Petroleum Research 10 (2025) 342–351

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/

Review Article

The role of hydrocyclone and induced gas flotation technologies in offshore produced water deoiling advancements

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ARTICLE INFO

Article history:
Received 15 May 2024
Received in revised form
2 October 2024
Accepted 24 October 2024
Available online 28 October 2024

Keywords:
Wastewater treatment
Offshore produced water deoiling
Hydrocyclones
Induced gas flotation
Environmental regulations

ABSTRACT

Produced water, a byproduct of oil and gas extraction, presents significant environmental challenges if not properly treated. This review focuses on advancements in two primary offshore deoiling technologies, namely: induced gas flotation and hydrocyclones, tracing their evolution from the 1940s to the present. The study provides a detailed comparison of these technologies in terms of efficiency, energy consumption, and waste generation, offering both qualitative and quantitative assessments. Particular attention is given to the integration of hydrocyclone-induced gas flotation (HIGF) systems, which enhance oil removal efficiency while reducing energy consumption, making them an important solution in offshore produced water management. Additionally, the review identifies specific design improvements in flotation units, such as multistage configurations, and explores the role of operational control in optimizing hydrocyclone performance. Global variations in produced water discharge standards are examined, emphasising the need for stricter environmental regulations. In addition, this study highlights the combined use of hydrocyclone and flotation technologies as a comprehensive approach for addressing both environmental and operational challenges in offshore produced water treatment.

1. Introduction

Produced water, the largest volume waste stream from oil and gas extraction, consists of a complex mixture of formation water, injected flowback and condensation water (Jiménez et al., 2018; Gamwo et al., 2022). Its composition varies based on geological location, reservoir characteristics and extraction methods (Fakhru'l-Razi et al., 2009). As wells age, the volume of produced water increases, driving up operational costs and environmental impact (Lusinier et al., 2019). Deoiling produced water is crucial when discharging into the environment due to several factors (Cordes et al., 2016; Olajire, 2020):

- Stringent regulations demand the removal of oil and grease to prevent environmental harm.
- The visible impact of oil and grease, such as surface slicks and marine ecosystem damage.
- Public and media attention during oil spills has underscored the environmental risks associated with oil and grease.

The development of induced gas flotation and hydrocyclones marked a significant improvement in deoiling efficiency and compactness (Richerand, 2012; Eyitayo et al., 2023). While individual advancements in these technologies have been widely studied, there is limited research on their integration into a dual-stage treatment system, which could enhance overall efficiency while reducing energy consumption and operational footprint. This review aims to address this gap by examining the advancements in both technologies, their combined use in hydrocyclone-induced gas flotation (HIGF) systems, and the role they play in offshore oilfield applications. By analysing historical developments, recent technological improvements and global regulatory standards, this review highlights the ongoing importance of innovation in produced water treatment to ensure both environmental protection and operational efficiency.

2. Total Oil and Grease

Total Oil and Grease (TOG), commonly referred to as oil in water (OIW), includes a variety of hydrocarbons such as aliphatic hydrocarbons, aromatics, waxes, fats, and other organic compounds present in produced water (Amakiri et al., 2022). These

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https://doi.org/10.1016/j.ptlrs.2024.10.002

contaminants primarily originate from crude oil and pose significant environmental risks, necessitating effective treatment before produced water is discharged or reused (Oliveira-Junior and Pereira, 2020; Abbas et al., 2021). The concentration of TOG in produced water typically ranges from 2 to 565 mg/L, with variations arising due to factors such as geological location, reservoir age, formation depth, and hydrocarbon recovery methods (Fakhru'l-Razi et al., 2009; Siagian et al., 2018; Olajire, 2020).

Younger reservoirs often produce less water with higher oil content, while older wells generate more water with lower hydrocarbon concentrations (Zheng et al., 2016). Enhanced oil recovery (EOR) techniques, such as water flooding or steam injection, can further increase the presence of emulsified hydrocarbons, complicating the treatment process (Olajire, 2020). Regulatory standards for TOG concentrations in produced water vary by region, with limits ranging from 10 to 100 ppm, with stricter controls in regions like the European Union and China (Igunnu and Chen, 2014; Jiménez et al., 2018). TOG concentrations are also influenced by the design and operation of separation equipment, as factors like retention time, pressure, and flow rate can affect treatment efficiency (Bram et al., 2020). Additionally, environmental factors such as temperature play a role, with higher temperatures increasing hydrocarbon solubility and lower temperatures causing wax precipitation (Zheng et al., 2016). Managing TOG effectively is crucial to meet regulatory compliance and minimize environmental impact, especially in offshore operations where space and resources are limited.

3. Offshore produced water deoiling

3.1. Historical perspective of produced water deoiling

In the six decades between 1940 and 2000, water treatment technology evolved significantly from basic to advanced methods, as depicted in Fig. 1, representing a timeline of the produced water deoiling.

In the 1940s and 1950s, the offshore industry self-regulated waste disposal, resulting in poor water treatment with inefficient gravity separation systems that required significant space. By the 1960s, regulatory standards introduced a no slick/no sheen requirement for oily water discharge, enforced through self-imposed guidelines and visual inspections. Despite continued use of gravity separation tanks, increasing oil production and limited offshore platform space led to challenges in handling larger volumes of produced water, resulting in reduced retention times and higher oil concentrations in discharged water (Richerand, 2012).

Technological advancements emerged in the late 1960s, with innovations like induced gas flotation and hydrocyclones. These technologies offered more efficient and space-saving alternatives to gravity separation, using gas bubbles and centrifugal force for oil-water separation. According to Eyitayo et al. (2023) and Richerand (2012), the evolution of these technologies was influenced by several key drivers, such as:

- Increasingly stringent discharge regulations which required more effective removal of oil and grease from produced water to prevent environmental harm.
- High-profile oil spills, which raised public awareness and media scrutiny, emphasising the need for better produced water management practices.
- Advances in engineering and materials science that enabled the development of more efficient and compact treatment technologies.
- The expansion of offshore oil production, which increased the volume of produced water, necessitating more effective treatment solutions.

By the 2000s, induced gas flotation and hydrocyclones became predominant methods for offshore deoiling of produced water, improving efficiency, space utilization and compliance with environmental regulations. These technologies continue to evolve, incorporating new materials and designs to address emerging environmental challenges (Richerand, 2012).

3.2. Induced gas flotation

Flotation is a process employed for the removal of absorbed particles and oil droplets from produced water, utilising gas bubbles as a transport medium (Amakiri et al., 2022). This technology has found extensive use in offshore produced water treatment due to its advantages, including the simultaneous removal of oil and suspended solids (Liu et al., 2021). Induced gas flotation is particularly effective, achieving oil removal efficiencies of up to 90% or more, effectively reducing oil concentrations to below 25 ppm under optimal conditions (Piccioli et al., 2020).

The gas flotation process, illustrated in Fig. 2, involves three primary stages. First, bubbles are generated; second, agglomerates form through contact; and finally, attachment occurs between the bubbles, the oil droplets and the suspended solids due to density differences forming an aerated solution (Al-Ghouti et al., 2019; Gamwo et al., 2022). These sequential steps lead to the formation of foam on the water surface, which is subsequently removed, leaving clarified water to be collected below the flotation zone (Jiménez et al., 2018; Al-Ghouti et al., 2019).

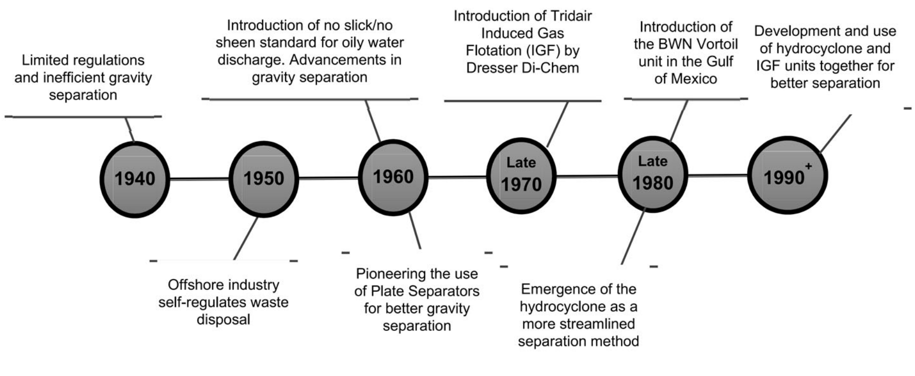

Fig. 1. Historical perspective on produced water deoiling (adapted from Richerand (2012)).

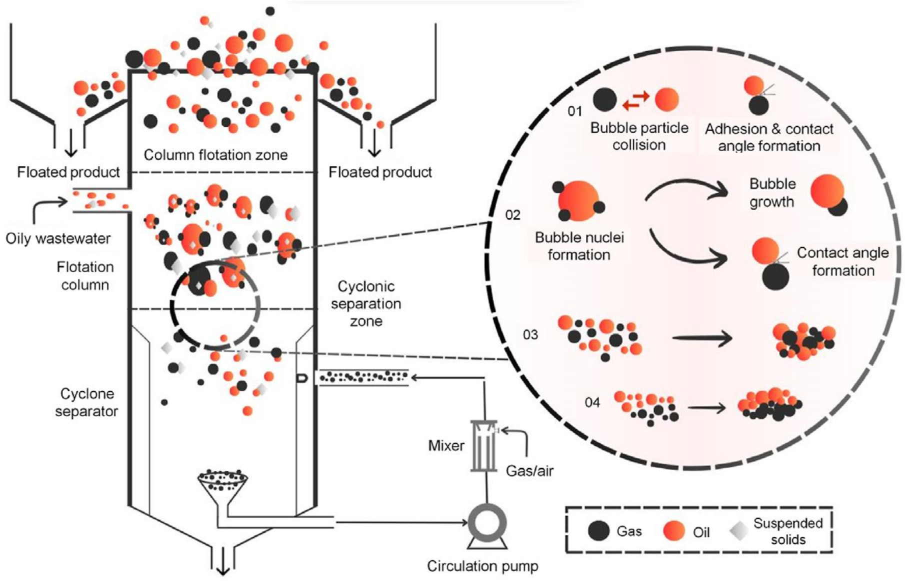

Fig. 2. Operating principle of the flotation technology (adapted and merged as a combination of Liu et al. (2021) and Amakiri et al. (2022)).

Enhancing collision and adhesion of the gas in the flotation process can lead to improved separation efficiency (Saththasivam et al., 2016). However, it is important to note that flotation comes with drawbacks, including high power consumption due to the need for increased energy to pressurise the system for effective gas circulation. Moreover, the sludge generated during flotation necessitates removal and proper disposal (Amakiri et al., 2022). Saththasivam et al. (2016) validated that gas flotation is able to reduce oil concentration from 1000 ppm to 10 ppm in produced water and is able to provides a high removal efficiency at a larger throughput or a shorter retention time for any given flow rate. Particles of 25 μm can be removed by a dissolved gas flotation process and when using coagulation as a pre-treatment step, contaminants of 3–5 μm can be removed as well (Al-Ghouti et al., 2019).

According to Liu et al. (2021), Stokes' Law is applicable for calculating final floc flotation, but separation efficiency depends on the collision and adhesion of bubbles and substances, as well as floc formation. These processes involve the three-phase interaction of solid, liquid and gas. Under the influence of a flotation agent, bubbles adhere to pollutants, forming initial flocs that continue to grow through catching, wrapping and bridging until they cannot withstand fluid shear or reach the separation area (Liu et al., 2021; Amakiri et al., 2022).

Two different types of flotation exist based on the method of bubble generation and the resultant bubble size, namely dissolved gas flotation, which is achieved by means of a gas compressor; and induced gas flotation, which makes use of mechanical, hydraulic or sparging systems (Gamwo et al., 2022; Liu et al., 2021; Abbas et al., 2021). Dissolved gas flotation uses a gas compressor to dissolve gas into the liquid under high pressure, forming microbubbles that adhere to particles and rise to the surface due to reduced density in contrast, IGF directly injects gas into the flotation chamber, producing larger bubbles, which can slightly reduce efficiency compared to smaller bubbles used in DGF (Jiménez et al., 2018).

The efficiency of the flotation process depends mainly on the contaminants to be removed, the liquid phase's density differences, the temperature of the inlet fluid and the size of the oil droplets. The flotation process has been reported to work well for the treatment of produced water with high and low total organic carbon (TOC) concentrations, as well as water with oil, grease and particulates of less than 7% solids (Guerra et al., 2011; Al-Ghouti et al., 2019). A pilot plant study by Mastouri et al. (2010) examined the effect of temperature and impeller speed on IGF performance for oil removal from produced water with total dissolved solids (TDS) ranging from 5 to 300 g/L. The study found that IGF could achieve up to 90% oil removal efficiency at high temperatures (80 °C) in a single flotation cell without chemicals (Mastouri et al., 2010).

Recent advancements in flotation unit designs, such as multi-stage configurations and internal swirl mechanisms, have significantly improved gas separation by enhancing the coalescence of oil droplets. These innovations achieve this by creating lower terminal velocities and increasing the frequency of collisions. Furthermore, the addition of separate inlet chambers enhances flotation efficiency by preventing counter current flow and increasing the residence time for bubbles and droplets, leading to more effective separation. Compact Flotation Units operate with capacities ranging from 10 to 900 m^3/h and have a retention time of less than 1 min. They generate bubbles between 200 and 300 μm using stable, independent systems, effectively reducing oil concentrations to below 25 ppm and achieving up to 90% removal efficiency. These advancements make CFUs indispensable for modern offshore oil and gas operations, providing efficient and flexible solutions for water treatment (Piccioli et al., 2020)

3.3. Hydrocyclone

Hydrocyclones make up more than 90% of current deoiling facilities in offshore oil and gas installations (Durdevic et al., 2017). The technology dates back to 1891, but it became widely used for liquid-liquid separation in 1980. This was due to the challenges of reduced platform space and greater depths in the offshore oil and gas industry (Richerand, 2012). The University of South Hampton in the United Kingdom developed this approach, using g-force to separate oil, sand, and water effectively. Richerand (2012) noted that the technology's initial field trials occurred in the Gulf of Mexico, marking it as a groundbreaking method. It was poised to replace standard separation equipment on offshore platforms.

As technology advanced, the hydrocyclone became a compelling

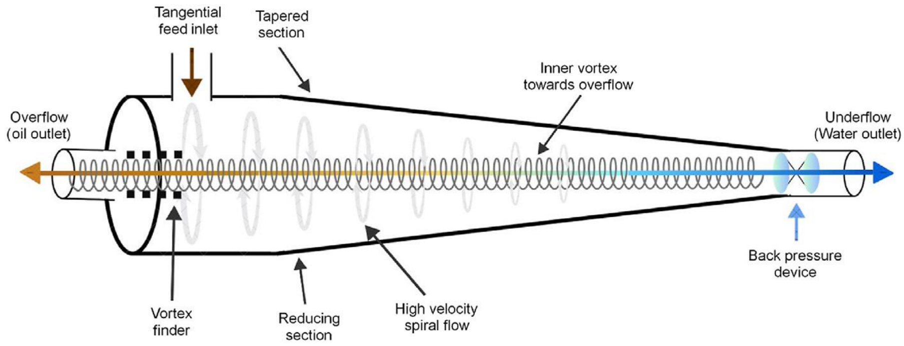

Fig. 3. Illustration of the Modus operandi of deoiling hydrocyclone (retrieved as a combination from Bram et al. (2020), Liu et al. (2021) and Amakiri et al. (2022)).

solution for enhanced separation. It was particularly well-suited for limited platform space and dynamic offshore structures. The hydrocyclone is insensitive to orientation, mechanically robust, and operates as a pressure vessel. It alleviated concerns about platform movement when filled with liquid (Richerand, 2012; Bram et al., 2020). Furthermore, using liners reduced the equipment's footprint. Liners were introduced inside the vessel instead of the manifold (Richerand, 2012; Abuhasel et al., 2021).

The hydrocyclone structure, shown in Fig. 3, consists of a cylindrical chamber connected to a conical body. This leads to the cone apex at the bottom outlet (Jiménez et al., 2018; Amakiri et al., 2022). In operation, a de-oiling hydrocyclone has a mixture of water and oil entering tangentially. This creates two distinct vortices within the cyclone (Bram et al., 2020). The centrifugal force causes denser fluids, like water, to move towards the wall, forming the underflow. Meanwhile, less dense oil migrates towards the inner axis and exits as overflow (Liu et al., 2021; Ghafoori et al., 2022). This gravity-driven separation relies on the density difference between the fluids. Hydrocyclones use rotating flow to enhance the acceleration field, reaching 2000 to 3000 times gravitational acceleration (Bram et al., 2020).

Hydrocyclone dynamics involve the three components of fluid velocity: tangential, axial and radial. Tangential velocity acts perpendicular to the cyclone's wall, generating centrifugal force to separate particles based on density. Radial velocity directs lighter particles towards the overflow and denser particles to the cyclone wall, facilitating separation (Adewoye, 2020). Saidi et al. (2013) notes that in liquid-liquid hydrocyclones, separation of large droplets begins in the cylindrical section, shifting towards the underflow as droplet size decreases. Studies indicate that centrifugal and drag forces in hydrocyclones are influenced by particle size distribution (Saidi et al., 2013), while some, like Zhang et al. (2017), highlight the significance of pressure gradient forces emphasising that larger particles are mainly affected by outward drag and centrifugal force acting radially outwards. Smaller particles experience inward drag, moving towards the cyclone's centre (Zhang et al., 2017).

The terminal slip speed of oil droplets that are dispersed in water can be estimated by Stokes law, with the substitution of the acceleration factor by centripetal acceleration (T^2/r), which is directed towards the hydrocyclone centre axis as shown in Eq. (1), where $\Delta\rho$ represents the density difference between the oil and water (kg/m^3), D_d is the oil droplet diameter (m), μ is the dynamic viscosity of water (Pa.s), T is tangential speed (m/s) and r is the radial position inside the hydrocyclone (Bram et al., 2020).

$$U_d = \frac{\Delta\rho D_d^2 T^2}{18\mu r} \quad \text{(Eq. 1)}$$

According to Amakiri et al. (2022), under the effects of centrifugal force, radial velocity gradient force, fluid resistance, centrifugal buoyancy and magnus force, hydrocyclones may reduce oil in water concentration from produced water to as low as 20 ppm. Hydrocyclones have the capacity of achieving a 99% removal efficiency for oil droplets higher than 50 μm with the efficiency dropping significantly for droplets of 5 μm or smaller (Igunnu and Chen, 2014; Nasiri et al., 2017; Liu et al., 2021; Amakiri et al., 2022; Ghafoori et al., 2022). A description of centrifugal force (F_c), centrifugal buoyancy (F_b), fluid resistance (F_S), Magus force (F_M) and radial velocity gradient force (F_a) is given in Table 1.

To maintain processing capacity on offshore platforms, multiple cyclone tubes known as liners are installed within a horizontal vessel with hydrocyclones. Efficient operation requires optimizing each tube, but the fixed processing capacity of hydrocyclones is a significant limitation. In the offshore petroleum industry, adjusting equipment capacity involves plugging or unplugging liners, which fails to address real-time changes in produced water volume (Liu et al., 2021).

3.3.1. Performance criteria

Achieving optimal efficiency in a deoiling hydrocyclone is contingent on a well-designed hydrocyclone, along with the right balance of flow rate and flow split. A proper flow rate, indicative of an adequate energy quantity, is essential for establishing a robust gravity field within the hydrocyclone. Additionally, an appropriate flow split is crucial for effective separation, as emphasized by Liu et al. (2021).

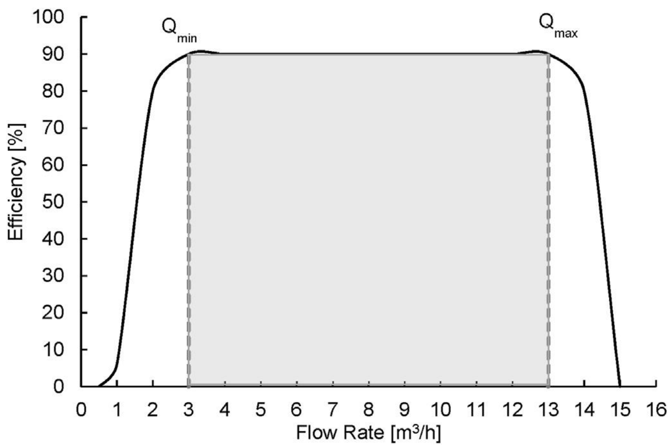

Fig. 4. Relationship between the efficiency and flow rate in a hydrocyclone (adapted from Husveg et al., 2007).

Table 1
Types of effects applied in oil particles during the deoiling process (Adewoye, 2020; Liu et al., 2021).

Type of Effect	Mathematical Formula	Description
Centrifugal Force	$F_c = m\frac{u_t{}^2}{r} = \frac{\pi d^3 \rho u_t{}^2}{6r}$	Driving force for radial sedimentation
Centrifugal Buoyancy	$F_b = \frac{\pi d^3}{6}\frac{dP}{dr} = \frac{\pi d^3 \rho u_t{}^2}{6r}$	Force caused by the fluid pressure difference between the inside and outside in the radial direction
Fluid Resistance	$F_S = 3\pi\mu d v_r$	Force caused by the relative motion between the droplet and the continuous phase
Magus Force	$F_M = k\rho d^3 \omega v_t$	Lift force perpendicular to the relative velocity direction between the droplet and the continuous phase generated by the droplet rotation
Radial Velocity Gradient Force	$F_a = \frac{\pi}{d}\rho d^3 v_r \frac{dv_r}{dr}$	Force generated by the gradient of the velocity fluctuation in the radial direction
Legend	where m is the mass of droplet (kg), r is the radius (m), u_t is the tangential velocity of the droplet at radius r in (m/s), d is the drop diameter (m), ρ is the droplet density (kg/m^3), P is the pressure at the radius r (Pa), μ is the viscosity of two-phase flow (Pa.s), v_r the relative velocity between the droplet and the continuous phase in the radial direction (m/s), k is the constant coefficient related to droplet size; ω is the rotational angular velocity of the droplet; v_t is the relative tangential velocity between the droplet and the continuous phase (slip velocity) and v_r is the radial velocity of the continuous phase.	

3.3.1.1. Flow rate. The flow rate versus efficiency relationship in Fig. 4 is a common characteristic of deoiling hydrocyclones. When the flow rate reaches the value of minimum flow rate (Q_{min}), the efficiency of the hydrocyclone is at a maximum. If the flow rate is increased to beyond maximum flow rate (Q_{max}) the efficiency will decrease as the retention time is too low for the separation to finish before the mixture leaves the hydrocyclone. The decline in efficiency beyond Q_{max} is due to either a significant increase in droplet break-up due to excessive shear-forces and turbulence or due to a lack of sufficient pressure gradient required to propel the separated oil-core through the overflow. This inadequacy arises from reduced pressure at the hydrocyclone axis during high flow rates (Husveg et al., 2007).

3.3.1.2. Flow split. Maintaining a minimum flow split is essential to ensure that only a minimal amount of oil exits through the underflow. The flow split is defined in Eq. (2), where Q_o and Q_i represent the overflow flow rate (m^3/s) and inlet flow rate (m^3/s), respectively. In situations with a small flow split, where the overflow flow rate (i.e., Q_o) and the underflow flow rate (i.e., Q_u) are almost the same, it becomes convenient to use the approximation expressed in Eq. (3) (Husveg et al., 2007; Bram et al., 2020):

$$F_S = \frac{Q_o}{Q_i} \quad \text{(Eq. 2)}$$

$$F_S = \frac{Q_o}{Q_u} \quad \text{(Eq. 3)}$$

Achieving and maintaining an optimal flow split in hydrocyclones is essential for effective oil and water separation. While historical flow splits exceeded 5%, modern deoiling hydrocyclones commonly maintain a range of 2–3% (Husveg et al., 2007). Initially, increasing the flow split enhances separation efficiency, but it eventually plateaus with marginal improvement. Striking a balance is crucial to prevent oil loss through the underflow (Durdevic et al., 2017; Bram et al., 2020). The relationship between flow split and efficiency as described in Fig. 5, remains constant for different flow rates, serving as a fundamental factor in hydrocyclone operational control (Durdevic et al., 2017).

3.3.2. Operational control

Deoiling hydrocyclones assume a critical role in navigating the

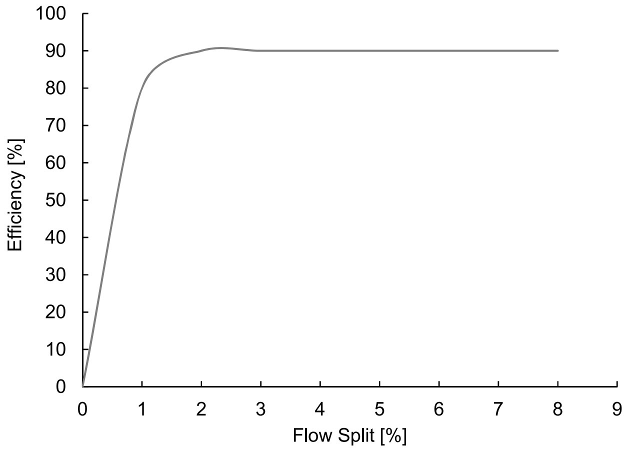

Fig. 5. Relationship between the efficiency and flow split in a hydrocyclone (adapted from Husveg et al., 2007).

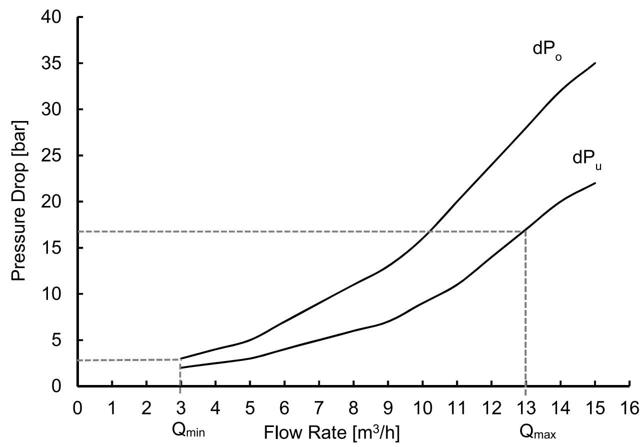

Fig. 6. Relationship between the flow rates and the pressure drop in a hydrocyclone (adapted from Husveg et al., 2007).

complexities of dynamic operations marked by varying water production rates (Durdevic et al., 2017). According to Husveg et al. (2007), it is imperative to ensure that the flow rate remains within the defined range of Q_{min} and Q_{max}, with concurrent adjustments to the flow split in response to rate fluctuations. According to Bram et al. (2020), the controller output to the hydrocyclone underflow control valve often incorporates the use of differential pressures corresponding to Q_{min} and Q_{max} as limits in flow rate control, as illustrated by the lower dP_u curve in Fig. 6.

Fig. 6 illustrates the relationship between inlet-to-overflow and inlet-to-underflow pressure drops (dPo and dPu, respectively) and inlet flow rate under a constant flow split (Husveg et al., 2007). An integral element in this control mechanism is the pressure drop ratio (PDR), as expressed in Eq. (4).

$$PDR = \frac{dP_o}{dP_u} = \frac{P_i - P_o}{P_i - P_u} \quad \text{(Eq. 4)}$$

Where, P_i (Pa) is the inlet pressure, P_o (Pa) is the overflow pressure and P_u (Pa) is the underflow pressure. Maintaining a consistent PDR as throughput varies, is critical for stabilizing the flow split, particularly at flow rates aligned with the efficiency plateau between Q_{min} and Q_{max} (Fig. 4), which is the preferred operational range for hydrocyclones (Liu et al., 2021). According to Husveg et al. (2007), PDR influences the axial pressure gradient toward the overflow, with a roughly linear relationship between the flow split percentage and the PDR. Typically, deoiling hydrocyclones are configured with the PDR ranging between 1.5 and 3, with the specific value dependent on the size of the hydrocyclone (Husveg et al., 2007).

The direct correlation between hydrocyclone pressure drop and flow rate, conveniently render flow split to be monotonically increasing with PDR. This relationship between PDR and flow split enables control solutions to use PDR obtained through three pressure measurements instead of relying on flow rate measurements, which are less reliable and more expensive than pressure measurements (Bram et al., 2020).

When evaluating the hydrocyclone separation performance, two metrics are commonly used: 1) The concentration reducing separation efficiency (ε_{red}), which describes the percentage of oil-in-water concentration reduction from inlet to underflow as given in Eq. (5); and 2) The oil removal efficiency (ε_{oil}), which describes the volumetric percentage of oil introduced at the inlet that exits the overflow as given in Eq. (6). C_i, C_o and C_u are the volumetric oil-in-water concentration at the inlet, overflow and underflow, respectively, and Q_i, Q_o and Q_u the flow rates at the inlet, overflow and underflow, respectively (Kharoua et al., 2010; Bram et al., 2020).

$$\varepsilon_{red} = 1 - \frac{C_u}{C_i} \quad \text{(Eq. 5)}$$

$$\varepsilon_{oil} = \frac{C_o Q_o}{C_i Q_i} = 1 - \frac{C_u Q_u}{C_i Q_i} \quad \text{(Eq. 6)}$$

3.3.3. *Types of deoiling hydrocyclones*

Deoiling hydrocyclones are critical in the oil and gas industry for separating oil droplets from produced water. They are categorized based on inlet geometry, swirl tube configuration, and flow direction, each impacting their efficiency and suitability for various applications (Van Campen, 2014; Adewoye, 2020; Ekechukwu et al., 2024)

3.3.3.1. Inlet geometry. (1) Tangential inlet hydrocyclones: Enhance oil-water separation efficiency by creating a strong rotational flow that increases centrifugal forces. Ideal for fluctuating feed conditions like offshore platforms, they accommodate varied flow rates and minimize turbulence, reducing wear and maintenance. (2) Axial inlet hydrocyclones: optimize the separation of fine oil droplets by allowing fluid to enter in an azimuthal direction. These hydrocyclones are effective for fine separation but require precise control of feed conditions to maintain efficiency.

3.3.3.2. Swirl tube configuration. (1) Traditional hydrocyclones: feature conical parts that gradually reduce diameter along the swirl tube to enhance the separation process. These are suitable for general oil-water separation tasks in both onshore and offshore facilities and offer a balance between efficiency and cost-effectiveness, making them a popular choice for many operators. (2) Cylindrical hydrocyclones: maintain a constant diameter throughout the swirl tube, affecting separation dynamics by lacking the typical conical shape. While these may offer lower separation efficiency compared to traditional designs, their compact form factor is beneficial in space-limited.

3.3.3.3. Flow direction. (1) Co-current hydrocyclones: allow both oil and water phases to exit through the downstream side, facilitating straightforward, continuous separation without phase redirection. These are used in applications requiring seamless integration and offer reliable performance across a wide range of operating conditions. (2) Counter-current hydrocyclones: facilitate distinct separation paths by allowing the water to exit downstream and the oil to exit upstream. These are used when enhanced oil and water separation is necessary, especially in systems prioritizing oil recovery.

3.3.4. *Effect of geometrical parameters in hydrocyclones*

The geometrical parameters of hydrocyclones, including the overflow section, inlet section, underflow diameter, overall size, and cone angle, play a critical role in determining separation efficiency. Each parameter affects the fluid dynamics within the hydrocyclone, which in turn impacts its ability to separate oil from water.

3.3.4.1. Overflow section. The relationship between the vortex finder and the underflow diameter has traditionally been viewed as a key design parameter. However, Shah et al. (2006) challenged this assumption, suggesting that the vortex finder and underflow orifice should be considered independently. This insight is supported by Ghodrat et al. (2016) and Ni et al. (2019), who emphasized the importance of the vortex finder's diameter in optimizing separation efficiency. Smaller overflow diameters, as noted by Zhao et al. (2019), typically improve separation by reducing turbulence and allowing for more controlled fluid flow. The optimal vortex finder length, as highlighted by Chakraborty et al. (2018), is critical in maximizing efficiency, but overly long vortex finders can reduce overall efficiency, as confirmed by computational simulations from Tian et al. (2020). In general, optimizing the vortex finder size and length is essential for achieving higher separation efficiency in hydrocyclones.

3.3.4.2. Inlet section. The inlet diameter and geometry significantly influence the initial flow conditions, which are vital for effective separation. Larger inlet diameters tend to enhance performance by facilitating smoother fluid entry, as observed by Erikli and Okay (2015). Studies by Vieira and Barrozo (2014) and Tang et al. (2018) support this, highlighting that the inlet design directly affects the cyclone's ability to generate the necessary centrifugal forces for separation. Dual inlets, as proposed by Osei et al. (2015) and Al Kayiem et al. (2014), are shown to improve separation efficiency by reducing turbulence and ensuring more uniform flow. Overall, improvements in inlet geometry, particularly the use of dual inlets, can significantly enhance separation performance by stabilizing flow conditions and reducing turbulence.

3.3.4.3. Underflow diameter. The underflow diameter is a critical parameter that influences the separation of oil and water. Ni et al. (2019) stressed the difficulty in predicting its effects due to its complex interaction with feed concentration and flow dynamics. Studies by Ghodrat et al. (2016) found that larger underflow diameters improve efficiency for high feed concentrations, while smaller diameters are more effective for lower concentrations. However, as underflow diameters increase, efficiency can drop due to larger low-pressure zones forming within the hydrocyclone, as noted by Rakesh et al. (2014). In summary, optimizing the underflow diameter is essential for maintaining separation efficiency, particularly in dynamic operational conditions with varying feed concentrations.

3.3.4.4. Hydrocyclone size. The size of the hydrocyclone, particularly its length-to-diameter ratio, has a direct impact on separation efficiency. Brar et al. (2015) demonstrated that increasing the length up to an optimal ratio enhances performance by increasing the residence time and allowing more thorough separation. However, beyond this optimal point, efficiency declines due to higher pressure drops. The cylindrical-conical ratio is also important, with the diameter of the cylindrical section being a key factor in determining the size of particles that can be effectively separated (Adewoye, 2020). Larger hydrocyclones may struggle with the separation of smaller particles, as noted by Endres et al. (2012), highlighting the need for balance between hydrocyclone size and particle size.

3.3.4.5. Cone angle. The cone angle is a fundamental design parameter that influences the velocity profile within the hydrocyclone. Cilliers (2000) recommended a cone angle between 15° and 30°, where smaller angles provide better efficiency for finer particle separation and larger angles work better for coarser particles. Vieira and Barrozo (2014) and Saidi et al. (2013) observed that cone angles larger than 30° reduce separation efficiency due to increased radial velocity, which drags more particles into the overflow. Jiang et al. (2011) added that larger cone angles reduce pressure within the cyclone, further impacting separation. Various innovative designs, such as convex cones and tapered shapes (Vakamalla and Mangadoddy, 2019), show promise for improving cut sizes and recovery rates, though their impact on finer particles remains limited. Overall, selecting the appropriate cone angle is crucial for optimizing the separation of different particle sizes, particularly in produced water treatment applications.

3.4. Hydrocyclone-induced gas flotation systems (HIGF systems)

In the realm of produced water treatment, hydrocyclones play a pivotal role as a primary separation device, often supplanting the need for traditional technologies like corrugated plate interceptors or skimmer vessels (Richerand, 2012). The evolution of hydrocyclones into a practical solution, functioning as pressure vessels and incorporating liners within the vessel to reduce equipment size, has been driven by technological advancements (Liu et al., 2021). To further enhance the effectiveness of gas flotation, there is a recognised need to intensify and increase the probability of three-phase collisions between oil, gas and solid particles post-floc formation.

A common approach in offshore oil and gas, especially in floating facilities, involves synergistically combining hydrocyclone and gas flotation technologies in series as primary and secondary treatment methods, respectively. The combination of these technologies exploits the strengths of both: hydrocyclones provide rapid initial separation, while gas flotation ensures the removal of smaller oil particles that may have escaped the primary stage (Ekechukwu et al., 2024; Gangwar et al., 2024). This integration not only improves the overall oil removal efficiency but also reduces the equipment footprint, which is critical in offshore settings where space is at a premium (Gangwar et al., 2024). The following key aspects highlight the advantages and applications of the HIGF system:

- Sequential Treatment: The hydrocyclone handles the bulk removal of larger oil droplets and solids, reducing the load on the induced gas flotation unit. This sequential approach enhances overall efficiency and extends the operational life of the induced gas flotation unit (Gangwar et al., 2024).
- Compact Design: Which is particularly beneficial for offshore platforms where space is limited (Ekechukwu et al., 2024). HIGF systems can be designed to fit within the constrained space while maintaining high treatment efficiency.
- Energy Efficiency: Hydrocyclones require minimal energy, as they rely primarily on the feed pressure to create the necessary centrifugal force. Induced gas flotation, while requiring energy for gas generation, can benefit from the reduced load provided by the hydrocyclone, leading to overall energy savings (Amakiri et al., 2022; Ghafoori et al., 2022).
- Enhanced Performance: The use approach of using primary and secondary treatment, yields higher oil removal efficiencies and lower residual oil concentrations, which is ideal for applications where stringent environmental regulations must be met (Gangwar et al., 2024).

3.5. Qualitative and quantitative assessments of hydrocyclone and gas flotation systems

Table 2 outlines the features, advantages, disadvantages and waste streams associated with hydrocyclone and gas flotation technologies in the treatment of produced water. From separation mechanisms to energy consumption, chemical use and waste stream composition, the comparison provides insights for selecting the most suitable technology based on specific water characteristics and treatment requirements.

Fig. 7 provides a graphical representation of the influent produced water's OIW and TSS concentration ranges that can be effectively treated by a hydrocyclone as primary treatment, and induced gas flotation as the secondary treatment method. Polishing methods are usually employed for water treated for reuse (Larson, 2018).

Amakiri et al. (2022) outlined key criteria for evaluating produced water treatment technologies as shown in Table 3. The hydrocyclone and flotation technologies were scrutinised based on various performance parameters and both exhibited similar ratings. However, the hydrocyclone outperformed flotation in terms of robustness, receiving a higher score, while both showed equal consistency ratings. In terms of flexibility to treat a diverse range of wastewater, the hydrocyclone demonstrated intermediate flexibility, whereas flotation had a comparatively lower score. These assessments provide nuanced insights into the comparative performance of hydrocyclone and flotation technologies in wastewater treatment applications, which could serve as basis for technology selection throughout the oil and gas industry.

Table 2
Comparative analysis of hydrocyclone and gas flotation technologies for produced water treatment (adapted as a combination of Igunnu and Chen, 2014; Nasiri et al., 2017; Jiménez et al., 2018; Liu et al., 2021; Amakiri et al., 2022; Gamwo et al., 2022; Ghafoori et al., 2022).

Criteria	Hydrocyclone	Gas Flotation
Separation Mechanism	Separation of oil occurs freely through the centrifugal force created by the pressurised tangential input of the incoming stream.	Oil particles undergo separation from water by adhering to induced gas bubbles, causing them to ascend to the surface for recovery.
Feasibility	Effective for treating all varieties of produced water, regardless of total dissolved solids (TDS), organic content and salt concentrations.	Suitable for treating produced water characterised by elevated total organic carbons (TOC) and particulate content, with solids concentration exceeding 7%.
Efficiency	90–95% for oil droplets >20 μm	80–85% for oil droplets between 5 and 25 μm
Energy Consumption	Low, relies on feed pressure	Moderate to high, requires gas generation
Chemical Use	None.	May require coagulants
Pre/Post-Treatment	Pre-treatment is unnecessary, but post-treatment may be necessary to eliminate additional contaminants from the outlet water.	Post-treatment is unnecessary, though coagulation may be needed as a preliminary treatment step.
Waste Stream	Slurry containing suspended particles.	Oil with suspended solids and gases.
Advantages	• Operates without the need for chemicals and energy. • Achieves high recovery of treated water. • Capable of lowering oil and grease concentrations to 10 ppm. • Uses compact modules. • Effectively handles produced water with elevated oil content.	• Nearly 100% water recovery. • No need for post-treatment. • Absence of moving parts. • High efficiency attributed to coalescence. • Simple and user-friendly to operate. • Exhibits robustness and durability. • Provides separation effects on suspended solids.
Disadvantages	• Inlet blockage by solids and scale formation may result in additional cleaning costs. • Disposal is necessary for the secondary waste produced. • Energy is needed to pressurise the inlet. • Incapable of removing solids, phenols, and aromatic hydrocarbons. • Susceptible to fouling. • High maintenance costs. • Limited range of optimal operating parameters. • The effectiveness of separation is influenced by blockage and wear of one or more cyclone tubes.	• Unsuitable for high-temperature feed water. • Disposal of sludge is necessary for managing generated solids. • Results in the generation of a significant amount of gas. • Separation is Influenced by the retention time. • Secondary pollution (i.e., scum), due to the use of chemical agents. • The efficiency of separation is affected by the volume of the injected gas.

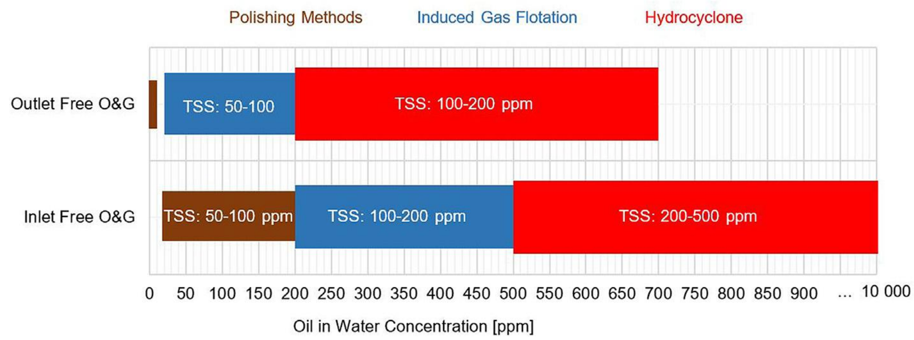

Fig. 7. Influent and effluent oil and grease concentration by treatment method (adapted from Larson, 2018).

Table 3
Qualitative assessment of hydrocyclone and gas flotation technologies (Amakiri et al., 2022).

Criteria	Hydrocyclone [Primary Treatment]	Flotation [Secondary Treatment]
Waste Generation	●●○○	●●○○
Chemical Demand	●○○○	●○○○
Energy Demand	●●○○	●●○○
Adaptability for Easy Upgrades	●○○○	●○○○
Durability in Tough Conditions	●●●●	●●○○
Consistency / Low-Failure Operation	●●●○	●●●○
Effective in the Treatment of Diverse Water Compositions	●●○○	●○○○

●○○○ Low ●●○○ Average ●●●○ High ●●●● Very High

4. Produced water regulations for environmental discharge

In offshore operations, it is standard practice to release treated produced water into the sea. The primary treatment goal is to decrease both dissolved and suspended oil to acceptable levels depending on location and minimize the toxic effects on marine fauna and flora (Gamwo et al., 2022). Oil and grease within offshore produced water has garnered significant attention and evolved into pivotal regulatory standards for lawmakers, while other hazardous substances have been largely disregarded (Dwyer, 2016). The concentration of dissolved oil in produced water is contingent on the production volume, the enhanced oil recovery method, the age of the well, as well as the characteristics of the predominant hydrocarbon in the oil. While the concentration of the suspended oil is influenced by the density of the oil, the historical shear forces acting on the droplets, the amount of oil precipitation and the interfacial tension between the water and oil (Nasiri et al., 2017; Amakiri et al., 2022).

The discharge of oil and grease into marine environments has far-reaching ecological implications. It poses a significant threat to marine life, as these contaminants are toxic to organisms, hindering their respiration, feeding and reproductive processes (Nasiri et al., 2017; Amakiri et al., 2022). According to Hedar (2018), the settling of oil and grease on the seafloor leads to habitat degradation, affecting benthic species like worms and clams. These pollutants enter the food chain, accumulating in marine organisms and posing health risks to humans who consume contaminated seafood. Additionally, the introduction of these contaminants can disturb the balance of marine ecosystems, potentially leading to shifts in species composition and diversity, further exacerbating the ecological disruption (Gazali et al., 2017).

Growing environmental awareness has prompted regulatory bodies in many countries to impose stricter limits on the discharge of oil and grease (Jiménez et al., 2018). This underscores the significance placed on safeguarding aquatic ecosystems. China stands out with the strictest regulations, setting a minimum oil in water discharge allowance of 10 ppm, emphasising a commitment to marine ecosystem protection. Conversely, higher allowances of 100 ppm are often associated with oil-producing nations like Egypt, Morocco, Tunisia and the Syrian Arab Republic, reflecting economic considerations in detriment to potentially higher environmental risks. The allowances exhibit wide variability globally, reflecting diverse levels of environmental protection measures. Regional clusters, like European countries with similar allowances around 30 ppm, highlight the influence of regional agreements aligning with the European Union's commitment to stringent environmental standards (Neff et al., 2011; Igunnu and Chen, 2014; Jiménez et al., 2018; Amakiri et al., 2022).

Evolving regulations reveal a recent trend of tightening standards, driven by a heightened awareness of oil and grease's detrimental impact on marine life (Gamwo et al., 2022). According to Jiménez et al. (2018), this shift is reinforced by increasing transparency in reporting and monitoring efforts to responsibly manage oil and grease disposal for the preservation of marine environments. In addition to legislation, many water-stressed countries with oilfields are looking for ways to supplement their limited freshwater resources by focusing on efficient and economical methods to treat produced water, so that it can be channelled to agricultural and industrial uses (Igunnu and Chen, 2014).

5. Future research directions

The treatment of produced water using hydrocyclones and induced gas flotation systems has experienced significant advancements. However, continuous research and development are crucial to address existing limitations and enhance the efficiency and applicability of these technologies. Future research need to focus on optimizing hydrocyclone design by investigating the impact of varying cone angles, inlet configurations and vortex finder dimensions to improve fluid dynamics and separation performance. Additionally, measuring and benchmarking hydrocyclone models against various droplet sizes can enhance accuracy (Ni et al., 2019; Bram et al., 2020).

Exploring the development of wear-resistant and anti-fouling materials for hydrocyclone and induced gas flotation's construction can significantly improve efficiency and automation. This is particularly vital for produced water treatment on offshore platforms, ensuring these systems remain green, efficient, secure and capable of handling challenges posed by deep and ultra-deep-water exploration (Liu et al., 2021). Research needs also to be conducted on verification of operational control systems in full-scale hydrocyclone optimisation programs to ensure they meet performance criteria and maintain efficiency. Developing reliable sensors and monitoring systems that provide real-time data on deoiling performance is essential and by utilising artificial intelligence and machine learning algorithms to predict system behaviour and optimize operating conditions could significantly improve reliability (Durdevic et al., 2017; Tian et al., 2020; Liu et al., 2021).

Further research on optimisation of gas flotation techniques by increasing the collision and adhesion efficiencies of oil droplets and gas bubbles is another important area. This could be achieved by developing new means of generating smaller gas bubbles, promoting oil droplet coalescence with coagulants and enhancing fluid path designs to maximize bubble-droplet interactions (Saththasivam et al., 2016; Liu et al., 2021)

6. Conclusion

Produced water treatment in the oil and gas industry remains a critical environmental challenge. The advancements in hydrocyclone and induced gas flotation technologies for produced water treatment are emphasized in this study. Hydrocyclones are highly efficient for larger oil droplets (>20 μm) and offer low energy consumption, making them suitable for primary treatment. However, their effectiveness declines with smaller droplets. IGF systems, while better at removing smaller oil droplets (down to 5 μm), face challenges related to higher energy use and fouling. The integration of both technologies into hybrid Hydrocyclone-Induced Gas Flotation (HIGF) systems proves to be an efficient solution, combining the strengths of both methods to enhance oil removal and reduce energy consumption.

Global regulatory variations in oil-in-water limits (10–100 ppm) highlight the need for further improvements in treatment efficiency. Continued research should focus on optimizing system design, improving energy efficiency, and incorporating advanced control systems using AI and machine learning to ensure compliance with stringent environmental standards.

CRediT authorship contribution statement

Sandro Duarte César: Writing – original draft, Methodology, Investigation, Conceptualization. **Debbie De Jager:** Writing – review & editing, Supervision. **Mahomet Njoya:** Writing – review & editing, Supervision.

Compliance with ethics guidelines

All authors (Sandro César, Debbie de Jager and Mahomet Njoya) declare that they have no conflict of interest or financial conflicts to disclose.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would also like to express their gratitude to various oil and gas professionals consulted to review this paper.

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