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IMPROVING THREE-PHASE SEPARATION STABILITY UNDER TRANSIENT WELL FLOW AND VARIABLE TEMPERATURE CONDITIONS

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ABSTRACT

This paper presents the results of an offshore field trial conducted to evaluate a newly developed demulsifier under actual operating conditions. The primary objective was to identify a more suitable chemical formulation and assess its performance against existing operational specifications, while determining its impact on three-phase (oil–gas–water) separation efficiency under varying production conditions. The trial was conducted using a structured methodology designed to ensure a reliable performance comparison without interrupting production operations. The results confirmed that separation efficiency is strongly influenced by chemical formulation. Improved separation stability had a positive impact on overall process performance, including effective residence time, liquid slugging response, and thermobaric behavior. These findings demonstrate the importance of integrated chemical and process optimization rather than reliance solely on increased chemical dosage. The enhanced stability observed under transient inlet conditions and prevailing temperature ranges is largely attributed to the diesel-based carrier solvent, which improved oil-phase compatibility and ensured consistent transport of active components to the oil–water interface. Appropriate process optimization further supported compliance with oil export and produced water quality specifications. The field trial demonstrated stable three-phase separation performance with sustained compliance with operational specifications. Optimization of the demulsification program reduced chemical consumption, improved cost efficiency, and minimized logistics-related operational risks, providing a practical framework for offshore chemical evaluation and implementation.

Keywords: oil and gas production; temperature influence; demulsifiers; oil and gas separation; oil–water emulsions.

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1. Introduction

During oil and gas production, the production well stream typically consists of a complex multiphase mixture of hydrocarbons, formation water, dissolved gases, suspended solids, and inorganic compounds. Although efficient phase separation is a fundamental requirement for ensuring safe operation, stable production, and compliance with downstream processing and export specifications, maintaining separation effectiveness can be challenging [1, 2]. Primary separation of the multiphase flow is therefore achieved using oil and gas separators, which are critical pieces of equipment in both onshore and offshore production facilities [3, 4].

The separation process strongly depends on the type of separation equipment and the control technology employed. Depending on process requirements and field operating conditions, separators may be configured as vertical, horizontal, or spherical pressure vessels. Based on their separation objectives, separators are commonly classified as two-phase (gas–liquid) or three-phase (oil–gas–water) systems [3], with additional space often provided for the accumulation of sand or other mechanical solids. Three-phase separators are widely used in offshore facilities due to their compact design and ability to simultaneously separate gas, oil, and produced water within a single vessel.

In three-phase separation systems, the first stage typically involves controlled pressure reduction to facilitate gas disengagement while maintaining stable liquid-phase separation. This step is critical for maximizing liquid recovery, ensuring oil and gas stabilization, and enabling effective gravity separation of produced water [4]. Excessive pressure reduction within a single separation stage may induce flash evaporation, leading to operational instability and increased safety risks (fig. 1).

Traditionally, the performance of first-stage three-phase separators has been characterized in terms of nominal residence time. Under stable operating conditions, these separators are typically designed to achieve partial removal of free water, corresponding to a reduction of approximately

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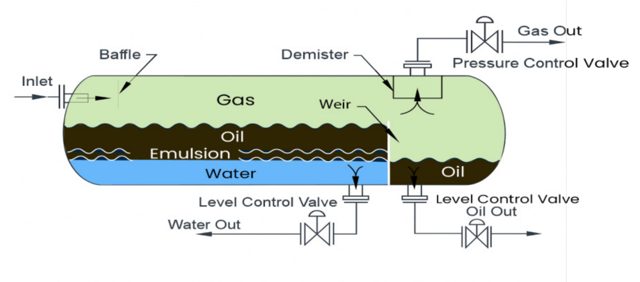

Fig. 1. Three-phase (oil–gas–water) separation process flow diagram

5–10 % of the inlet water content [3, 4]. However, residence time alone does not adequately describe separation performance, particularly under transient or slugging flow regimes, where hydraulic instability and fluctuating phase distributions significantly influence coalescence and settling behavior [5, 6].

In practice, the required separation "retention" is more appropriately expressed in terms of liquid holdup and target outlet quality, rather than fixed residence time, as separation efficiency is governed by droplet-size removal capability, phase interface stability, and transient hydraulic behavior. The separation objective can therefore be related to a separable droplet size, which defines the residual concentration of dispersed phase remaining in the continuous phase. For instance, removal of water droplets larger than approximately 250 μm from the oil phase corresponds to about ~3 vol.% water – in - oil, while removal of oil droplets larger than approximately 150 µm from the water phase corresponds to ~1000 ppmv oil -in - water [7].

Consequently, the first stage of a three-phase separator should be characterized by its ability to provide sufficient holdup and surge capacity to accommodate transient inflow conditions, such as liquid slugging and fluctuations in flow rate, pressure, and temperature, while consistently meeting outlet quality specifications for both oil and produced water. Maintaining stable separation performance becomes particularly challenging when wells operate under unstable conditions caused by liquid loading, sand and water production, or wax and scale deposition. In addition, complex phase behavior, including emulsion formation from crude oil–water mixing, further intensifies separation challenges [8].

The formation of stable water-in-oil (WIO) emulsions poses a significant operational challenge in oil and gas production, leading to fouling, under-deposit corrosion, reduced separation efficiency, and increased chemical consumption. Stable emulsions may also adversely affect downstream equipment, including heat exchangers and produced water treatment units [9]. Conventional emulsion-breaking methods such as gravitational settling, heating, centrifugation, electrostatic separation, chemical demulsification, and filtration are often applied in combination to maintain performance under variable thermobaric conditions [10].

Ineffective demulsification further increases hydraulic and contaminant loading on produced water polishing systems, raising the risk of non-compliance with discharge specifications. Similar challenges related to unstable emulsions, demulsifier underperformance, and transient multiphase flow behavior have been widely reported in offshore operations [11, 12]. Therefore, a systematic and application-specific approach to chemical selection is essential under dynamic operating conditions.

In this paper, we studied the operating conditions of the first-stage three-phase separator, where the existing demulsifier demonstrated insufficient separation performance at elevated production rates. The chemical exhibited limited robustness under transient flow conditions, particularly during periodic liquid slugging caused by well surging. These conditions resulted in fluctuating residence times within the separator and reduced the effectiveness of interfacial film rupture, leading to increased oil-in-water (OIW) concentrations at the produced water outlet and elevated water-in-oil (W/O) content at the oil outlet. This work demonstrates that the chemical selection process can be optimized to identify a fit-for-purpose demulsifier capable of managing instabilities associated with well production and dynamic thermobaric conditions.

2. Fundamentals of the demulsification process and key challenges in separation and chemical selection

Signs of operational inefficiency were observed when well production had to be adjusted to maintain separation stability, prompting a detailed investigation to identify alternative solutions. This section outlines the key factors evaluated in selecting the new chemical formulation and describes the methodology applied to manage the challenges associated with its replacement.

2.1. Fundamental aspects of demulsification process

Crude oil demulsification is governed by the coupled effects of interfacial phenomena and separator hydraulics. In produced fluids, naturally occurring surface-active components, such as asphaltenes, resins, and fine solids, can adsorb at the oil-water interface and form mechanically strong, viscoelastic interfacial films. These films inhibit liquid-film drainage and droplet coalescence, thereby stabilizing WIO emulsions and reducing the efficiency of gravitational separation [11, 13, 14].

The separation process is strongly dependent on both pressure and temperature. Pressure is typically the primary parameter used to control separation performance; however, increasing temperature reduces crude oil viscosity and enhances droplet mobility, thereby increasing collision frequency and promoting droplet coalescence and gravitational settling. Temperature variations may also modify interfacial film properties by influencing the interfacial activity and solubility balance of asphaltenes, which in turn affect film strength and drainage rates. These temperature-driven effects have been widely reported in recent studies [15, 16].

From a physical standpoint, once droplets have grown sufficiently, their gravitational separation rate under laminar settling conditions can be described by Stokes' law, which relates settling velocity to the square of the droplet diameter, the density difference between phases, and the viscosity of the continuous phase. Consequently, effective demulsification depends both on the ability of the chemical treatment to promote droplet growth and on favorable hydraulic and viscosity conditions that enable efficient settling. In practical field applications, however, oil–water separation becomes increasingly complex due to unstable flow rates and transient operating conditions arising from unpredictable well performance.

The demulsification mechanism is illustrated schematically in figure 2. Demulsifiers are surface-active chemical agents used to destabilize and break crude oil emulsions by disrupting the interfacial films formed by natural emulsifying agents such as asphaltenes, resins, waxes, and fine solids [11, 17].

Chemical demulsifiers primarily accelerate phase separation by migrating to the oil–water interface, displacing or weakening natural stabilizers, reducing interfacial viscoelasticity, and facilitating faster film drainage and droplet coalescence. This mechanism, along with key influencing variables, including temperature, water cut (phase ratio), salinity, demulsifier dosage, crude oil composition, and emulsion aging, has been consistently discussed in the literature [10, 18-21]. In addition, produced water salinity and brine composition can modify interfacial electrostatic interactions and the adsorption/behavior of surface-active species at the interface, changing emulsion stability and demulsifier performance. The influence of resin-asphaltene balance on emulsion stability is also widely recognized and helps explain why chemical performance may shift with crude composition and operating envelope [13, 14].

The demulsifiers are commonly classified according to the nature of their hydrophilic functional groups, including nonionic, cationic, anionic, and amphoteric types, with nonionic and cationic demulsifiers (fig. 3) being the most widely applied in crude oil dehydration and oil–water separation processes [17].

Figure 3 illustrates the basic molecular structures of cationic and nonionic demulsifiers. CP represents the cationic demulsifier structures, while NP represents nonionic demulsifier structures. The symbols x, y and z indicate variable polymer chain lengths, and R represents an alkyl group [8].

As evident from the above review, the selection of an appropriate demulsifier is critical, as crude oil emulsions can vary significantly in composition, salinity, viscosity, interfacial film strength, and overall stability depending on reservoir fluid characteristics and operating conditions. Temperature plays a key role in demulsification efficiency; in general, increasing temperature reduces oil viscosity, weakens interfacial films, and enhances droplet coalescence, thereby improving demulsifier performance [20, 21, 23].

Consequently, demulsifier selection should be based on the emulsion type (W/O or O/W), crude oil and produced water properties, and key operating parameters such as temperature profile, residence time, and shear conditions. In addition, a practical constraint in offshore operations is that demulsifiers are typically supplied as formulated products comprising active ingredients dissolved in carrier solvents, which influence delivery, dilution behavior, and interfacial accessibility. Industrial formulations commonly employ carrier solvents such as heavy aromatic hydrocarbons, alcohols, and, in some cases, diesel-range solvents; the choice of solvent can significantly affect oil-phase partitioning and performance robustness under transient flow conditions.

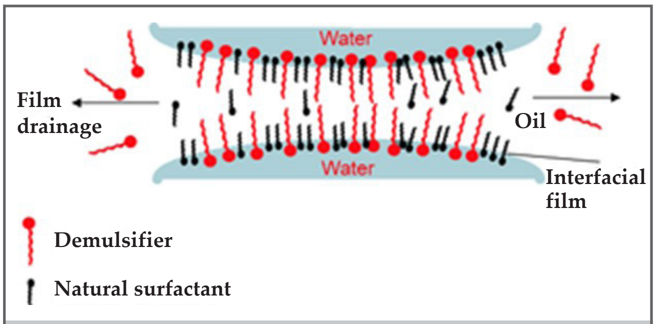

Fig. 2. Schematic mechanism of chemical demulsification adapted from crude-oil emulsion demulsification literature [18, 22]

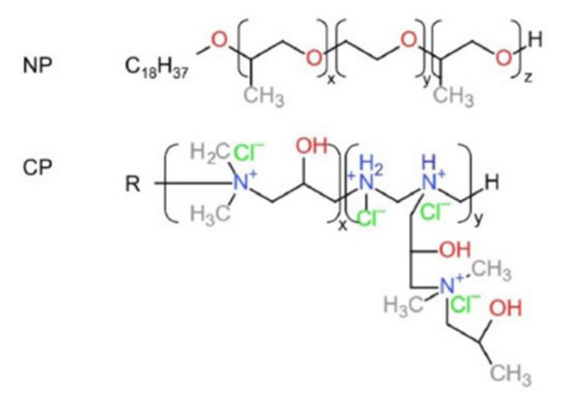

Fig. 3. Basic molecular structures of cationic and nonionic demulsifiers [22]

2.2. Case study: operational challenges in gas–oil–water separation

For the case study, an offshore production platform located in the Chirag–Gunashli field in the Caspian Sea was selected. The facility comprises 13 producing wells feeding the separation trains, with a total liquid production rate of 125.83 m^3/h and an average water cut of approximately 17%. The liquid level in the first-stage three-phase separator exhibited frequent fluctuations within a ±25% operating range, as the oil and water outlet level control valves were unable to maintain stable levels under the prevailing inlet instability. Intermittent liquid carryover through the gas outlet was also observed, periodically disturbing the suction scrubber of the downstream gas compressor. In addition, both OIW concentrations at the produced water outlet and water content in the oil phase frequently exceeded specification limits.

In the studied first-stage three-phase separation system, overall separation performance was significantly affected by transient inlet conditions, including frequent liquid slugging associated with well surging and changes in multiphase flow regimes. These unstable dynamics disrupted the oil–water interface, altered the effective liquid holdup, and reduced the available time for droplet coalescence and gravitational settling. In practice, this behavior manifested as repeated excursions in outlet quality, including elevated OIW levels in the produced water and increased water carryover in the oil phase.

The cyclic nature of these flow instabilities also resulted in separator temperature fluctuations of approximately 7 °C. Such temperature variability further impacted both separation efficiency and demulsifier performance. Periods of reduced liquid throughput combined with lower operating temperatures increased oil viscosity and reduced droplet mobility and settling velocity, while stronger and more persistent interfacial films slowed film drainage and coalescence. As discussed previously, mechanistic studies and literature reviews confirm that temperature influences both bulk fluid viscosity and interfacial behavior, thereby directly affecting demulsification kinetics and overall separator performance [15, 10].

The baseline chemical program utilized Demulsifier A, which delivered acceptable separation under steady-state conditions but showed limited robustness during transient slugging and temperature fluctuations. A site-based assessment indicated that alternative mitigation measures such as stabilizing flow rates, smoothing pressure variations, or expanding operating limits would impose operational constraints, potentially reducing production through additional choking. Increasing the demulsifier dosage was also deemed unsuitable, as overdosing is neither cost-effective nor operationally sustainable and may create downstream treatment issues.

To address these limitations, Demulsifier A was replaced with Demulsifier B, a diesel-based formulation designed to enhance oil-phase compatibility and improve transport of active components to the oil–water interface under dynamic conditions. The role of formulation composition and carrier solvent selection in demulsifier performance is well documented [18]. The revised chemical program was therefore expected to provide greater robustness under transient flow and variable thermobaric environments.

Following laboratory screening and commercial evaluation, a new demulsifier was selected as a potential replacement for the incumbent product based on its expected comparable separation performance and improved cost efficiency. However, confirmation of demulsifier performance under actual operating conditions is essential prior to full-scale implementation. Such validation is particularly challenging in offshore environments, where uninterrupted production must be maintained and operational risks carefully minimized.

3. Field trial of a chemical agent to examine its reliability and mitigate operational challenges without production interruption

For the reasons outlined above, a dedicated field trial methodology was developed to evaluate the new demulsifier under ongoing operating conditions without interrupting production. The approach was designed to generate reliable, representative data while maintaining stable process conditions and production integrity. This section outlines the methodology used to conduct the controlled offshore evaluation and to confirm compliance with operational separation specifications.

3.1 Materials and methods

A key distinguishing feature of the new demulsifier was the use of a diesel-based carrier solvent. The diesel-range solvent was selected to enhance oil-phase compatibility and to facilitate more effective transport of active demulsifying components to the oil–water interface. This formulation improves chemical distribution under dynamic offshore operating conditions, including transient flow regimes, variable residence times, and temperature fluctuations associated with liquid slugging. As a result, the diesel-based demulsifier demonstrates improved robustness compared to the incumbent formulation while maintaining equivalent separation performance at similar injection rates.

Although the commercial composition of Demulsifier A and Demulsifier B is proprietary, both products can be classified according to their functional behavior. Demulsifier A represents a conventional oil-soluble nonionic demulsifier system, while Demulsifier B is also based on nonionic active demulsifying components but uses a diesel-range hydrocarbon carrier solvent. Therefore, the main difference between the two products is not the active demulsifier class, but the solvent package, which improves oil-phase compatibility, chemical dispersion, and transport of active components to the oil–water interface under transient offshore operating conditions.

In addition, cost optimization opportunities were identified through the use of locally sourced solvents in the chemical formulation. A new demulsifier was introduced that contains the same active ingredients as the incumbent product, but with a modified solvent package incorporating locally sourced diesel. This substitution replaced a significant portion of the previously imported solvent, resulting in both cost savings and a substantial reduction in carbon emissions associated with logistics.

Prior to full deployment, a controlled field trial was required to confirm that the modified solvent system would not adversely affect separation efficiency or produced water quality, and to ensure that implementation could be managed without impacting current operations.

A temporary field trial program was developed to evaluate the performance of the new demulsifier relative to the incumbent product. To ensure a fair comparison, demulsifier injection rates to individual separators were maintained at existing set points throughout the trial period, with no operational adjustments permitted. A single tank containing 4.6 m^3 of the new demulsifier was allocated for offshore testing, and the trial continued until the tank was fully depleted. The trial duration was estimated at ten days based on the hourly injection rate.

During the trial, systematic sampling was conducted across the oil and produced water treatment systems. Performance assessment was based primarily on oil export quality and produced water specifications. The key performance indicators (KPIs) selected for evaluation were Basic Sediment and Water (BS&W) in export oil and individual separators, as well as OIW concentration at multiple stages of the produced water treatment system. Sampling locations and methods were carefully reviewed and revised, and critical process parameters were monitored using the process control system. This approach ensured that the collected data could reliably confirm whether the new demulsifier delivered separation performance comparable to the incumbent product, without adversely affecting oil or water quality or requiring increased chemical injection rates.

Overall, the field trial plan was designed to provide a precise and controlled evaluation of the performance of the new chemical formulation under realistic offshore operating conditions.

3.2 Preparations and critical requirements for field trial

The field trial was scheduled to ensure that no other tests or operational activities were ongoing that could affect well performance or separation system behavior. Plant operating conditions were maintained in a steady state throughout the trial to eliminate external factors that could influence the results and lead to misinterpretation of demulsifier performance. No changes were made upstream or downstream of the separation system, and the trial was conducted during a period of normal platform operation to ensure that the collected datawere reliable and representative.

Given that changes in demulsifier formulation can directly impact oil–water separation efficiency and produced water treatment performance, a defined set of dedicated sampling points was selected for monitoring. These included export oil (BS&W), separator oil outlet (BS&W), separator water outlet (OIW), hydrocyclone water outlet (OIW), and degasser water outlet (OIW). Baseline data were established prior to the start of the field trial to provide a reference for performance comparison. The baseline values were 7 and 7.8 % BS&W for export oil and separator oil outlet, respectively, and 1551, 267 and 23.9 mg/L OIW for the separator water outlet, hydrocyclone outlet, and degasser outlet, respectively.

In coordination with the production chemistry team, chemical injection rates were maintained constant throughout the trial period to eliminate external influences on separation performance. In addition to the demulsifier injection rate (80 ppm), the dosing rates of the reverse demulsifier (50 ppm) and flocculant (37 ppm) were also kept unchanged.

4. Results and discussion

Overall, the field trial validated the effectiveness of the developed methodology for online demulsifier change-out and performance assessment under real offshore operating conditions. The results provide a strong technical basis for full-scale implementation of the new demulsifier and support subsequent chemical optimization initiatives aimed at reducing operating costs and environmental impact.

This section discusses the key findings of the trial and presents the evidence supporting the general outcomes outlined above.

4.1. Enhancement of three-phase separation performance

Across the trial period, export oil quality and produced water specifications were consistently maintained within operational limits. Improved separation stability was primarily attributed to enhanced control of the oil–water interface and more robust produced water treatment performance under the prevailing operating temperatures. The field comparison showed that Demulsifier B provided more stable separation performance than Demulsifier A under the same injection rate. The improvement was observed in both oil and produced water quality: BS&W values decreased at the separator oil outlet and export oil line, while OIW concentrations were reduced at the separator water outlet, hydrocyclone outlet, and degasser outlet. Since the injection rate was kept constant during the trial, the improvement can be attributed to the modified formulation and diesel-based carrier solvent rather than increased chemical dosage. Importantly, these results were achieved without increasing the demulsifier dosage, confirming that the performance gains were inherent to the new formulation rather than the result of chemical over-injection.

The findings further indicate that separation efficiency is strongly influenced by chemical formulation, while improvements in separation stability also positively affected overall process conditions, including effective residence time, liquid slugging behavior, and thermobaric dynamics. This underscores the importance of integrated chemical and process optimization, rather than reliance solely on dosage adjustments. The observed stability of the separation process under the given temperature range and transient inlet conditions is largely attributed to the diesel-based carrier solvent, which enhances phase compatibility and ensures consistent delivery of the active components to the oil–water interface.

Figure 4 presents the BS&W results for the separator oil outlet and the common oil export line, comparing the pre-trial and trial periods. As shown in the trends, oil quality improved during the trial and exhibited greater stability relative to baseline conditions. Specifically, BS&W values decreased by factors of 6.8 and 5.7 % at the separator oil outlet and the export oil pipeline, respectively, demonstrating a substantial enhancement in dehydration efficiency and overall separation performance.

Similarly, positive trends were observed in the OIW results, as illustrated in figure 5. The performance of the produced water treatment system improved in parallel with the enhanced primary separation efficiency. Significant reductions in OIW concentrations were recorded at all monitored stages: 98% at the separator water outlet, 90% at the hydrocyclone outlet, and 80% at the degasser outlet. These results confirm the overall improvement in water quality and the increased stability of the separation process during the trial period.

Trend analysis of produced water quality in relation to OIW and BS&W values demonstrated strong alignment with the produced water export rate (fig. 6). As observed from the trend, the produced water export rate increased by approximately 16% following the chemical replacement. This indicates a clear positive correlation between improved separation efficiency and hydraulic throughput capacity.

4.2. Chemical optimization and cost impact

The successful completion of the demulsifier field trial enabled a broader chemical optimization programme without compromising three-phase separation, oil export quality, or produced water compliance. Progressive optimization of demulsifier injection rates was implemented in collaboration between offshore operations and asset production chemistry.

As shown in the table, the consumption of other chemicals used to maintain stable three-phase separation was reduced following the replacement of the demulsifier formulation. The reduction programme applied to all three chemicals-

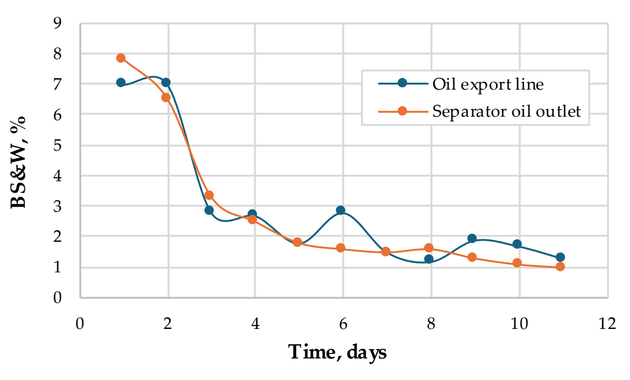

Fig. 4. Results of basic sediment and water analysis

demulsifier, reverse demulsifier and flocculant. In parallel, the operation conditions allowed to optimize antifoam agent injection rate without impacting gas separation performance. Overall, the initiative achieved notable additional savings, including reductions in chemical costs, transportation requirements, and overall energy consumption for operations.

These results demonstrate that appropriate chemical selection and optimization can sustain stable operational performance, even in the presence of normal process fluctuations, when supported by a robust and well-structured field trial. Furthermore, the findings indicate that such optimization can significantly reduce operating costs while maintaining the required separation efficiency.

4.3. Expected future challenges and areas for improvement

While the field trial confirmed the technical suitability of the new demulsifier for offshore installations in the Caspian Sea region, several aspects warrant further investigation. Separation performance remains sensitive to process disturbances, including reject oil routing, rapid fluctuations in produced water export rates, and variations in operating temperature. Future efforts should therefore focus on enhancing dynamic process control strategies to mitigate these effects and improve overall system resilience.

Moreover, much of the published literature on demulsification is based on laboratory-scale experiments using synthetic emulsions. The present field study underscores the importance of pilot- and full-scale investigations employing real crude oil systems under representative thermobaric and hydraulic conditions. Future research should further examine the coupled effects of temperature variation, emulsion aging, and the synergistic integration of chemical and mechanical separation techniques.

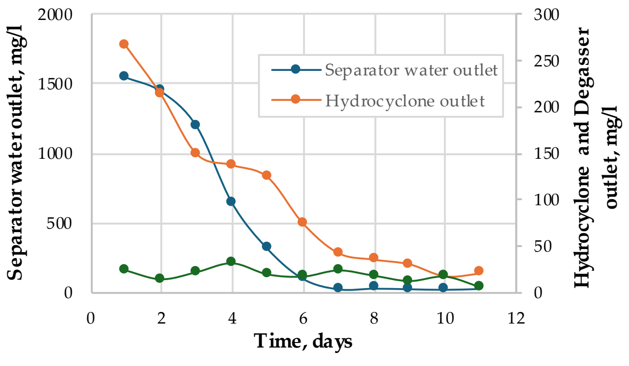

Fig. 5. Results of oil-in-water analysis

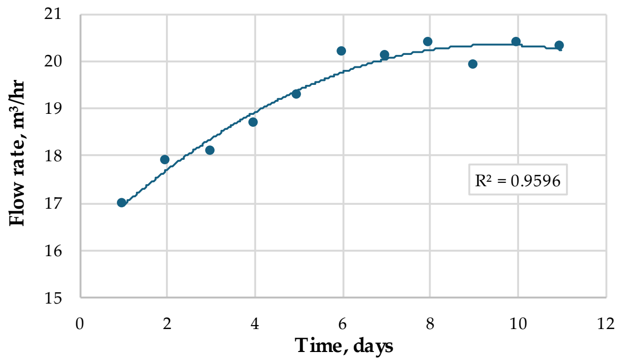

Fig. 6. Produced water export rate following chemical replacement

Environmental considerations also represent a critical direction for continued development. Although the adoption of locally sourced solvents has reduced logistics-related carbon emissions, further advancement toward low-toxicity and biodegradable demulsifier formulations would enhance the environmental sustainability of offshore chemical treatment programs.

Table

Chemical injection rates before and after trial

Injection rates, ppm	Demulsifier to separator (ppm)	Reverse Demulsifier to separator (ppm)	Flocculant to separator (ppm)
Before trial	80	50	37
End of the trial	27	40	32
After trial	65	32	20

Conclusions

This study confirmed the successful selection and offshore implementation of a newly formulated demulsifier without production interruption. The new product delivered separation performance better than the incumbent demulsifier at identical injection rates, demonstrating its technical suitability for full-scale deployment.

The results show that separation efficiency is primarily governed by chemical formulation and its interaction with dynamic process conditions. The diesel-based carrier solvent enhanced phase compatibility and ensured consistent delivery of active components to the oil–water interface, resulting in improved stability of separation process under transient flow and temperature variations. Importantly, performance gains were achieved without increasing chemical dosage, confirming that integrated chemical and process optimization is more effective than over-injection.

In addition to its technical advantages, the optimized formulation created operational flexibility for further optimization of chemical injection rates, while delivering measurable cost savings and reducing logistics-related environmental impacts. The field-trial methodology presented herein provides a practical and scalable framework for evaluating and implementing demulsifier changes under real offshore operating conditions.

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