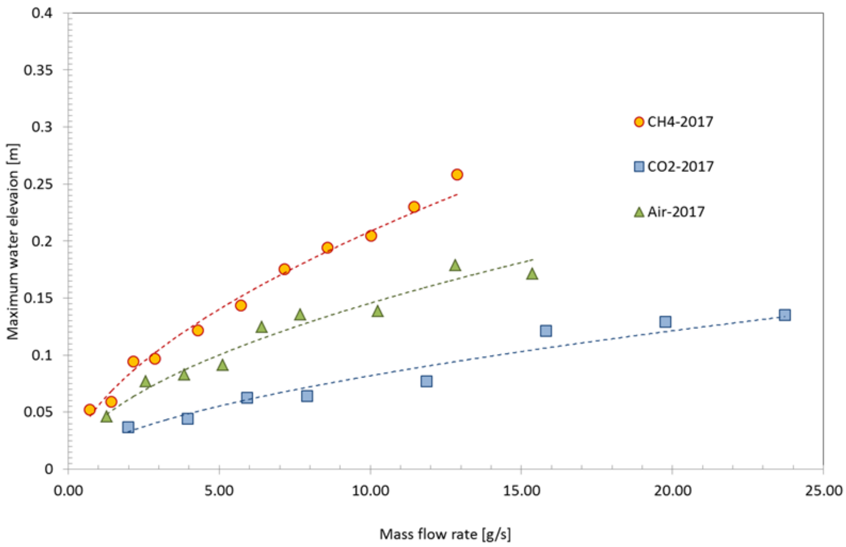

Figure 7: Comparison of the maximum water level variation regarding to gas mass flow rate for the tested fluids

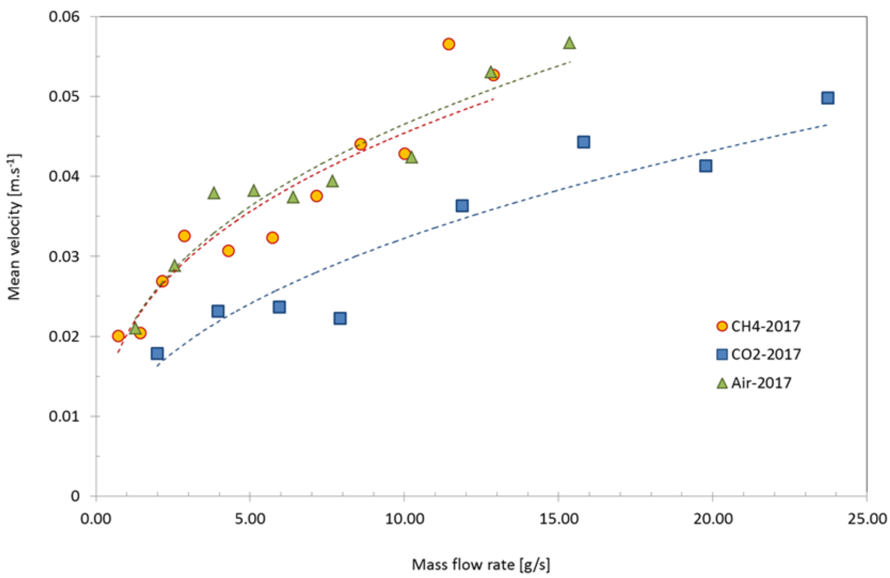

Figure 8: Comparison of the variation of the mean water velocity regarding to gas mass flow rate for the tested fluids

4. Conclusions

A source of error for small-scale experiments is mainly due to the use of simulated gas as compressed air or nitrogen in comparison with quantities measured, such as fountain height or wter surface velocity. The present paper presents the results obtained for tests performed in Brest in the Cedre's basin. These tests are realized with three fluids (air, CO_2 and methane) in order to evaluate the consequences of underwater gas release and in particular in the case of blowout accident with methane. Water elevations due to fountain effect were measure at different radial distance with 7 capacitive probes. On the other hand, the results obtained for maximum water elevation show strong influence of gas flow rate with an increase of elevation with decrease of gas density. Results obtained for current velocity measurements at the surface level show an increase of water surface velocity with gas flow rate. It noticed the same trends for current velocity for air and methane release. On the contrary, water surface velocities obtained for CO_2 release are lower than those obtained for air and methane release. This may be due to solubilization process of CO_2 in water column involving decrease of gas momentum.

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