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Autonomous real-time sea spray measurement system for offshore structures

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ABSTRACT

Sea spray icing can pose a risk to offshore structures in cold climate, affecting the operability and in the worst case the stability of the structure. One of the most uncertain parameters when attempting to estimate the design load from sea spray icing is the flux of sea water reaching the topside. Typically, the only available measurements of sea spray have been recorded on smaller fishing or navy vessels, with estimates varying with orders of magnitude and being of less relevance for large, stationary offshore structures. One of the challenges with observations of sea spray has been that the applied measurement principles have required frequent manual intervention by dedicated personnel. The present paper describes a real-time measurement system designed for recording sea spray flux on producing offshore oil and gas facilities as part of the joint industry project RigSpray. Two of the principal requirements for the system was that it had to be autonomous and that it satisfied ATEX directives for equipment in potentially explosive atmospheres. This is accomplished by live wireless data transfer from the flux meters and utilizing standard ATEX certified components as building blocks. The system consists of both flux meters and a video recording system and has been in operation on the Equinor operated ship-shaped floating production, storage and offloading (FPSO) unit Norne in the Norwegian Sea since September 2017. Prior to full-scale deployment, a prototype was tested at the VELUX wind tunnel facility at variable wind speed and water injection rates. Along with accompanying environmental data and vessel motions, the spray measurements are providing a vital calibration data set for spray models on large ship-shaped offshore structures.

KEY WORDS Sea Spray Icing; Spray flux; Fluxmeter; ATEX.

INTRODUCTION

Sea spray icing is one of the environmental actions that needs to be considered when designing offshore structures in cold climate regions. According to the ISO19906:2010 standard (International Organization for Standardization [ISO], 2010), theoretical models of marine icing may be used to estimate ice accretion if “suitably calibrated against observations”. Several theoretical models have been developed during the past decades with the purpose of estimating loads from sea spray icing, e.g. ICEMOD (Horjen, 1990), RIGICE (Forest et al 2005), MARICE (DNV, 2014; Kulyakhtin, 2015), NuMIS (Hansen & Teigen, 2015). One common trait with the theoretical models is the need for empirical data to calibrate the spray flux associated with wave-interaction for different structure types, since attempts to model the entire spray generation process numerically have so far been proven to be computationally demanding and still suffers from lack of observational data to compare with (Shipilova & Kulyakhtin, 2012). Kulyakhtin (2015) showed that the empirically based spray flux used by ICEMOD and RIGICE differs with a factor of several orders of magnitude and points to spray flux as the main uncertainty in icing estimates, recommending doing more spray measurements. Bøckmann et al. (2019) showed that more accurate data and modelling of the extent of run-up/wave washing on vertical structures is also essential, since the maximum accreted ice thickness occurs right above the zone being washed by the waves. The sensitivity of icing estimates to spray flux is illustrated by running the NuMIS model with the same parameters as the base case in (Hansen & Teigen, 2015) and just scaling the incoming spray flux (Figure 1). For this case, which simulates spray icing on a semi-submersible drilling rig, a 50% increase in the incoming spray leads to a 25% increase in the total accreted ice mass. For lower spray amounts, the relationship becomes closer to 1:1 (mass limited ice accretion).

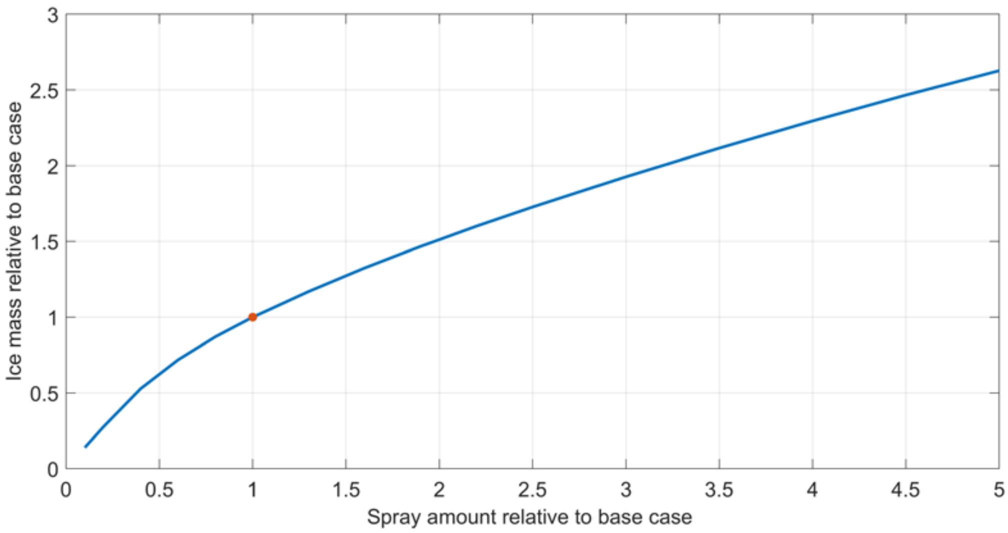

Figure 1. Dependency between amount of accreted ice and spray simulated with NuMIS for the base case considered in (Hansen & Teigen, 2015).

A few data sets form the basis for calibrating spray flux, droplet size distribution, spray duration and spray interval in the existing icing models (Bodaghkhani et al., 2016), employing a variety of measurement techniques. Around 1970, Soviet researchers made spray measurements on medium-sized fishing vessels, that were later used by researchers at University of Alberta to calibrate their model (Zakrzewski, 1987). Details about how the observations were carried out are not known (Minsk, 1977). Itagaki (1977) refers to sea spray measurements carried out by weighing absorbing material (toilet paper tissue) that was exposed to sea spray at different locations in the bow area of a vessel, which required changing the absorbing material every 5-6 minutes. At the artificial island Tarsuit, which was constructed for doing exploration drilling in the Canadian Beaufort Sea in the early 1980s, measurements of spray were performed by measuring the water level at hourly interval in 45-gallon drums that were placed around the island (Muzik & Kirby, 1992). This data set was later used to calibrate the RIGICE model (Forest et. al, 2005). In Norway, measurements of spray flux on supply vessels and semi-submersible drilling rigs were carried out as part of the research program “Offshore icing” (Jørgensen, 1986; Horjen et al., 1986) and used for calibrating the ICEMOD model (Horjen, 1990). Spray measurements were carried out with two different concepts, one being absorption panels (with paper diapers as absorbing material) and the other being pipe bend collectors funneling the incoming spray into a graduated measuring glass. The measurements required manual weighing of the absorption panels or reading the water level of the measuring glass every 1-3 hours. For vertical structures (like semi-submersible drilling rigs), this is the only known data set and is also used by the more recent MARICE and NuMIS models. Ryerson (1995) carried out measurements of sea spray flux and icing on a cruise with the U.S. Coast Guard cutter “Midgett” in 1990. Spray collectors with vertically and horizontally oriented funnels were used, with collected water running down into chambers where the water level was automatically measured using a water level sensing capacitor. In addition, two video recording systems and a stroboscopic camera were installed to monitor the spray cloud formation and record droplet sizes.

Ship-shaped floating production, storage and offloading (FPSO) units are often considered for development of offshore oil and gas fields in intermediate/deep water in northern areas where sea ice and/or icebergs may occur (e.g. offshore Newfoundland or the Barents Sea). Ship-shaped floaters for oil and gas production are typically much larger structures than the small fishing and navy vessels where spray observations have been done previously. Spray events are expected to be relatively infrequent and require high sea states to reach the topside, due to the high freeboard of a ship-shaped FPSO. As part of the Joint Industry Project RigSpray, a novel measurement system for monitoring sea spray real-time onboard offshore structures has been developed and installed onboard the Norne FPSO in the Norwegian Sea. The present paper presents the major requirements to the measurement system, how these were satisfied by the design and how the system was tested before full-scale deployment. The installation at the Norne FPSO is also described, along with experiences from the first measurement season during winter 2017/2018.

REQUIREMENTS TO THE SEA SPRAY MEASUREMENT SYSTEM

The purpose of the sea spray measurement system is to provide data that is useful for improving sea spray modelling in relation to marine icing. User requirements consist of both what is needed by the system to fulfil this purpose and restrictions to the system. The following principal user requirements were identified for the sea spray measurement system (in addition to adhering to other relevant internal operator requirements and requiring final acceptance from the operator (Equinor)):

- U1. The RigSpray measurement system shall generate continuous flux measurements of incoming sea-spray at six (6) different locations in the bow area and record video of the bow area of the FPSO for a period of up to 6 months.
- U2. The measurements from the fluxmeters shall be made available in "near real-time" and video recordings at suitable time intervals to the project team.
- U3. As default, the fluxmeter measurements shall be output every 1 (one) second, with the possibility of changing this parameter during operation.
- U4. The design and capacity of the fluxmeters shall reflect the expected sea spray flux.
- U5. The instrumentation platform must adhere to the rules of Technical safety as given by "NORSOK Standard S-001 Technical safety" (NORSOK S-001, 2018).

U6. Any equipment to be installed in the bow shall either be certified as intrinsic safe for ATEX Zone 2 or must be turned off from a single gas event.

U7. All equipment to be installed at the FPSO shall undergo a Factory Acceptance Test (FAT).

An overarching principle was also to minimize impact for the daily operation of the FPSO, which was affecting the design in addition to the user requirements above. This prescribed a high level of autonomy. Relevant weather data (wind speed/direction, wave height/direction) and vessel motion data are also needed to correlate the observed sea spray with key environmental and structural variables. These are routinely recorded by the operator and made available to the project team.

To minimize the offshore installation scope, a battery-powered solution with wireless communication was preferable. With a relatively short time line from the operator indicated its willingness to let the project instrument the FPSO (December 2016) until the installation had to take place (September 2017), there was also a need to identify off-the-shelf components that could help meeting the requirements. At the same time, the choice of components was limited to those adhering to ignition source control by being ATEX Zone 2 certified and supporting a wireless standard that was qualified by the operator of the FPSO. For this reason, the rugged Yokogawa ISA100.11a Field Wireless system (the ISA100.11a standard already being qualified by the operator) and ISA100.11a pressure sensors were considered a good candidate for measuring the amount of collected sea spray. In metal-heavy, non-line-of-sight, closed spaces typically encountered on offshore installations, the transmission range of ISA100.11a is usually around 30-50 meters. Given the expected spatial distribution of the fluxmeters at the Norne bow, the wireless performance should be sufficient for establishing a wireless network with adequate coverage.

Based on the user requirements and subsequent considerations, prototyping and evaluation, the RigSpray measurement system is divided into four separate functions or sub-systems. The overall system architecture for the RigSpray measurement system is presented in Figure 2, illustrating the main components of the subsystems that were developed to meet the user requirements:

A. Fluxmeter instrumentation platform
   - Consists of six fluxmeters (described in more detail below) and one reference fluxmeter, the latter with a fixed amount of water. The fluxmeters communicate spray measurements wirelessly to Equinor's Information Management System (IMS) through an ISA100.11a wireless infrastructure established by the project (wireless repeaters, wireless access point and wireless management station) and Equinor’s network.
   - Fluxmeter data is stored on and can be queried from Equinor's IMS.
   - The wireless management station can be accessed remotely, allowing for reconfiguration of the sensor network.

B. Video recording system
   - Consists of a video camera and a camera workstation which record sea spray events in the bow of Norne.

C. Weather data acquisition
   - Existing systems on Norne already collect and store weather data, available to the project team as quality controlled monthly reports and time series from MIROS

D. Vessel data acquisition
   - Existing vessel data from Norne is already stored on and can be queried from Equinor's IMS.

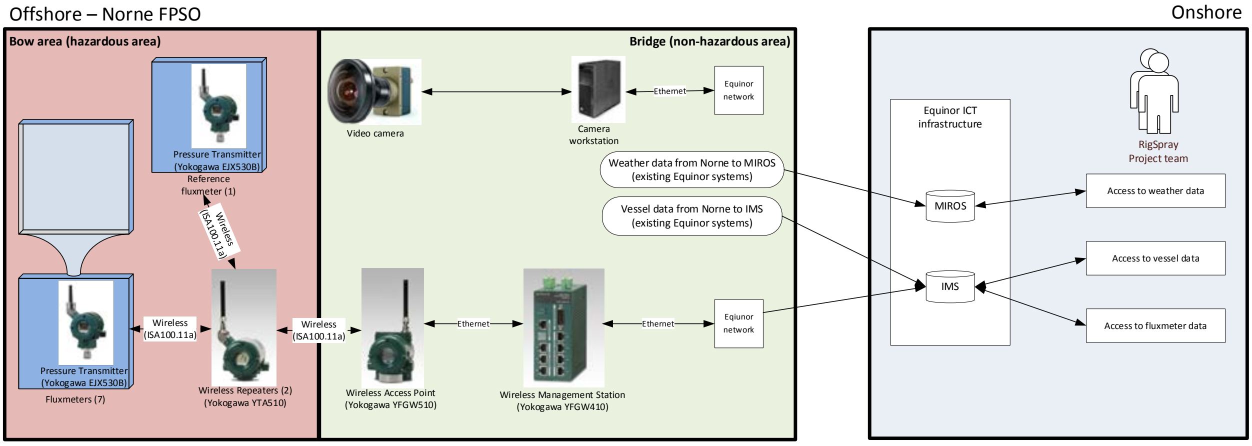

Figure 2. Schematic system architecture for the spray measurement system onboard the Norne FPSO.

DETAILS OF FLUXMETER DESIGN

Principles of operation

Figure 3a shows a technical drawing of the RigSpray fluxmeter. Sea spray hitting the collector plate (dimensions 0.5 x 0.5 m) is channeled down via a short hose into a tipping bucket inside the instrument cabinet (Figure 3b). The collector plate and instrument cabinet are constructed with coated 5 mm thick steel and designed to withstand green sea loading that may occur close to the bow of the FPSO. The water level in the tipping bucket is measured with a Yokogawa wireless gauge pressure transmitter. The pressure transmitter is ATEX Zone 1 intrinsic safe (Ex ia IIC T4 Ga), with battery capacity to broadcast for minimum one year with a measurement frequency of 1 Hz. Silicone oil is used in the last section between the pressure sensor and the sea water to avoid problems with freezing of the sensor. The tipping bucket empties by itself when the centre of gravity crosses the center line of the axis of rotation and rotates back into position once it is empty. Water drains out of the cabinet through a hole in the bottom. An antenna extends out into a PVC enclosure on the back side of the instrument cabinet, allowing for wireless data transfer.

The volume of water added to the tipping bucket (ΔV [mm^3]) can be calculated as

$$\Delta V = \Delta P * A / (\cos(\alpha) * k_{\text{sea water}}) , \qquad (1)$$

where ΔP [mmH_20] is the change in pressure, A [mm^2] is the effective cross-sectional area of the tipping bucket, α is the angle of the tipping bucket in resting position and $k_{\text{sea water}}$ is the ratio between the density of sea water and the density of fresh water.

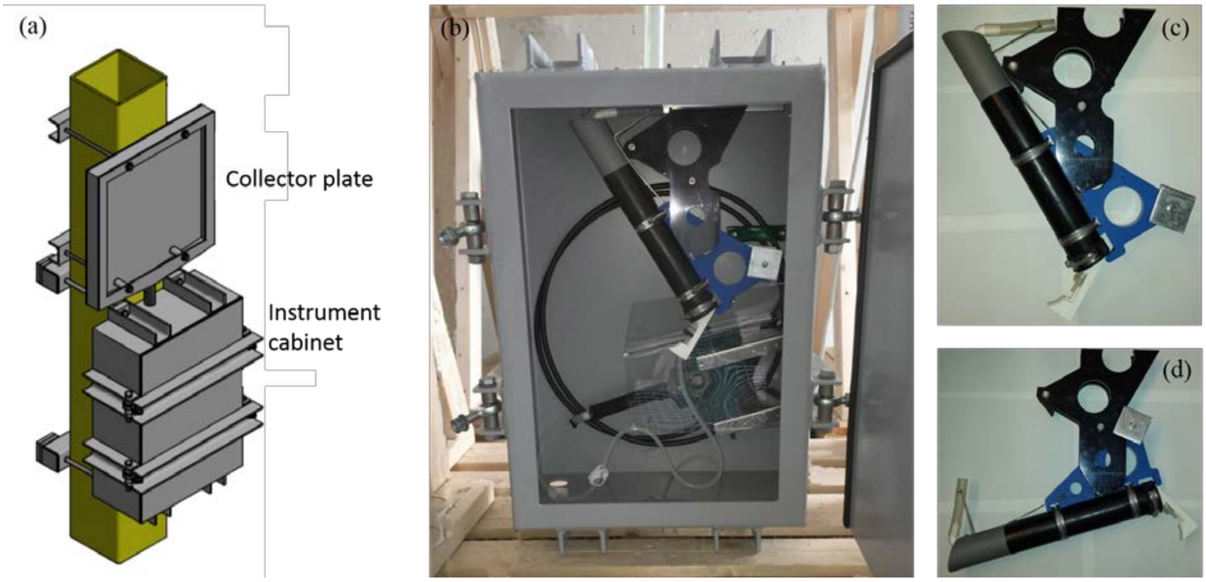

Figure 3. (a) Technical drawing of the collector plate and instrument cabinet assembly mounted on a vertical column, (b) Internal view of the instrument cabinet, (c) Close-up of tipping bucket in upright position, (d) Close-up of tipping bucket in tilted position.

Wind tunnel testing of prototype fluxmeter

A prototype of the fluxmeter was tested in a wind tunnel at VELUX in Østbirk, Denmark (Figure 4). The wind tunnel at VELUX is designed for being able to test windows in storm conditions with water injected to simulate rain. A prototype of the fluxmeter was tested in variable wind speeds up to 30 m/s, with variable orientation towards the wind and variable water injection rates.

Figure 4. Testing the prototype flux meter at 30 m/s wind speed in the Velux wind tunnel. The air flow is entering from the left, passing through the array of nozzles in the spray rig and catching the ejected water. The door of the prototype instrument cabinet is made of plexiglass to enable visual monitoring of the instrument during the tests.

A total of 86 tests were conducted. The tests were considered a “proof of concept”, since the set-up did not allow for controlling/monitoring the “undisturbed” spray flux (only the total water volume injected to the spray rig was measured). The filling time was consistent between subsequent cycles of filling/tipping of the tipping bucket and the tests showed good repeatability. A leakage in the instrument cabinet door was introduced to see if this would affect the measurements. This did not appear to have any effect on the spray collection or tipping bucket, as the observed collection rate was very similar with/without the leakage. Indicative tests of the collection efficiency were attempted by closing all nozzles but one or two and manually measuring the total water output with buckets. No technical problems with the equipment were observed during the tests and no changes had to be made to the design based on the observations from the wind tunnel.

FULL-SCALE DEPLOYMENT

In September 2017, the measurement system was deployed at the Norne FPSO, taking advantage of the regular autumn maintenance campaign onboard the vessel. The Norne field is located in 380 m water depth in the Norwegian Sea, ~200 km from shore. The field was developed with a ship-shaped FPSO, which started production in 1997. Key data about the FPSO is given in Table 1. The Norne FPSO experienced green sea events (Ersdal & Kvitrud, 2000) during its first years of operation, leading to implementation of operational measures during winter time (a static trim angle and reduced maximum draft) to increase the bow height.

Table 1. Key data, Norne FPSO

Parameter	Value
Latitude	66.0256ºN
Longitude	8.0850ºE
Water depth [m]	380
Length overall [m]	260.2
Breadth [m]	41.9
Draft [m]	18.7

Fluxmeter installation

The fluxmeters were assembled at SINTEF in Trondheim and underwent a FAT prior to being shipped to the Norne FPSO, checking that the measurement system was in conformance with the requirement specification. The instruments were mounted on the columns supporting the helideck in the bow area of the FPSO (Figure 5a), at different elevation above deck to capture the vertical variation in sea spray flux. The fluxmeters were configured to 1 Hz update rate. This was reduced to one sample per 10 minutes during the summer months, when few spray events were expected.

Wireless infrastructure

Two wireless repeaters (Yokogawa temperature transmitters, YTA510) were placed on the railing outside the control room to ensure wireless signal transfer to the indoor access point (Yokogawa YFGW510). One of the repeaters is visible in the foreground in Figure 5b and c. During installation it was discovered that the window had heat tracing, which affected the quality of the wireless transmission. However, the repeaters and the indoor access point were sufficiently close for the signal to pass through.

Video camera system

The video camera (Dalsa Genie Nano with a Fujinon FE185C057H1- 1 wide-view lens) was mounted with suction cups in the one of the windows of the control room overlooking the bow area. Examples of the view of the video camera can be seen in Figure 5b and c. The recorded video was transferred to a dedicated workstation via an ethernet cable. The camera was configurable and video from interesting episodes could be transferred to shore. Figure 5c displays an example spray event from a storm with 9 m significant wave height on January 15, 2018. This particular spray event was registered as a pressure increase of 120 mmH_20 on the lowest fluxmeter on the aft port column. This corresponds to 0.9 kg/m^2 hitting the collector plate from this single spray event.

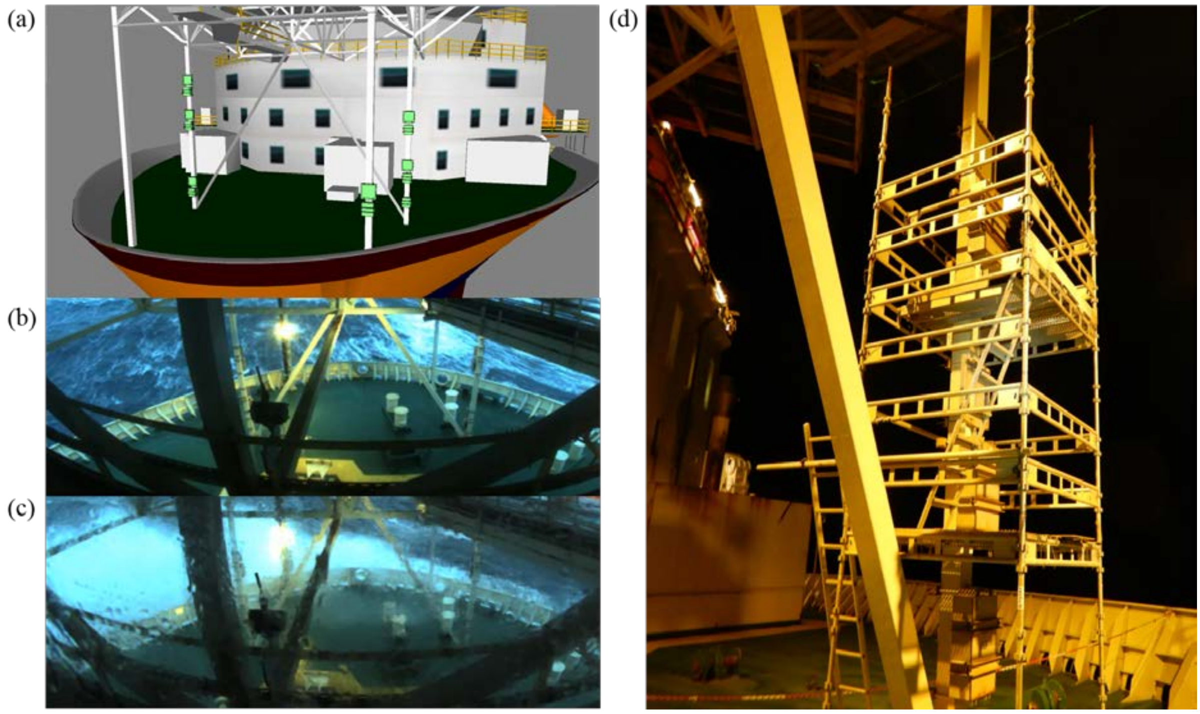

Figure 5. (a) 3D drawing of the mounting positions of the fluxmeters in the bow of the Norne FPSO, (b) View from the video camera monitoring spray events, (c) Example of recorded sea spray event on January 15, 2018, (d) Fluxmeters on the aft port column, with scaffolding used during inspection and maintenance in November 2018.

EXPERIENCES AFTER ONE YEAR OF OPERATION

The data stream from the fluxmeters was perfectly stable, except for a week-long fallout in November 2017 and one hour of data loss in March 2018. The battery status of the pressure sensors and repeaters was monitored continuously, and the sensors were noted to have higher power consumption than the repeaters. This is attributed to the pressure sensors using power for pressure measurements in addition to the radio communication. The pressure sensors were just 1-2 months short of having enough reported battery capacity for two winter seasons of operation. The video system experienced more instability, with approximately 30% data loss due to mismatch between software versions (this error was discovered and corrected) and the workstation controlling the camera rebooting from time to time due to mandatory updates (required in order to remain connected to the network). The challenges with the camera system demonstrated the usefulness of being able to monitor and troubleshoot the system from shore.

In November 2018, the measurement system underwent inspection and maintenance (Figure 5d) in preparation for a second winter season. All batteries were replaced and fluxmeters recalibrated/function-tested. The condition of the measurement system was good, apart from some corrosion on external surfaces. Traces of foreign substances had accumulated inside the tube connecting the pressure sensor with the tilting bucket, but not to any extent that would affect measurements.

CONCLUSIONS

A sea spray measurement system has been developed to satisfy requirements for collecting observations of sea spray at an offshore oil and gas facility. The autonomous measurement system operated reliably on the Norne FPSO throughout the winter season 2017/18 and continued to operate throughout the 2018/19 winter season. Another objective of the RigSpray project is to improve numerical modelling of sea spray icing (Bøckmann et al, 2019) and the measurements performed at the Norne FPSO are currently being analysed with the purpose of developing an updated empirical spray model suitable for large ship-shaped stationary structures.

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REFERENCES

Bodaghkhani, A., Dehghani S., Muzychka, Y. S. & Colbourne B, 2016. Understanding spray cloud formation by wave impact on marine objects, *Cold Regions Science and Technology*, 29, pp. 114-136.

Bøckmann, A., Shipilova, O. & Ekeberg, O., 2019. Model assumptions in rig icing and their implications, *Proceedings of the 25th International Conference on Port and Ocean Engineering under Arctic Conditions*, Delft, The Netherlands.

DNV, 2014. *MARICE project summary*, DNV Report no 2014-0096, Høvik:DNV.

Ersdal, G. & Kvitrud, A, 2000. Green Water On Norwegian Production Ships, *Proceedings of the 10th International Offshore and Polar Engineering Conference*, Seattle, USA.

Forest, T. W., Lozowski, E. P. & Gagnon, R., 2005. Estimating Marine Icing on Offshore Structures using RIGICE04, *Proceedings of the 11th International Workshop on Atmospheric Icing of Structures*, Montréal, Canada.

Hansen, E. S. & Teigen, S. H., 2015. An efficient numerical model for marine icing, *Proceedings of the 23rd International Conference on Port and Ocean Engineering under Arctic Conditions*, Trondheim, Norway.

Horjen, I., Løset, S. & Vefsnmo, S., 1986. *Icing hazards on supply vessels and stand-by boats*, Norwegian Hydrotechnical Laboratory, Trondheim, Report no. STF60 A 86073.

Horjen, I., 1990. Numerical modelling of time-dependent marine icing, anti-icing and de-icing. Ph.D. Trondheim: Norges Tekniske Høgskole (NTH).

International Organization for Standardization (ISO), 2010. *Petroleum and natural gas industries - Arctic offshore structures* (ISO Standard No. 19906).

Itagaki, K., 1977. *Icing on Ships and Stationary Structures under Maritime Conditions*, USA Cold Regions Research and Engineering Laboratory, CRREL Special Report 77-27.

Jørgensen, T. S., Vefsnmo, S. & Horjen, I., 1986. *Offshore Icing – Phase II Final Report*, Norwegian Hydrotechnical Laboratory, Trondheim, Report no. STF60 F 86084.

Kulyakhtin, A., 2015. *Numerical Modelling and Experiments on Sea Spray Icing*. Ph.D. Trondheim: Norwegian University of Science and Technology (NTNU).

Muzik, I. & Kirby, A., 1992. Spray overtopping rates for Tarsiut Island: model and field study results. *Canadian Journal of Civil Engineering*,19, pp. 469-477.

NORSOK S-001, 2018. *NORSOK Standard S-001 Technical Safety*, Standard Norge, Norway.

Ryerson, C. C., 1995. Superstructure spray and ice accretion on a large U.S. Coast Guard cutter. *Atmospheric Research*, 36, pp. 321-337.

Shipilova, O. & Kulyakhtin, A., 2012. Spray generation in marine icing of vessels. *International Conference on Violent Flows*, Nantes, France.

Zakrzewski, W. P., 1987, Splashing a ship with collision-generated spray, *Cold Regions Science and Technology*, 14, pp. 65-83.