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Coalescence Process: An Optimal and Economical Solution for Offshore Produce Water Treatment

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ABSTRACT

Produced water (PW) is the largest by-product of oil and gas production, which has a serious impact on water pollution in the offshore oil and gas industry. In industrial processes, it is necessary to separate hydrocarbons and oil along with water by methods such as gravity sedimentation, enhanced gravity sedimentation, and hydrocyclones from produced water. However, conventional technologies cannot achieve optimal separation requirements in a compact space under extreme conditions, such as emulsions and large volumes of PW. The PW treatment system must be green and efficient in order to benefit from the extensive exploration, production of offshore oil and gas in the future. Therefore, factors such as improving the purification efficiency, reducing the space occupation and the cost of practical use of a PW purification process on an offshore operational scale along with the new method of Combined fibers coalescence were investigated according to the operational works.

1. Introduction

The plentiful resources of oil and gas can be found in the oceans, which are often referred to as the blue planet [1]. In 2019, approximately 30% of the total production of oil was from offshore drilling [2, 3]. The generation of wastewater is the result of extracting oil from underground during the production process, and it is known as produced water (PW). On most offshore platforms, this wastewater is the biggest byproduct in terms of volume in oil and gas production operations. The composition of pw is intricate and consists of diverse organic and mineral compounds, both soluble and insoluble [4-7]. Due to the rise in oil and gas production, there has been a growth in the volume of water generated by oil fields all over the world [8]. Consequently, the global disposal of this water in an environmentally sustainable manner has become a significant worldwide environmental concern [9].

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Therefore, effectively managing produced water is essential in enabling its reutilization, retrieval, and secure release. [10]. However, developing efficient produced water treatment technologies that meet acceptable discharge limits Continues to be a major obstacle for the oil industry. The demand for oil extraction is anticipated to lead to a rise in the production of produced water, along with an increase in global production activities. The three major regions that have the highest increase in volumes of produced water are North America, the Middle East/Africa, and Europe/Central Asia. These regions also happen to be the top three countries that produce the most hydrocarbons globally. (Fig. 1).

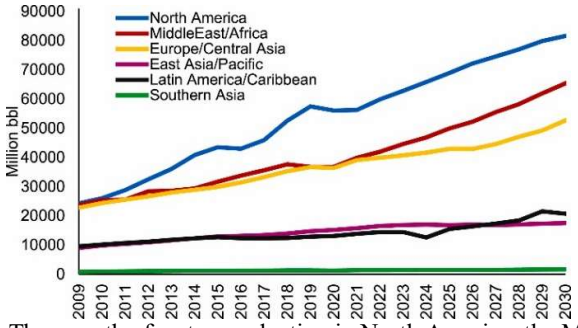


Fig. 1. The growth of water production in North America, the Middle East/Africa, and Europe/Central Asia over time [8]

In the initial stages of oil field extraction, the water content in the produced fluid is less compared to the mid and late stages. The water to oil ratio also significantly increases with the age of the well (Fig. 2 [11]). The fluids generated from offshore oil fields across the world typically contain around 75% to 80% water, and the ratio of water to oil can vary from 3:1 to 4:1 [12, 13]. In certain oil wells that are at the final or concluding phases of oil retrieval, the proportion of water could go over 98% [14].

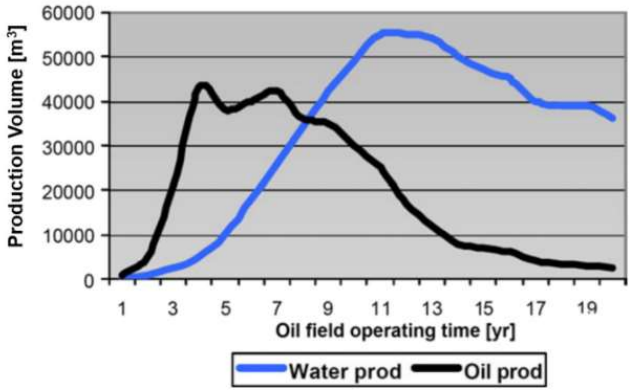


Fig. 2. Water versus oil production in different well ages [11]

Since the global development of offshore oil and gas industries, the produced water has had a significant impact on marine oil pollution near platforms. Treating organic pollutants and removing oil from produced water are crucial tasks in mitigating marine environmental pollution during offshore oil and gas production, particularly when hydrocarbons are involved [15]. Water management expenses can make up around 5% to 15% of drilling costs when viewed from an economic standpoint [16]. Therefore, choosing appropriate treatment procedures and technologies for disposing of wastewater generated during offshore oil and gas production is crucial. Produced water management

is based on its characteristics. In this study, the focus was on new technologies like integrated, compact, and operational platforms suitable for offshore platforms as feasible solutions for this process that which could industrial utilized.

2. Research method

2.1. New alternative technologies for offshore produced water treatment

In order to address the typical problems associated with water treatment methods, such as lengthy methods, occupying large space, and limited treatment efficiency, a new process has been introduced that combines new technologies: pipe separation, combined fibrous coalescers (CFC) and membrane separation. These are incorporated in three main stages of treatment: pre-treatment, standard treatment, and advanced purification. Furthermore, it is expected that this combination will meet increasingly strict regulations and standards for water treatment. Among the existing water treatment processes, integration technology has been widely used in liquid-liquid separation devices based on features such as compact structure, easy operation, and long-term use of integrators, effective separation, and no need for chemical additives.

With the operation of oil and gas fields reaching the middle and end stages of well life, reservoir pressure and therefore production and operational pressures decrease, and the volume of production increases to maintain performance. Therefore, the problem of emulsions created by phase displacement and transformation becomes more serious, and a large number of emulsified oil droplets with a size smaller than 10 micrometers are formed. These small emulsion droplets are beyond the capability of common separation methods and equipment available on platforms for produced water treatment. As a result, a significant amount of oil pollutants is discharged with the produced water. Therefore, compared to separation methods that perform oil-water separation based on gravity (such as API methods, Coagulated Plate Interceptor interceptors and parallel plate interceptors), Coalescing filter and fibrous

Coalescers have a higher accuracy of separation and can separate emulsified oil droplets smaller than 10 micrometers that cannot be separated by hydro cyclones [17-20]. To separate oil emulsions less than 10 micrometers, Coalescing filter and fibrous coalescer's platforms can be used. However, the Coalescing filter cannot withstand complex conditions such as flow intensity fluctuations, severe pressure and gas release, collected sludge and solid particles, and it blocks the compact flexibility layer. This leads to poor performance and even permanent damage to the filter components. Unlike the coalescing filter, fibrous beds have porosity, permeability, and large bed depth, wide range of efficiency, high sludge tolerance and high capacity to withstand flow fluctuations. Therefore, fibrous coalescers are suitable for purifying produced water in offshore facilities [21].

2.2. Improving the produce water purification process with the combined fibers coalescence

In order to meet the standards for discharging produced water into the sea, especially the reduction of oil concentration, it is necessary to further treat the treated water by standard treatment processes after primary treatment. In the standard treatment process for produced water, two-stage technologies such as inclined plate separators, hydrocyclones, and floatation equipment are commonly used. In areas where there is light crude oil or during the initial years of well extraction, the conventional method of treating water with chemicals is sufficient to meet the necessary discharge standards as emulsion breaking is not complicated. However, the equipment and treatment methods typically used may not be adequate to meet the necessary guidelines for discharge of produced water in oil fields that contain heavy crude oil or are in the middle or later stages of extraction. In a standard treatment process,

inclined plate separators, hydrocyclones, and floatation equipment are usually used. Long surface area and large size are common challenges in such a two-stage process [22].

The development of alternative purification techniques can bring about stability and growth in production for existing offshore platforms, while also reducing the need for constructing new ones. To solve the problems of the standard treatment process such as space and weight limitations as well as the problems of breakdown of heavy oil-in-water emulsions, the Combined fibers coalescence (CFC), which is a new method for separating produced water containing heavy oil-in-water emulsions, has been proposed [23]. In fact, CFC is a novel technique based on droplet size separation of oil (as shown in Fig. 3) to meet spatial and weight constraints in offshore platforms. The fast sedimentation unit and the coalescence unit are created to segregate dispersed and emulsified oil, respectively [24].

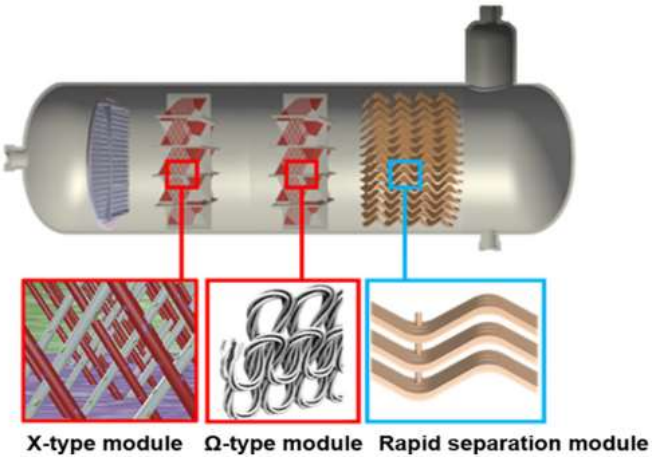


Fig. 3. Scheme of Combined fibers coalescence structure [23]

This method uses CFC modules, which are fibrous substrates woven in a specific configuration with a particular ratio of hydrophilic and hydrophobic fibers, acting as the operation core [25, 26]. CFC has been implemented in offshore platforms for primary water treatment. In the main treatment process, After the installation of a one-stage CFC separator, a hydrocyclone with two stages and an air floatation tank can be removed and Demonstrating better separation effectiveness within a smaller area occupation as compared to a traditional one [21]. According to research conducted, this technology can meet the common water treatment needs of offshore oil and gas fields [27].

However, the issue of inadequate segregation for produced water containing a high amount of emulsifiers and surfactants, and with greater oil viscosity and density, still persists. The collision of small oil droplets with fibers is difficult due to the viscous fluid flow. In addition, due to the steric and electrostatic repulsion barriers of surfactants, cohesion between oil droplets is prevented. However, the utilization of CFC, which is presently in its initial phases of improvement, offers a novel alternative for the conventional treatment procedure. Efficient elimination of oil and grease in emulsions can be achieved through a process of coalescing, which involves minimal chemical and energy usage, as well as an uncomplicated maintenance and operation approach. Nevertheless, the drawback of this technology is that it requires the individual removal of oil-contaminated equipment and periodic replacement of the filters [28]. Coalescence separation increases the diameter of oil droplets to enhance separation speed, thus allowing for effective separation [29].

Studies of the Coalescence process on a fibrous platform can be divided into three main stages: droplet approaching a fiber, droplet attaching to the fiber, and releasing a large droplet from the surface of the fiber. Each stage involves

significant complexity or alternative mechanisms [30]. Here, the Coalescence process can be observed in four stages: joining, approaching, coalesce, and release, as shown in Fig. 4. The fluid flows through the inlet distributor, passing through multiple fiber beds and plate components along the way from inlet to outlet, all of which are movable components. The inlet distributor was used to create stability in the flow regime, and multiple fiber beds were used to combine and enlarge oil droplets by fiber coalescence at each stage. The plate component was used to quickly separate large droplets from the previous bed components. After separation, the oil phase is collected at the top and continuously discharged, controlled by a level sensor, and the treated water is continuously discharged through the lower outlet, which is controlled by a low liquid level valve [21].

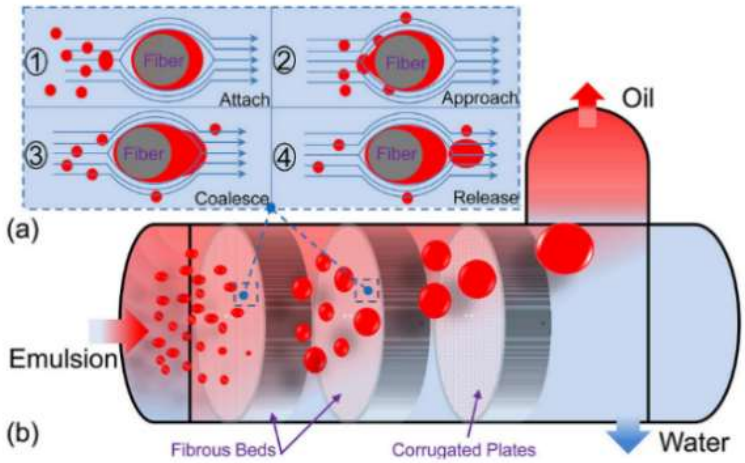


Fig. 4. Schematic of novel fiber coalesce [21]

The coalescer mechanism is based on the fact that when two droplets are forced to approach each other within a liquid, a thin liquid film is formed between the droplets, and then the process of discharging this surface film begins. When the thickness of the film is small enough (about 1000 angstroms) and the magnitude of the electrostatic attraction (or van der Waals forces) is large enough to break the film, coalescence occurs [31].

2.3. Factors influencing the coalescence process

The coalescence process is affected by several significant elements, such as the impact of fluid speed, bed properties, fiber qualities, characteristics of the two liquids (the generated oil and water), and coalescer mechanisms [30, 32-36].

2.3.1. Operating conditions: flow direction and speed and bed direction

The efficiency of the coalescing process is greatly affected by the flow direction. At higher speeds, coalescers with a horizontal flow state are more efficient than those in a vertical flow state, while no significant difference is observed at lower speeds. At higher speeds, the vertical flow state shows the least efficiency. When the surface tension is greater than 3 dyn/cm, a vertical coalescer is used to separate water from hydrocarbons. In horizontal settings, a sedimentary zone is capable of separation by gravity. When the surface tension is less than 3 dyn/cm or for separating oil from the aqueous phase or simply for separating hydrocarbons, a horizontal integrator is used [33]. The fluid velocity (v) plays a fundamental role in emulsion flow, as it controls the mechanisms of droplet absorption, dispersed phase distribution, and retained oil separation. The critical velocity (v*) is defined as the velocity at which droplet redispersion occurs, and at this critical velocity, the degree of droplet coalescence on the bed is not sufficient for

complete separation. The critical velocity determines the maximum operating velocity for use in the mixing bed and is of vital importance in designing a mixing bed project. The actual optimal mixing velocity must be below this critical velocity [31].

2.3.2. Total concentration of oil and grease (TOG) in the input feed

The concentration of oil and grease present in the feedstock, along with the filtration coefficient and droplet size, can have a significant impact on the efficiency of the separation process with coalescence. Studies have also shown that when the input oil concentration increases from 100 to 300 milligrams per liter and from 2000 to 10000 milligrams per liter, the removal efficiency continuously decreases [37, 38]. When the flow velocity exceeds its critical value, the effect of input oil and grease concentration becomes prominent [31]. The most important characteristics of fibrous media are their structural and geometric properties, such as size, shape, and arrangement, considering the coalescence of the media [32]. Different studies on the effect of wettability on the efficiency of oil separation by the coalescence process indicate an increase in separation efficiency with an increase in this parameter [31].

2.3.3. Phase properties: droplet diameter, difference in density and viscosity

Studies on the effect of droplet size diameter on the separation of oil and water emulsions in fibrous environments show that as the flow rate increases, the average size of the sample decreases and as a result, the separation efficiency decreases from 80% to 55% [39]. The oil separation efficiency decreases with an increase in the density of the horizontal and vertical coalescer beds for both types of coalescer beds [30, 32, 34]. For commercial coalescers with a vertical flow configuration (upward and downward vertical) and a horizontal flow configuration, an increase in viscosity leads to a decrease in the efficiency of the integration process in each integrator [32].

2.3.4. Effect of bed depth

Increasing the depth of the bed results in a longer path in the bed, thus creating more contact time for droplets to coalscence. It is difficult to capture small droplets, so when the oil content is lower than 20 milligrams per liter, further reduction becomes more difficult. Therefore, to ensure the production of treated water with oil content in accordance with the standard, the depth of the fiber beds must be increased [36].

2.4. Long life, cleaning and maintenance of the coalscer bed

After repeated use over time, excessive accumulation of pollutants occurs on the filter elements, resulting in a decrease in remaining filter volume for filtration. Therefore, to prevent any potential entry of solid particles and mineral oils into the discharged wastewater, accumulated pollutants must often be removed. It may be necessary to remove fibers and sponges from the filter element and wash them thoroughly. However, the composite filter should be cleaned every 1-2 months. If cleaning is necessary, remove the stainless steel filter housing and wash it with a water jet. However, to eliminate loose materials, deposits, and also clean entry and exit tunnels, the services of authorized waste disposal personnel will be required. Note that 1) the frequency of cleaning depends on the amount of oil and grease. 2) Never use toxic or poisonous chemicals (insecticides, bleaching agents, aggressive detergents, disinfectants, solvents) for cleaning [40]. The coalescer filter should be replaced at an appropriate time. Whenever the pressure drop indicates a decrease from 8 psi to 10 psi, the filter should be checked and replaced if necessary.

Clogging of the coalescer filter with pollutants causes a pressure drop. Common maintenance methods for these systems include inspection, filter cleaning, and complete filter replacement. For desirable separation, the coalescer filter should be inspected similar to cleaning, every 1-2 months. However, the replacement time of the integration filter is not specific and depends mainly on the pressure drop [40]. Based on the reviewed methods for separation, water-oil separation can be achieved using fiber-coalscer beds with the lowest maintenance and repair costs and higher efficiency than other methods. The cost of replacing each coalescers filter cartridge after consecutive inspections of 1-2 months, if necessary, is between 40-60 dollars (related to PALL integrated cartridge). Miran's average annual cost for fiber-coalescer beds is around $9,000 [41].

3. Investigating successful industrial application of the coalescence process

There are four main types of mechanical separators which include plate coalescing separators, packing-type coalescing separators, coalescing filter separators, and fiber-bed coalescers. Effective separation devices are necessary for removing liquid-liquid dispersion containing droplets less than 20 micrometers in size, as plate or packing separators are unable to easily eliminate them. Under these conditions, fiber-bed coalescers can be used as pre-treatment equipment to increase droplet size for removal by coalescing separators [42, 43]. In the following, the operational uses of the technology of fiber integrators in recent studies will be discussed.

A research was carried out by Lu et al. to investigate how different crucial factors such as packaging density, specific surface area, bed depth, superficial velocity, and input oil content affect the separation efficiency of two commercial oleophilic fiber types. In this study, an industrial-scale experiment was also conducted on an offshore platform. In this study, the separation of oil-water emulsion mixtures was investigated using fiber beds and corrugated plates at laboratory and industrial scales. The effects of surface velocity, bed depth, input oil content, packaging density, and specific surface area on separation performance were examined. Increasing surface velocity resulted in a decrease in separation efficiency and performance coefficient, while pressure drop across the fiber bed increased. High packaging density, large specific surface area, and long bed depth could generate good integration and increase separation efficiency, but due to significant pressure drop, it reduced the separation performance coefficient. In wastewater treatment, the integration device was investigated in various positions in this study, achieving 79.2% efficiency with an output oil of 7.7 and 10 milligrams per liter of discharged water [36].

Another industrial project called "Full scale Produced Water Treatment Process" has been carried out on the Bohai Sea platform in China [44]. The amount of water produced from this platform has been reported to be more than 90% to 98% in some wells, compared to oil. The US Department of Energy (DOE) has classified the oil obtained from this oil field as heavy crude oil, with an API ranging from around 15.6 to 22. This type of produced water cannot be treated with common processes unless the platform is enlarged to accommodate more of these devices. In this process, a new type of coalescence separator (combiend fiber coalescer) was used on a full scale. In these platforms, two or more types of woven fibers in "x" and "Ω" structural forms were used in the separator [44]. The occurrence of emulsion failure and phase separation takes place at the intersection of heterogeneous fibers. This type of separation method cannot accurately separate as membranes, carbon nanotubes, or absorption due to the high porosity of the fibers. However, the deficiencies caused by the fibers are resolved by increasing the fiber layer thickness. A larger pore size is also beneficial for the stable purification of industrially produced complex water. Various types of fibers were utilized in CFC separators during laboratory experiments, having varying surface energies, including polypropylene fibers, polytetrafluoroethylene fibers, and 316 stainless steel. Subsequently, these fibers were

subjected to pilot testing [39, 44]. The result of this modification process using a combined fiber platform meets the standard for re-injection of produced water in terms of oil content (less than 30 milligrams per liter) and yields a 33% reduction in oil content. The schematic of full scale procedure has shown in Fig.5. The required reverse demulsifier and water clarifier concentrations were reduced by more than 40% and 60% respectively. This process resulted in over 40% and 50% capacity increase in liquid and produced water, respectively, which could lead to an increase of 30,000 cubic meters in crude oil production [44].

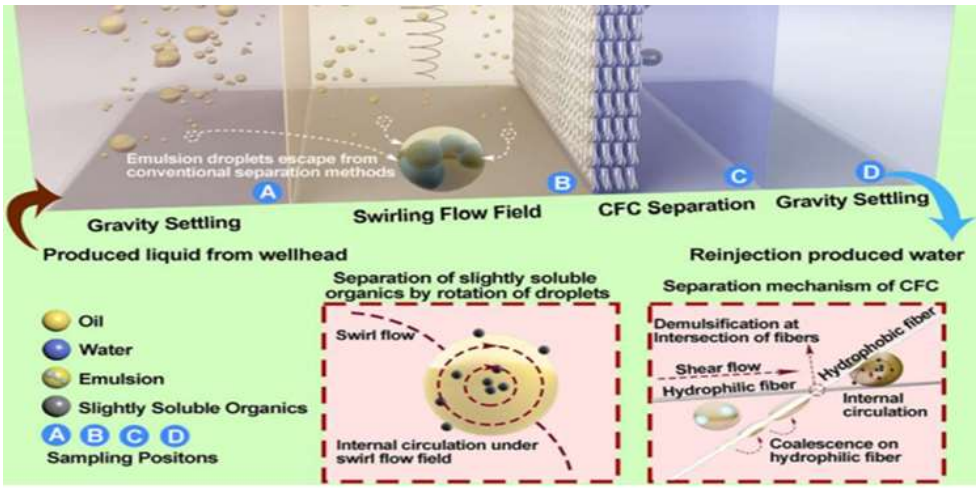


Fig. 5. Full scale procedure for produced water treatment

A new combination of hydrophilic and hydrophobic fibers that have different levels of attraction to water can enhance the separation yield of droplets in emulsions. The successful application of this novel method can be seen in alkylization plants, where it effectively separates acids and hydrocarbons, as well as in the processing of LPG, gasoline, or diesel. Additionally, it has been used to remove oil from acidic water or wastewater in a sulfur desalination unit, with commendable results. The new technique shows promising potential for future applications in liquid-liquid separation due to its compact design, effective separation, and ability to easily handle fluctuations in feed and performance [45].

This method has been successfully applied in an offshore gas field for the first time, and it offers a viable solution to address the problem of treating produced water in other gas fields. It has the potential to safeguard the marine ecosystem [28]. After adding combined fiber coalescers on the Chinese offshore platform, the resulting average oil content of the coalescer effluent was approximately 23 milligrams per liter and consistently measured below 25 milligrams per liter throughout the testing period. This is compared to the pre-improvement produced water oil content of 330 milligrams per liter from hydrocyclones and 250 milligrams per liter from discharged seawater. The novel combined fiber coalescer on the Chinese offshore platform, which began operation in December 2016, is continuously in operation. The pressure drop was reduced from 10 to 30 psi and the average oil content of the effluent was below 25 milligrams per liter, achieving the expected design effect.

4. Conclusion

The main wastewater generated during offshore platform exploration and oil production processes is produced water. This wastewater contains pollutants in the oil phase that must be removed to meet legal standards. To minimize

environmental harm, various technologies can be employed for treating produced water. The primary treatment method used depends on the characteristics of the wastewater. The coalescence process, which has demonstrated promising outcomes in past research and proven effective in industrial practices, consumes less energy, and is suitable for offshore platforms with limited space and efficient emulsion removal. It is also a cost-effective solution. This study suggests that the coalescence process's characteristics are necessary for reliable wastewater treatment in offshore platforms and restricted areas. However, further research is required to understand the physical phenomenon of coalescence and improve operational conditions.

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