Petroleum Science 20 (2023) 569–576

Contents lists available at ScienceDirect

Petroleum Science

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

Original Paper

Produced-water treatment: Application and research of combined fiber coalescence technique in offshore oilfield

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A R T I C L E I N F O

Article history:
Received 23 January 2021
Accepted 18 June 2021
Available online 26 November 2022

Edited by Xiu-Qiu Peng

Keywords:
Combined fiber coalescence
Production water
Oil–water separation
X/Ω weaving

A B S T R A C T

When the process of extraction of oil from an offshore oilfield enters the advanced stages, the water content in the extracted fluid can be above 90%. The water quality is complex with many types of pollutants and highly emulsified water. Therefore, a key consideration in the production process of offshore oilfields is the efficient and economical treatment of the oil-containing produced water to make it suitable for discharge and recover oil pollutants. In this study, we developed a hydrophilic and hydrophobic combined fiber coalescence separator with composite fiber shapes using fiber induction and X/Ω-weaving. The separator is designed based on experimental observations of the mechanism of structure coalescence in the physical oil removal method. A pilot test was performed on an oil exploration platform in the Bohai Sea. At the designed flow rate, the separator reduced the total concentration of petroleum in the produced water from 2000 to 3000 mg/L to below 60 mg/L, with an average oil removal efficiency of 98.24%. Furthermore, it effectively reduced the number of organic compounds present in the water from 120 to 17 and removed 70% of the SS. The test results show that the proposed device can be used fr produced-water treatment on offshore platforms.

1. Introduction

The ocean is an important replacement area for land resources. In addition, the green and sustainable development of marine oil and gas resources is important to ensure national energy security (Sarah, 2020; Lu et al., 2019). Produced oily water forms the largest proportion of by-product in the process of offshore oil exploitation. Meanwhile, the efficient separation of produced water is highly significant for marine environmental protection and platforms to explore the potential capacity (Liu et al., 2008). Owing to the influence of geological conditions, production periods, and field conditions, produced water is generally characterized by a large volume, a complex composition, and variation in water quality (Utvik, 1999), as described below:

(1) High oil content. The produced water contains over 3000 mg/L of oil.
(2) High emulsification. The particle size of certain emulsified oil droplets is less than 5 μm, and the crude oil/condensate is mixed thoroughly with water during the production process. Therefore, the produced water contains a variety of alkanes, naphthenic hydrocarbons, aromatic hydrocarbons, and other types of complex petroleum organic matter.
(3) High content of suspended matter (SS). The produced water contains various solid particles such as clay, paraffin, mud, sand, and insoluble organic matter. These cause scaling and corrosion in the gathering and transportation pipelines and the water injection systems (Xiao et al., 2019).
(4) High degree of mineralization. Because of the different strata conditions and the oil-well mining cycle, produced water contains several minerals. Their concentrations range from thousands to hundreds of thousands of ppm. In addition, produced water contains a variety of ions such as cations of metals including potassium, calcium, sodium, magnesium, and iron, and chloride, sulfur, sulfate, and carbonate anions. These ions have a strong corrosive effect on equipment and pipelines, and cause salt scale formation.

Furthermore, if the produced crude oil has a higher density than at a level of 0.92 g/cm^3 and a higher viscosity than 100 mPa s, the separation of produced water becomes more difficult. Chemical

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https://doi.org/10.1016/j.petsci.2022.11.013
1995-8226/

flooding, polymer flooding, alkali–surfactant–polymer (ASP) flooding, and other enhanced oil recovery methods also result in the production of several agents and polymers in production water (Soheila and Sadrpoor, 2020; Gavrielatos et al., 2016). This further increases the complexity of its treatment. In general, the key to produced water separation is the separation of petroleum organic matter and SS under the interference of external factors.

However, existing oil–water separation technologies have various disadvantages such as complex processes, high cost, large land requirements, low separation accuracy, and short component life. The above requirements for produced water separation cannot be satisfied, which limits the development of the entire industry. Thus, it is necessary to develop more economical and efficient deep-oil removal technologies to ensure the continued growth and development of marine oil fields while reducing their environmental impact.

1.1. Traditional offshore oil–water separation technologies

In traditional oil–water separation methods, the oil present in water is classified and processed based on the size of oil droplets (Bande et al., 2016). This is shown in Table 1.

Traditional oil–water separation methods include physical, chemical, physicochemical, microbial, and electrochemical methods (Ma, 2016). The water treatment technologies used in oilfields in China are different owing to the variations in water quality and the complexities of the platform.

The most economical and effective two-phase separation methods to treat the different forms of oily wastewater are gravity separation and coalescence. In general, emulsified oil and oil-in-water are often present in sewage, and are the most difficult to treat (Yuliya et al., 2019; Lu et al., 2016a, b, c). Their high oil content, small oil-droplet size, and uniform distribution are the focus of several studies.

Membrane treatment technology and biological treatment technology have been researched extensively in recent years. Membrane treatment technology has the advantages of selective separation, non-occurrence of phase transformation, and high separation accuracy (Federico et al., 2020). However, it is generally expensive and requires a large area. Biological treatment technology can completely degrade pollutants without pollutant transfer and secondary pollution. However, it requires a long treatment cycle, which makes it unsuitable for continuous industrial production (Benito et al., 1998). Although both the technologies have received significant attention in recent years and have been used in several sewage treatment systems, these cannot be used to treat emulsified oil in industrial production owing to their many limitations.

2. Combined fiber coalescence technique for produced water treatment

This study is aimed at addressing the drawbacks of existing oil-water separation technologies by using the combined fiber coalescence (CFC) technique for produced-water treatment.

As shown in Fig. 1, the experimental set-up consists of a microfluidic jet that produces oil droplets, and high-speed cameras that record the microscopic interactions between the oil droplets and fibers as well as the process of collision, adhesion, coalescence, and migration of the oil droplets during the oil–water separation process (Milinkumar et al., 2020; Kang et al., 2012; Wang et al., 2018; Lu et al., 2016a, b, c; Lu et al., 2016a,b,c, 2016a,b,c). The observations revealed many differences in the oil and water separation process based on the location of droplet coalescence and fiber wettability.

Lu et al. (2021) studied the action of droplets at liquid–liquid and liquid–solid interfaces. They observed the occurrence of physical demulsification during the flow owing to the cross-linking of the hydrophilic and hydrophobic fibers. Lu et al. (2019) studied the relationship between the polar adhesion of hydrophilic and hydrophobic fibers and the shear force of flow field. Based on the above research, we developed an innovative technical concept of a combined weave of hydrophilic and hydrophobic fibers (Wang et al., 2020). Furthermore, a new physical separation method for hydrophilic and hydrophobic fibers using an "X/Ω-type" weave structure was developed (Yang et al., 2014, 2015).

PTFE, 316L, and PP hydrophilic and hydrophobic materials were selected according to the contact angles of oil drops and water drops on the material surface, as shown in Fig. 2. Table 2 presents the characteristic sizes of the fibrous materials. The fibers listed in the table were used for Ω weaving (the proportion involved in industrial secret) to form fiber modules.

Considering the droplet distribution characteristics of the highly emulsified oil-bearing production wastewater, we developed a new technique called the CFC technique for micro-droplet demulsification separation and large-droplet rapid sedimentation separation. We also designed equipment based on this technique (Zeng et al., 2016). It adequately satisfies the requirements for the advanced standard treatment of oily production wastewater. More specifically, it achieves a high degree of emulsification, high concentration of suspended solids, high salinity, and high viscosity (Liu et al., 2019) notwithstanding variations in the feed characteristics and flow rate in offshore platforms. In addition, it displays desirable characteristics such as a high oil removal efficiency, strong anti-pollution capability, strong adaptability to pressure fluctuation, marginal pressure drop, long life, and compact structure (Hua et al., 2007; Wu, 1986).

The highly efficient water-separation equipment developed in this study was installed on the Bohai oilfield platform, and a pilot test was performed.

3. Pilot test

3.1. Platform produced-water treatment process

The test platform uses a traditional produced-water flow process, as shown in Fig. 3. The subsea well fluid is treated successively through the Christmas tree, production separator (Ma et al., 2019), inclined plate separator, gas flotation separator, and walnut shell separator. The oil phase is then transferred to the oil storage tank and eventually transported by marine pipes to the floating production storage and offloading (FPSO) unit for unified treatment.

Table 1
Distribution of oil-droplet size and treatment methods.

Sl. No.	Classification	Particle size range	Handling method
1	Oil slick	> 150 μm	Gravity settling
2	Dispersed oil	15–150 μm	Hydrocyclone separation
3	Emulsified	1–15 μm	Coalescence, air flotation, and electric field separation
4	Dissolved oil	< 1 μm	Adsorption, membrane, and chemical means

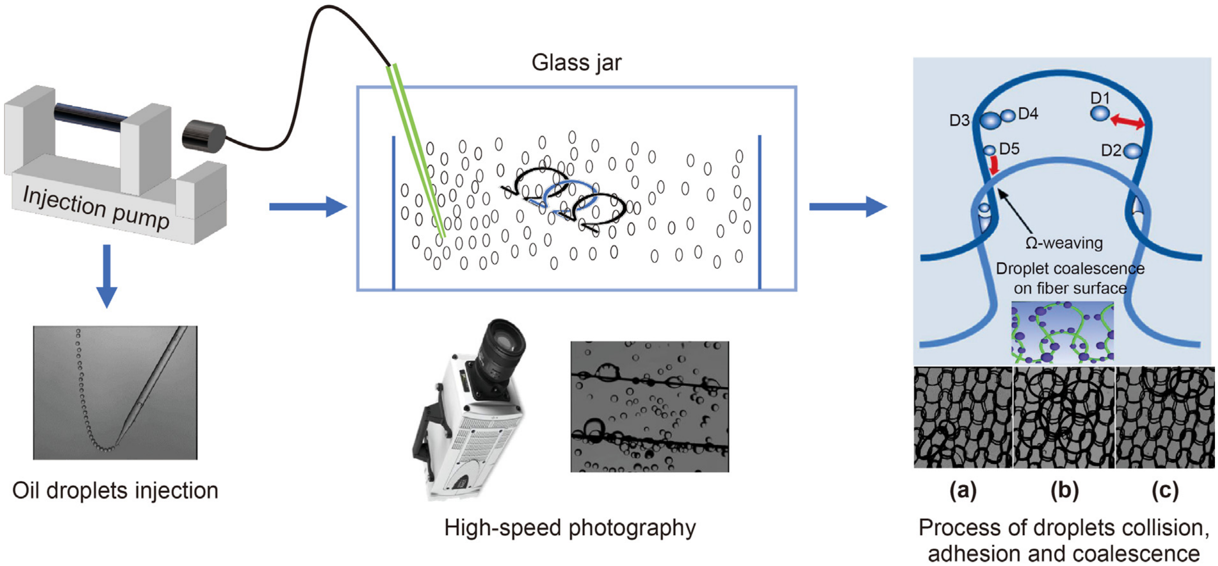

Fig. 1. Process of droplet collision, adhesion, and coalescence.

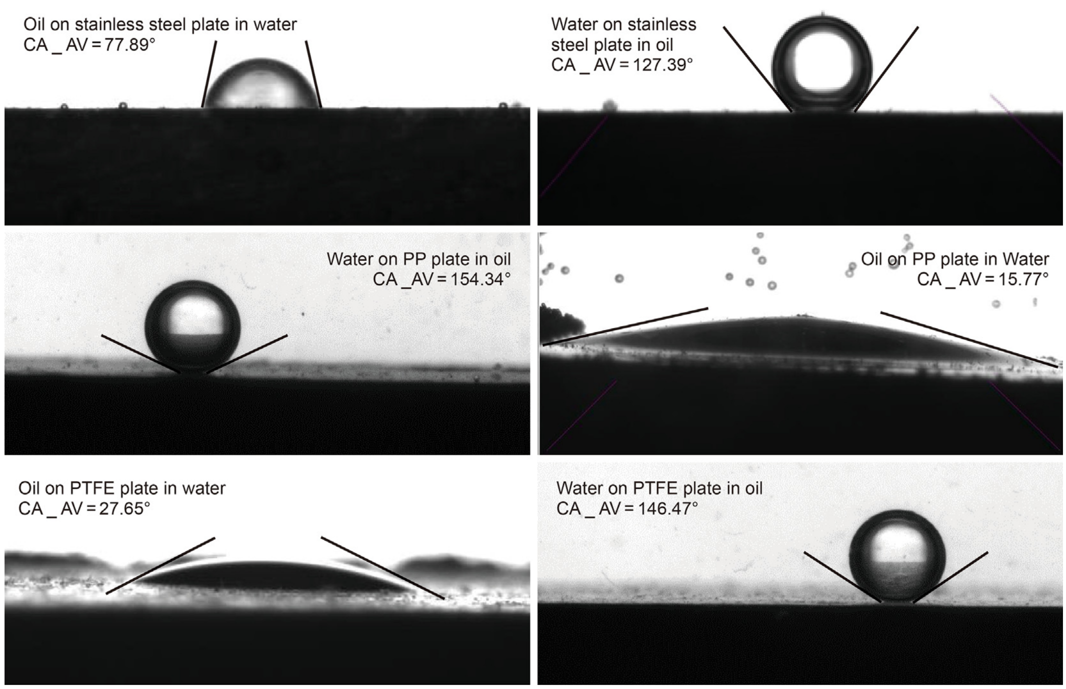

Fig. 2. Fiber weaving module materials used.

Table 2
Characteristic sizes of the fibrous materials.

	Weaving material		
	PP fiber	PTFE fiber	Stainless steel fiber
Characteristic size, μm	20	52	120
Specific gravity	0.92	2.2	7.98
Specific surface area, m^2g^{-1}	2.17×10^5	3.49×10^4	4.18×10^3

Once the water phase attains the prescribed treatment standard, it is injected back into the ground by the water injection wellhead. This completes the production and injection cycle.

For the pilot test, the inclined plate separator and gas flotation separator were replaced with the test device (Yang et al., 2019). The water phase outlet of the production separator is connected to the feed port and that of the test device is connected to the walnut shell filter. In addition, the oil phase outlet of the test device is connected to the sewage tank for further processing in the FPSO.

3.2. Water composition analysis

The CFC separator was designed after analyzing the water quality at the water phase outlet of the production separator. The results of the water quality analysis are shown in Table 3. The main parameters that affected the treatment process were the petroleum content, SS concentration, and particle-size distribution.

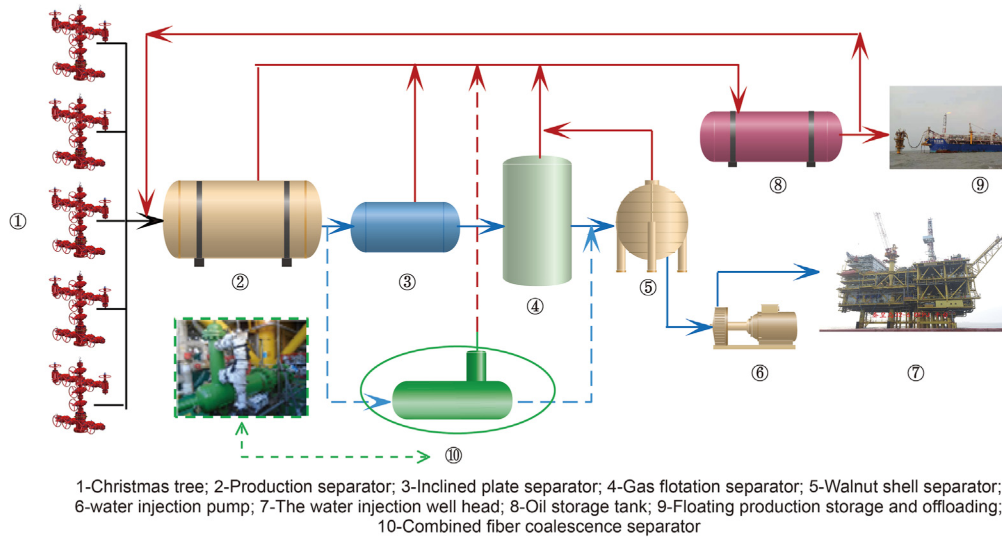

Fig. 3. Process flow diagram of produced-water treatment.

Table 3
Parameters of production separator outlet.

Project	Content	Unit
Oil	2247	mg/L
SS	217	mg/L
Mean	7.315	μm
Median	6.688	μm
D75	8.964	μm
D90	9.703	μm

The oil content at the water phase outlet of the production separator was 2247 mg/L. The concentration of suspended solids was 217 mg/L, and 90% of the SS particle had sizes below 9.703 μm.

The corrosive effect of ions present in the produced water was considered in addition to the concentration and particle size of SS. Water samples were tested for cations and anions, and the results are shown in Table 4. The content of chloride ions at the outlet of the water phase of the production separator was 3341.62 mg/L. This indicates that it was highly corrosive.

These test results indicate that the produced-water quality is relatively complex, with several pollutants, large concentrations of SS, small oil-droplet size, and high degree of emulsification. Consequently, the separation of petroleum pollutants from the water is highly difficult.

3.3. Test equipment and separation principle

The weave proportion of the hydrophilic–hydrophobic composite fiber module was specially adjusted considering the produced-water quality. With the dimensions of the fiber module maintained constant, the density of the internal components was increased by adding titanium alloy fibers with a diameter of 100 μm and increasing the number of PTFE fibers and PP fibers to two times. Meanwhile, the "Ω-type" weave structure results in fiber modules with gaps of over 100 μm, whereby suspended particles with size less than 100 μm could pass through. This significantly reduces the likelihood of blockage of the gaps in the fiber modules and improves the corrosion resistance and adaptive performance of the internal components.

The fiber module was used as the core inner part of the CFC separator. Compared with the traditional gas flotation separator,

Table 4
Zwitterions content at water phase outlet of production separator.

Determined contents	mg/L	mmol/L	mmol/%
Na^+	2105.47	91.54	47.47
K^+	29.01	0.74	0.38
Mg^{2+}	46.34	1.93	1.01
Ca^{2+}	87.96	2.20	1.14
Total	2268.78	96.41	50.00
Cl^-	3341.62	95.47	45.57
SO_4^{2-}	12.53	0.13	0.06
HCO_3^-	532.41	8.73	4.17
CO_3^{2-}	24.81	0.41	0.20
Total	3911.37	104.74	50.00

the CFC separator reduces the pressure drop by 0.2 MPa. This also enables the device to effectively remove oil and suspensions. The device was installed on the middle deck of the platform and connected in series to the water phase outlet of the production separator and tested for 17 days.

Fig. 4 shows a schematic diagram of the test device. The device consists of 11 parts. The produced water successively flows through each inner part of the device owing to self-pressure. The fluid director regulates the direction of produced water flow. The rectifying distributor enables a uniform distribution of the feed across the cross-section, thereby reducing the amplification effect caused by poor liquid distribution. The process of coalescence in a fibrous bed is divided into four main steps: (1) collision, the approach of a droplet toward a fiber or toward a droplet attached to a fiber; (2) adhesion, the adhesion of a droplet to a fiber or to a droplet attached to a fiber; (3) coalescence-the attachment of a droplet to a fiber or to a droplet already attached to a fiber; and (4) release, the release of an enlarged droplet from the surface of a fiber (Hazlett et al., 1969). This process is consistent with the phenomenon photographed in Fig. 1. The corrugated rapid settling module (which is incorporated with a corrugated structure with holes) increases the droplet floating speed and improves the separation efficiency.

During this process, the emulsified oil droplets in the water gradually coalesce, fuse, and grow into an oil slick that is larger than 150 μm. At an operating temperature of 70 °C, the viscosity of the oil exceeds 100 mPa s. Thereby, a large amount of SS would be captured and removed with the oil phase. The separated oil phase

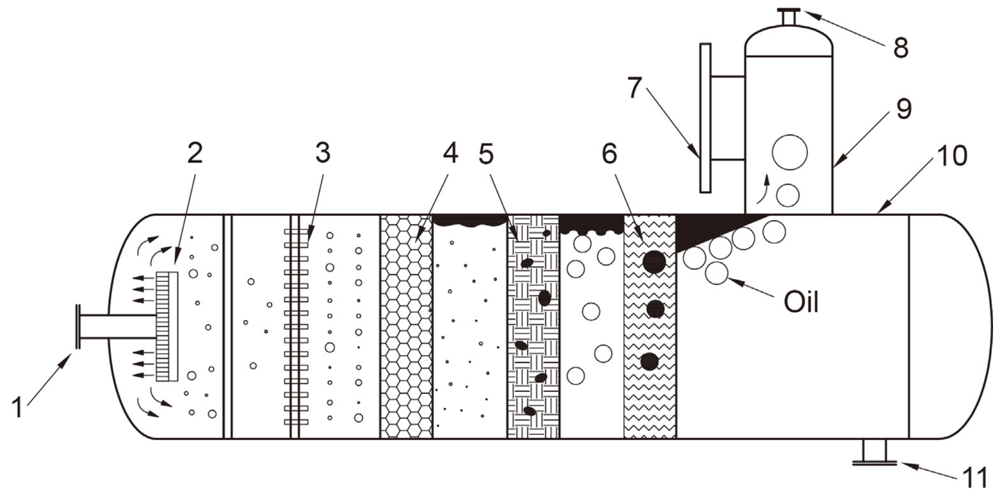

Fig. 4. Schematic diagram of combined fiber coalescence separator: (1) Inlet (2) Fluid director (3) Rectifying distributor (4) Oil drop coarse-grained module (5) Combined fiber module (6) Corrugated rapid settling module (7) Liquid level meter (8) Oil outlet (9) Oil pocket (10) Shell (11) Water outlet.

enters the oil ladle owing to gravity, and the separated water enters the next stage for further separation.

The CFC separator uses a modular design, involves a simple operation, and requires a small floor space. The specific equipment parameters are shown in Table S1.

3.4. Analytical detection method

The content of petroleum in the produced water was tested according to HJ 637-2018 "Water Quality; Determination of Petroleum and Animal and Plant Oils; Infrared Spectrophotometry." The concentration of SS in the produced water was tested according to GB 11901-89 "Water Quality; Determination of Suspended Matter; Gravimetric Method."

The following reagents were used: (1) perchloroethylene from Shanghai Titan, (2) anhydrous sodium sulfate from Shanghai Titan, (3) anhydrous magnesium silicate from Shanghai Titan, and (4) CN-CA filter membrane from Yue Cheng laboratory. These were analytically pure.

The following instruments were used: (1) InfraCal 2 ATR-SP water oil detector, (2) full glass microporous membrane filter, and (3) gas chromatography–mass spectrometer (GC-MS).

4. Results and discussion

4.1. Oil–water separation performance

The test device was operated continuously for 17 days, and the oil content in the water at the inlet and outlet of the CFC separator was recorded. The separation efficiency E was used to evaluate the oil–water separation performance of the separator. It is defined as shown in Equation (1):

$$E = \frac{C_{IN} - C_{OUT}}{C_{IN}} \times 100\% \tag{1}$$

where C_{IN} indicates the petroleum content in the produced water at the inlet of the device in mg/L, and C_{OUT} indicates the petroleum content in the produced water at the outlet of the device in mg/L.

Four samples were extracted from the inlet and outlet of the CFC separator on each day of the test period. This resulted in a total of 68 water samples. The petroleum content in each sample was measured. These data as well as the oil–water separator efficiency are shown in Fig. 5. The total concentration of petroleum in the produced water decreased from 2000 to 3000 mg/L to less than 60 mg/L after treatment in the CFC separator. The average oil removal efficiency was 98.24%. The oil content in the water at the inlet of the device increased substantially towards the end of the test period. However, the oil removal efficiency was unaffected.

4.2. Analysis of organic matter in water

The organic composition of the produced water was analyzed by performing a GC-MS test on water samples extracted from the inlet and outlet of the separator. The results are shown in Figure S1.

The peak number and peak height indicate that the amount and types of organic matter in the water were reduced substantially by the treatment in the separator.

The organic matter in the water phase at the inlet and outlet of the separator was classified and categorized as shown in Fig. 6. The red bars represent the inlet water phase of the separator, with a total of 120 organic compounds of 13 types. The blue bars represent the water phase at the outlet of the separator, with a total of 17 organic compounds, of 9 different types. The number atop each bar is the number of organic compounds of a given type contained in the sample. After treatment in the separator, there were 103 fewer organic compounds in the water. Of these, alcohols, furans, acids, toxoflavins, esters, anhydrides, and other substances were removed together with the oil phase. However, magnesium acetylacetone, aldehyde, benzene, ketone, naphthalene, and phenols still existed in the outlet water phase and were the main pollutants. Hydrocarbons accounted for the largest proportion of the pollutants. However, the number of organics was reduced from 26 species to 6. As the contents of isobutyl fennel and indene were negligible before separation, these are represented as part of the other organics.

The separation efficiency of the equipment can be reverified by comparing the HC and benzene class accounted for before and after separation. Among all the pollutants, HC (C9-C21) has the largest density difference with water, and its solubility in water is relatively low. Therefore, the reduction is the largest after the combined fiber demulsification.

4.3. Solid–liquid separation performance

In addition to the oil content, the concentration of suspended

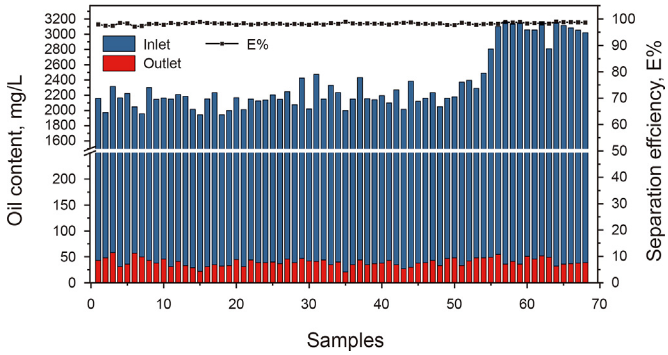

Fig. 5. Oil content in water and separation efficiency.

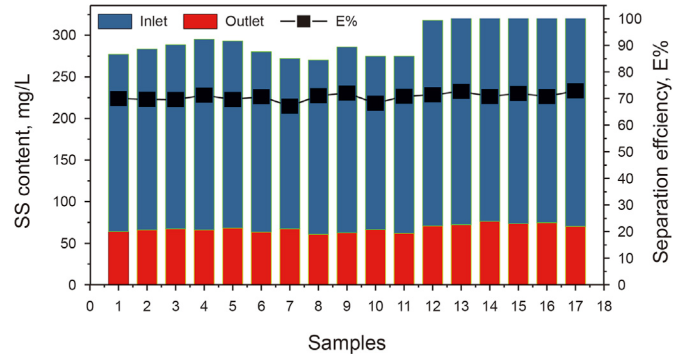

Fig. 7. Concentration of suspended solids at the inlet and outlet of the CFC separator.

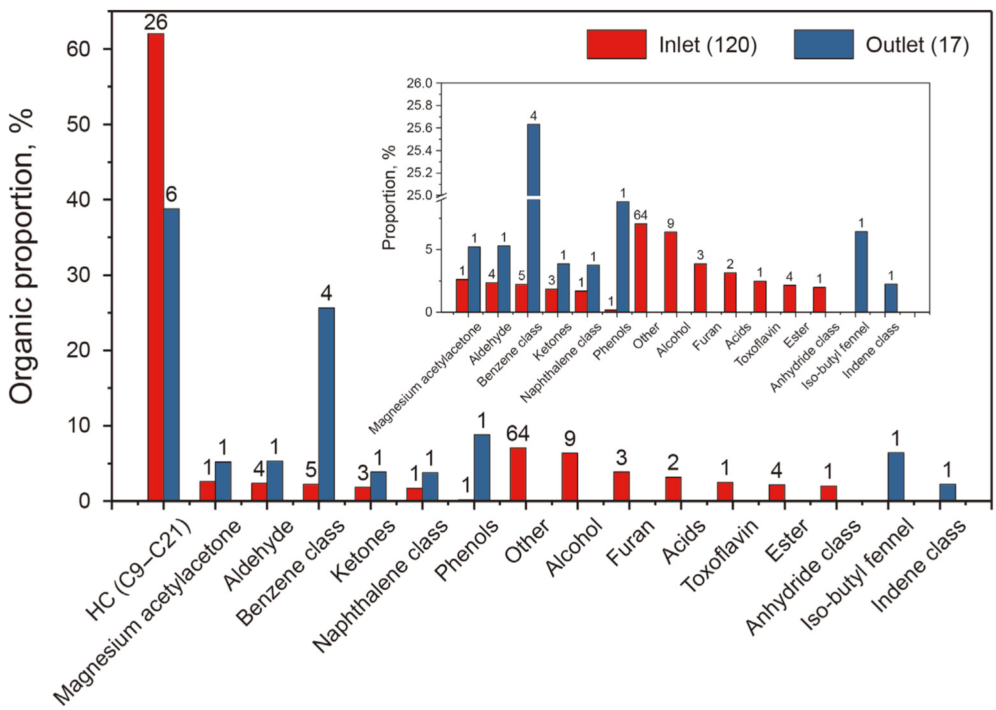

Fig. 6. Organic matter in water at the inlet and outlet of CFC separator.

solids at the inlet and outlet of the CFC separator was tested. The separation performance was evaluated by the separation effect *E*, which is defined as shown in Eq. (2):

$$E = \frac{SS_{IN} - SS_{OUT}}{SS_{IN}} \times 100\% \tag{2}$$

where SS_{IN} indicates the concentration of suspended solids in the produced water at the inlet of the device in mg/L, and SS_{OUT} indicates the concentration of suspended solids in the produced water at the outlet of the device in mg/L.

A set of water samples were tested every day during the test period. The results are shown in Fig. 7. The concentration of suspended solids in the produced water at the inlet and outlet of the device was 200–260 mg/L and 60–70 mg/L, respectively. The average removal rate of suspended solids by the separator was approximately 70%. Thus, the CFC separator can remove both oil and solid suspensions to a large extent.

4.4. Development prospects

Fig. 8 shows a sample extracted during the test period. The pilot test results clearly indicate that the CFC separator can treat complex produced water with high SS and oil content. The oil–water separation efficiency was above 98%, 103 types of organic pollutants were removed, and the SS separation efficiency was 70%. The device was stable, and the overall pressure drop was less than 50 kPa. Furthermore, the device uses physical methods to separate oil and water, without requiring chemicals. The amount of chemicals used by the CFC separator was approximately 50% lesser than that used by the existing produced-water treatment process. Thus, the CFC separator can potentially replace the existing inclined plate degreaser and gas flotation separator and offers many economic benefits and good development prospects.

5. Conclusion

Produced water from the offshore oilfield was successfully treated by replacing the inclined plate degreaser and gas flotation

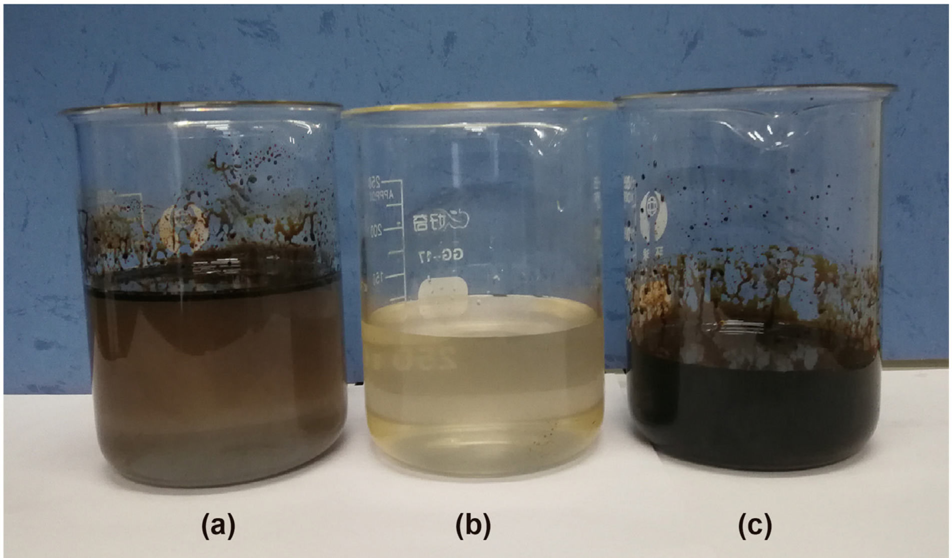

Fig. 8. (**a**) Separator inlet water (**b**) Separator outlet water (**c**) Separator outlet oil.

separator with a CFC separator. A 17-day pilot test indicated that the proposed device can maximize the platform's processing capacity while saving platform space. Moreover, it was observed to be superior to the traditional produced-water treatment processes used on offshore platforms. Thus, the CFC technique is of substantial importance for the development of offshore oilfields.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant Nos. 52025103).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petsci.2022.11.013.

References

Bande, R., Prasad, B., Mishra, I., Wasewar, K., 2008. Oil field effluent water treatment for safe disposal by electroflotation. Chem Eng J 137 (3), 503–509. https://doi.org/10.1016/j.cej.2007.05.003.
Benito, J.M., Rios, G., Pasoz, C., Coca, J., 1998. Methods for the separation of emulsified oil from water: a state-of-the-art review. Trends Chem. Eng. 4, 203–231.
Federico, T., Nicolás, T., Diana, G., Gerardo, H.R., Silvia, G., 2020. Hierarchical selective membranes combining carbonaceous nanoparticles and commercial permeable substrates for oil/water separation. Separ. Purif. Technol. 234, 116053. https://doi.org/10.1016/j.seppur.2019.116053.
Gavrielatos, I., Mohan, R., Shoham, O., 2017. Effect of intermediate wettability nanoparticles on oil-water emulsion stability. J. Pet. Sci. Eng. 152, 664–674. https://doi.org/10.1016/j.petrol.2016.12.040.
Hazlett, R.N., 1969. Fibrous bed coalescence of water. Steps in the coalescence process. Ind & Eng Chem Fun. 8 (4), 625–632. https://doi.org/10.1021/i160032a005.
Hua, F.L., Tsang, Y.F., Wang, Y.J., Chan, S.Y., Chua, H., Sin, S.N., 2007. Performance study of ceramic microfiltration membrane for oily wastewater treatment. Chem Eng J 128 (2–3), 169–175. https://doi.org/10.1016/j.cej.2006.10.017.
Kang, W., Guo, L., Fan, H., Meng, L., Li, Y., 2012. Flocculation, coalescence and migration of dispersed phase droplets and oil–water separation in heavy oil emulsion. J. Pet. Sci. Eng. 81, 177–181. https://doi.org/10.1016/j.petrol.2011.12.011.
Liu, Y., Song, S., Xu, Y., 2008. Application and research progress of treatment technology for oil and wastewater. Oil Gas Field Environ Prot 18 (2), 46–48. https://doi.org/10.3969/j.issn.1005-3158.2008.02.015 (In Chinese).
Liu, Y., Wang, C., Cai, J., Lu, H., Huang, L., Yang, Q., 2019. Pilot application of a novel Gas–Liquid separator on offshore platforms. J. Pet. Sci. Eng. 180, 240–245. https://doi.org/10.1016/j.petrol.2019.05.001.
Lu, H., Liu, Y., Cai, J., Xu, X., Xie, L., Yang, Q., Zhu, K., 2019a. Treatment of offshore oily produced water: research and application of a novel fibrous coalescence technique. J. Pet. Sci. Eng. 178, 602–608. https://doi.org/10.1016/j.petrol.2019.03.025.
Lu, H., Pan, Z., Wang, H., Liu, Y., Dai, P., Yang, Q., 2021. Fiber coalescence treatment of oily wastewater: a new theory and application. J. Hazard Mater. 412, 125188. https://doi.org/10.1016/j.jhazmat.2021.125188.
Lu, H., Xu, X., Xie, L., Wang, H., Sun, G., Yang, Q., 2019b. Deformation and crawling of oil drop on solid substrates by shearing liquid. Chem. Eng. Sci. 195, 720–729. https://doi.org/10.1016/j.ces.2018.10.017.
Lu, H., Yang, Q., Liu, S., Guo, H., Zhang, P., Zhang, G., 2016a. Experimental study on modular coalescence and oil removal of electric desalting wastewater. Ind. water Treat. 36 (2), 36–39. https://doi.org/10.11894/1005-829x.2016.36(2).036.
Lu, H., Yang, Q., Liu, S., Xie, L., Wang, H., 2016b. Effect of fibrous coalescer redispersion on W/O emulsion separation. Separ. Purif. Technol. 159, 50–56. https://doi.org/10.1016/j.seppur.2015.12.049.
Lu, H., Yang, Q., Xu, X., Wang, H., 2016c. Effect of the mixed oleophilic fibrous coalescer geometry and the operating conditions on oily wastewater separation. Chem. Eng. Technol. 39, 255–262. https://doi.org/10.1002/ceat.201400773.
Ma, S., 2013. Study on the Separation Effect of Oil and Water Based on Coalescence Technology. Tianjin University. https://doi.org/10.7666/d.D439639 (In Chinese).
Ma, Y., Cong, L., 2019. Development trends and progress in research on oil-gas-water separators. Chem Mach 46 (5), 495–500+552. CNKI:SUN:HGJX.0.2019-05-004. (In Chinese).
Milinkumar, T.S., Harisinh, B.P., Lee, D.R., Chris, K., Ranjeet, P., Vishnu, K.P., 2019. A novel settling tank for produced water treatment: CFD simulations and PIV experiments. J. Pet. Sci. Eng. 182, 106352. https://doi.org/10.1016/j.petrol.2019.106352.
Sarah, M.W., 2020. Greenhouse gas emissions from offshore oil and gas activities-relevance of the Paris agreement, law of the sea, and regional seas programs. Ocean Coast Manag. 185, 104942. https://doi.org/10.1016/j.ocecoaman.2019.104942.
Soheila, J., Sadrpoor, S.M., 2020. Demulsification of water in oil emulsion by surface modified SiO_2 nanoparticle. J. Pet. Sci. Eng. 184, 106547. https://doi.org/10.1016/j.petrol.2019.106547.
Utvik, T.I.R., 1999. Chemical characterization of produced water from four offshore oil production platforms in the North Sea. Chemosphere 39 (15), 2593–2606. https://doi.org/10.1016/S0045-6535(99)00171-X.
Wang, X., Ding, Y., Li, H., Tan, J., Yang, W., Yan, H., 2018. Research progress on high efficiency oil pollution treatment of polymer electrospun nanofibers. N. Chem. Mater. 46 (7), 48–51. CNKI:SUN:HGXC.0.2018-07-012. (In Chinese).
Wang, Y., Luo, S., Chen, A., Cui, S., Liang, P., Shao, J., Liu, Z., 2020. Environmentally friendly kaolin-coated meshes with superhydrophilicity and underwater superoleophobicity for oil/water separation. Separ. Purif. Technol. 239, 116541. https://doi.org/10.1016/j.seppur.2020.116541.
Wu, Q., 1986. Study of removing oil droplets from water with phase separation membrane. J. Environ. Sci. 4 (6), 1–5.
Xiao, Y., Dai, Q., Shi, Y., Qian, Y., 2019. Causes and control of the formation of suspended solids in injected water after treatment in an oil field in Bohai sea. Chem Manage 34, 213–215. CNKI:SUN:FGGL.0.2019-34-119. (In Chinese).
Yang, Q., Xu, X., Lu, H., Wang, C., Liu, S., 2014. A Ω-type of Fibers Weaving Method Which Was Suitable for Deep Separation of O/W Emulsions. SIPOP R C. CN103952853A. (In Chinese).
Yang, Q., Wang, C., Lu, H., Xu, X., Liu, S., 2015. A X-type of Fibers Weaving Method Which Was Suitable for Deep Separation of O/W Emulsions. SIPOP R C.

CN103952853A. (In Chinese).
Yang, Q., Dai, P., Liu, Y., Lu, H., Sun, G., 2019. A Water Treatment System and Method Suitable for Offshore Oil Platform. SIPOP R C. CN110078236A. (In Chinese).
Yuliya, N.R., Tatyana, A.M., Natalya, S.M., Evgeny, V.Y., Boris, Y.S., 2019. Demulsification of water-in-oil emulsions by exposure to magnetic field. J. Pet. Sci. Eng. 179, 600–605. https://doi.org/10.1016/j.petrol.2019.05.002.
Zeng, Q., Wang, Z., Wang, X., Zhao, Y., Guo, X., 2016. A novel oil–water separator design and its performance prediction. J. Pet. Sci. Eng. 145, 83–94. https://doi.org/10.1016/j.petrol.2016.03.015.