# Enabling Subsea Produced Water Reinjection through In-line Water Treating and Monitoring Technologies for Deep Water Applications

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## Abstract

ExxonMobil Upstream Research Company (EMURC) recently conducted a broad subsea technology development and qualification program which included subsea processing technologies. One specific focus was on development of in-line produced water de-oiling technology integrated with water quality monitoring sensors that can provide continuous measurements to monitor the level of oil and suspended solids content in produced water. Maintaining well injectivity in subsea processing applications in deep water requires liquid-liquid separation technologies capable of handling challenging water streams in terms of oil and solids content as well as subsea produced water quality monitoring (PWQM) technologies.

EMURC conducted a comprehensive test program of a two-stage de-oiling hydrocyclones system and evaluated its performance and sand erosion sustainability. The performance tests were conducted with crude oils with variations in flow rate, temperature, oil content and reject stream volumes. The test results demonstrated that a two-stage hydrocyclones system can treat challenging produced water streams with high oil-in-water content (up to 5%) to a few hundred ppm level. Accelerated sand erosion tests with different types of erosion resistant coatings for hydrocyclone liners helped identify a promising coating solution that can withstand continuous sand loads for long term operations. EMURC also co-developed a subsea microscopy-based PWQM technology that can measure the quality of reinjection water in terms of OIW and solids-in-water (SIW) concentrations as well as can facilitate separation system performance monitoring. Two microscopy-based sensor prototypes were tested with varying operating conditions such as flow velocity, temperature, pressure, and salinity. The measurement performance and effectiveness of the active sensor cleaning systems of the sensor prototypes were evaluated in flow loop tests. This paper provides the key outcomes of the qualification testing of these two technologies.

## Introduction

For subsea processing in deep water locations with long tiebacks, re-injection of produced water into the reservoir or disposal zones is envisioned to be a suitable solution for produced water disposal [1]. In such applications, subsea produced water treatment requires robust, reliable, and compact separation equipment as well as reliable water quality monitoring technologies.

Full well stream production of hydrocarbons in the form of crude oil, condensate, and natural gas produced from the reservoir contains varying quantities of produced water (PW) which varies widely in its composition but generally contains hydrocarbons in the form of dispersed and dissolved oil. Usually, dispersed oil droplets can be coalesced into hydrocarbon phase under proper conditions, and then separated from the aqueous phase to, generally, 0.1 to 10 volume percent using various separation devices. The dispersed oil droplets can range in size from 0.5 micron to over 200 microns [2].

Dispersed oil in produced water must be removed before re-injection because it can impair well injectivity. Even small amounts of dispersed oil, when injected with produced water, can increase oil saturation in the near-wellbore region, decreasing the effective permeability of formation to injection water. Over time, this decrease in the permeability can cause loss in injectivity and even result in loss of the injection well. Depending on the reservoir porosity and permeability, the recommended oil-in-water (OIW) content in the reinjection water ranges between 100 to 400 ppm (part per million) in volume. To meet the water reinjection requirements and maintain well injectivity, subsea water treatment can clean the produced water and can prevent loss of high-cost injection wells.

For subsea separation in deep water with generally less number of treating stages, and more compact in-line devices than that found on topsides or onshore, it becomes a greater challenge to achieve the same separation performance as the topsides equipment which generally has more stages. Subsea processing facilities are expected to become increasingly complex over time, which will require more reliable equipment to avoid costly subsea interventions. Subsea produced water treatment devices such as hydrocyclones must be capable of operating for several years with minimal maintenance, intervention, or configuration modifications to accommodate changes in production such as increase in water-cut. In addition, produced water may contain entrained sand which must be removed through upstream desanding devices [3] to avoid clogging of any downstream equipment or the reservoir. As there will always be some sand carryover in the overflow of the desander, hydrocyclones need to be erosion resistant for the extent of any maintenance interval, or preferably for the entire field life. For orifice plugging mitigation, reverse flow flushing of the hydrocyclones can also be performed on a routine basis.

Hydrocyclones-based water treatment is considered a promising solution for subsea in-line water treatment for deep water applications due to the hydrocyclone's compact design and non-moving parts [4]. EMURC conducted a comprehensive test program of a two-stage water treatment system based on mixed flow hydrocyclones [5] to evaluate its liquid-liquid separation performance [2]. The test program included performance evaluation of the water treatment system with respect to separation performance of individual hydrocyclone stages, overall system performance, and sand erosion resistance. Accelerated sand testing of hydrocyclone liners were performed with different types of erosion resistant coatings which resulted in identification of a coating solution that can withstand continuous sand loads for long term operations.

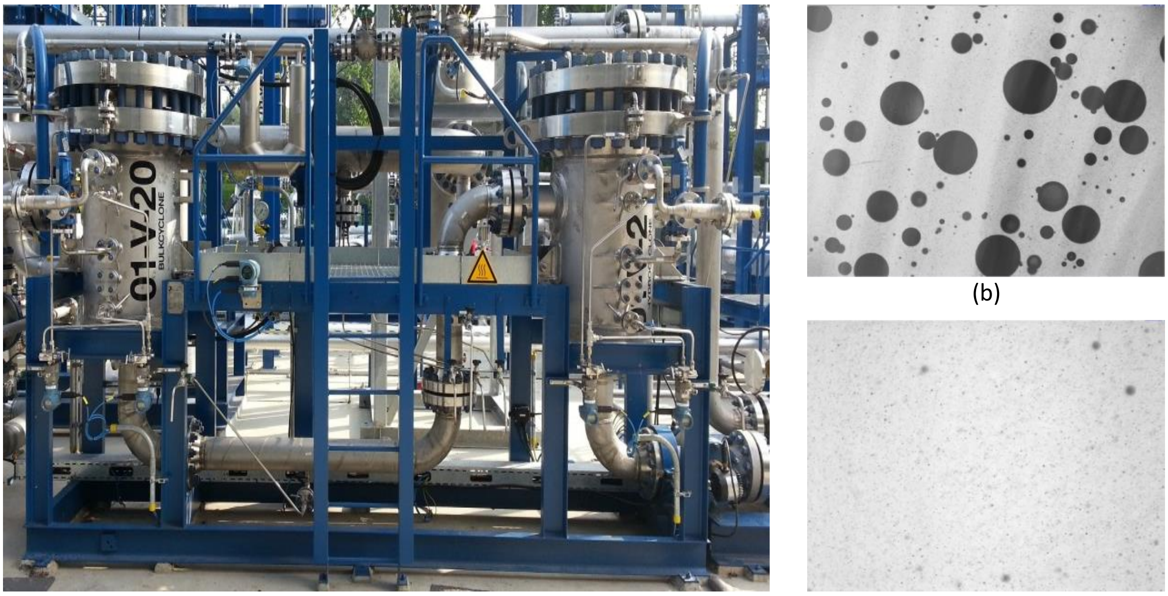
EMURC also co-developed a subsea microscopy-based PWQM technology with J.M. Canty that can measure the quality of reinjection water in terms of OIW and SIW contents as well as can facilitate separation system performance monitoring. Two sensor prototypes were built and tested in a flow loop with varying fluid conditions such as flow velocity, temperature, pressure, and salinity. Liquid jet-based active sensor cleaning systems were integrated in both prototypes to clean optical windows on the sensor head. The measurement performance of the prototypes and the effectiveness of the active sensor cleaning systems were verified through flow loop tests. This paper highlights the results of the two-stage hydrocyclone-based water treatment system and subsea water quality monitoring sensor prototype performance tests.

## Subsea produced water treatment technology – key testing results

EMURC conducted a comprehensive flow loop test program in low pressure (up to 10 barg) as well as high pressure (up to 45 barg) flow loops to evaluate the performance of the two-stage ASCOM Mixedflow de-oiling hydrocyclones [2]. Figure 1(a) shows the water treatment system that was installed in the high pressure flow loop, which consists of a bulk-cyclone (BC) stage for bulk oil removal and a second hydrocyclone (HC) stage for water polishing.

The test program included performance evaluation of the two-stage water treatment system with respect to separation performance of individual hydrocyclone stages and overall system performance in both the low pressure and the high pressure test loops, and sand erosion resistance in a separate low pressure flow loop. The performance tests were conducted with light, medium, and heavy crude oils, of gravities of 36 °API, 28 °API, and 19 °API, respectively, to map performance characteristics of the water treatment system to the various fluid conditions. Variations in test conditions such as the flow rate, temperature, inlet oil concentration, and the reject ratio of each stage were introduced to establish optimal operating ranges. The performance of the individual hydrocyclone stages and the integrated system were evaluated by determining separation efficiency break-points at different operating conditions.

The test results demonstrated that the two-stage hydrocyclone-based water treatment system with optimal settings of the hydrocyclones and sufficient flow feed rate can clean water streams with oil concentration exceeding 50,000 ppm to a few hundred ppm level. Figure 1(b) and 1(c) shows two typical microscopic images of water streams with dispersed oil droplets at the inlet and the discharge of the water treatment system respectively. These images provide a visual illustration of the performance of the water treatment system for removing oil content from the water stream. The multi-stage hydrocyclone-based water treatment system can be a suitable solution for subsea produced water treatment.




(a) (b) (c)

Figure 1. (a) Two-stage water treatment system installed in the high pressure flow loop; (b) microscopic image of water stream at the inlet of the water treatment system; and (c) microscopic image of water stream at the discharge of the water treatment system.

Accelerated sand erosion testing of hydrocyclone liners was also performed on a purpose-built test loop to evaluate different erosion resistant coatings. The sand slurry was continuously circulated through the single liner flow loop. The sand in water was about 1 (vol. %) which is significantly higher than the expected SIW concentration levels in the hydrocyclones. The tests were run for a normal non-coated duplex steel hydrocyclone liner and for two special erosion resistant liners: surface hardened (duplex steel) liner and a Tungsten Carbide (WC) coated liner. The test cycle time was 125 hours. The non-coated and surface hardened liners were significantly eroded in the accelerated sand loading tests whereas the WC coating showed resistant to sand erosion and can be a promising solution for subsea hydrocylone liners [2]. Another learning from this testing was the need of improvement of the design of the liner. By increasing the wall thickness of the liner in the step-section next to the swirl seating area, the liner integrity can be enhanced.

**Microscopy-based Produced Water Quality Monitoring Sensors – key testing results**

EMURC co-developed a microscopy-based subsea produced water quality monitoring (PWQM) technology that can provide information about the quality of re-injection water in terms OIW and SIW contents (concentration and size distribution) as well as facilitate separation system performance monitoring of subsea separation and produced water treating systems by identifying upset conditions such as oil slugs. Two microscopy-based PWQM sensor prototypes were developed for a low measurement range of 0 to 2,500 ppm OIW and a high measurement range of 0 to 50,000 ppm OIW, respectively. Liquid jet-based cleaning systems were integrated in both prototypes to avoid fouling of the sensor optical window and to enable long term operation without compromising the performance.

The sensor prototypes were tested in a flow loop over a broad range of operating conditions, including flow velocity, temperature, pressure, and salinity [6]. Figure 3(a) shows the flow loop where both prototypes were installed in a vertical test spool. The OIW measurement performance of the prototypes was verified in the flow loop tests. The impact of changes in test conditions such as flow velocity, temperature, and salinity on the measurement performance were also investigated. The active cleaning systems were also tested to validate their effectiveness under normal and extreme fouling conditions.

Figure 3(b) and 3(c) show the OIW concentration readings for each prototype as well as reference values. The acceptable range of ±20% of the reference values is also shown. Both sensors can measure their designed OIW ranges with sufficient accuracy to enable monitoring of water quality in future subsea processing and produced water re-injection applications. The new sensor designs with integrated active sensor cleaning systems can also be used for topsides applications.

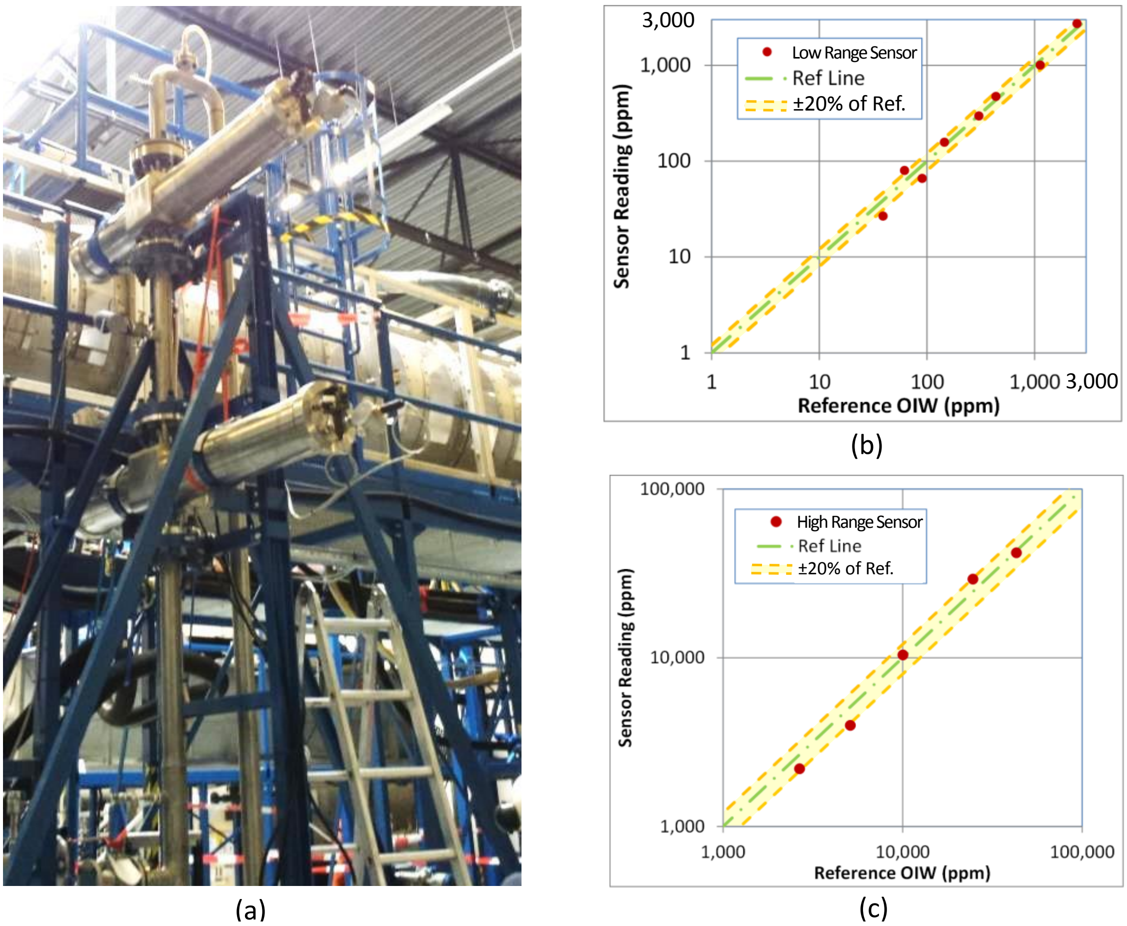



Figure 3. (a) Two PWQM sensor prototypes installed in the flow loop; (b) OIW measurement performance of the low measurement range PWQM sensor for 0 to 2,500 ppm OIW; and (c) OIW measurement performance of the high measurement range PWQM sensor for 0 to 50,000 ppm OIW.

## Conclusions

The system-level integrated testing for the two-stage hydrocyclone-based water treatment system showed high separation efficiencies for the tested crude oils with optimal settings of the hydrocyclones and sufficient inlet flow rates. Overall, the results of these tests were satisfactory for all the tests performed. Together with its compact design with non-moving parts, the two-stage hydrocyclone-based water treatment system is a good candidate for in-line water treatment for deep water applications.

Two microscopy-based produced water quality monitoring sensor prototypes were developed and tested in a flow loop over a broad range of operating conditions. The low measurement range sensor is intended to be installed downstream of the water treatment system to measure the quality of reinjection water, and the high measurement range sensor is to be installed upstream of the water treatment system to serve primarily as a trend monitor. The test results indicated that both sensors can measure OIW with sufficient accuracy for monitoring produced water in subsea applications.

The test program demonstrated that the two-stage hydrocyclone-based water treatment system together with the microscopy-based PWQM technology can meet challenging produced water treating requirements over a wide range of operating conditions.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