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Study on seawater nanofiltration softening technology for offshore oilfield water and polymer flooding

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A B S T R A C T

An integrated membrane system (IMS) of ultrafiltration–nanofiltration (UF–NF) technology has been investigated extensively as a means of seawater softening for offshore oilfield water and polymer flooding. The results showed that the softened water generated by the selected NF membrane could meet the water flooding standard for offshore oilfield. At appropriate mixing ratio of softened water and formation water, scales may be avoided completely. Furthermore, the reservoir formation sensitivity evaluation proved the compatibility of NF permeation water with the formation core, which indicates that the permeation water of the selected NF membrane module could be safely used for offshore oilfield water flooding. The prepared aqueous polymer solution using NF softened seawater showed relatively high viscosity and stability at formation temperature for long time, which could meet the demand for offshore polymer flooding. Therefore, the UF–NF integrated membrane technology could efficiently resolve the softened water shortage problem in offshore oilfield water flooding and polymer flooding and ensure continuous and stable oil production.

1. Introduction

With the current growing worldwide demand for oil, most of the world's giant fields are in an advance state of completion from conventional production processes. Enhanced Oil Recovery (EOR) processes have been applied for many years. EOR processes involve the displacement of crude oil by other fluid in a heterogeneous reservoir. Most often, water flooding or chemical EOR methods were used. For both water flooding and chemical EOR, water plays a critical role in the management of operations throughout the life of an oilfield.

Water flooding is one important process to enhance oil recovery. This procedure involves the injection of water into the input wells to force the oil through the surrounding formation toward the output wells from which it can be recovered. However, the principle shortcoming is that the injection of high saline water or high hardness water may react with the formation water and form serious scaling, and thus cause the formation to be gradually impermeable to further injection and oil recovery cease.

Chemical EOR process usually uses water solution of chemicals such as polymer, surfactant and/or alkali, etc., for injection. Among the various chemical EOR methods, polymer flooding has been considered as an attractive method for many reservoirs, which could substantially effect permeability reduction of the formation rock, and bring the ratio of mobility much closer to the crude oil to improve the sweep efficiency in the displacement of oil from the reservoir formation. However, the presence of high content divalent cations like calcium and magnesium ions leads to a reduction in the effective viscosity of the polymer flooding solution, resulting in sharp decrease of polymer sweeping coefficient and oil recovery in the implementation of any EOR project in a given reservoir.

Till now, most EOR processes are applied on land oilfield. However, along with the gradually decrease of land oilfield production, offshore oil production gradually receives much more attention and is considered as the new source to resolve the worldwide energy crisis. The production of offshore crude oil is usually performed on a kind of large oil platform with the design life generally only twenty to thirty years due to the severe ocean circumstance, which means that the time span of offshore oil production should match with the service life of offshore platform. Therefore, various technologies including water injection, polymer flooding, etc., should be adopted to enhance oil recovery in a much shorter time comparing with that of the land oilfields. And polymer flooding could be implemented as early as possible, with nearly no or little influencing on the final oil recovery [1]. For offshore oilfield EOR processes, softened water is a great demand for water injection and polymer flooding, and aquifer well water and processed produced water are the main resources at present. However, the water thus provided is usually not satisfactory in quality or quantity for injection. Therefore, new resource of water supply is urgently needed to meet the demand of softened water supply for water injection and polymer flooding and ensure the steady production of offshore oilfield.

Seawater is an abundant water resource which has been used for water injection by many offshore oilfields at home and abroad. Usually

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it takes very simple treatment before injection: water intake → sterilization → mechanical filtration → deoxygenation → injection [2]. However, there is high content of sulfate, calcium and magnesium ions in seawater, which could cause severe calcium anhydrite or other sulfate scaling problem when injected into reservoir. For example, during the early stage of the development of the South Brae oil reservoir, the injection of seawater containing approximately 2700 mg·L^{-1} sulfate caused severe scaling due to the reaction of the sulfate in the seawater with the barium in the formation water [2]. Furthermore, a combination of barium and radioactive radium sulfate could also be formed, which also cause severe blocking of the formation [3]. Adding scale inhibitor is a method of solving the scaling problem, but large amount of chemicals are needed, which is not convenient for offshore production, and the existing scale inhibitors are hard to get the satisfying effect of scale prevention.

Nanofiltration (NF) is a relatively new membrane technology which has unique selective separation characteristic of divalent ions as well as multivalent ions. The excellent characteristic of NF membrane is that it could remove divalent sulfate from seawater and generates low sulfate content saline water. The use of NF seawater softening technology on water flooding has long been investigated since the early 1980s and could be retrieved to Plummer's famous US patent on preventing plugging by insoluble salts in oilfield production wells using NF technology [4]. In that process, 98% of the sulfate ions in seawater could be eliminated by NF membrane and the softened seawater could then be used as injection water, which could avoid the formation of scaling with the barium ions in the formation water, thus avoid the plugging of the capillary in the reservoir formation and the decrease of the crude oil production. Since then, NF has been used for sulfate removal from seawater for oil injection, which was pioneered by Marathon Oil on the Brae Field. The NF membrane used is capable of reducing seawater sulfate levels from approximately 3000 mg·L $^{-1}$ to less than 40 mg·L^{-1} under the operating pressure of 2.0–3.0 MPa [5]. The Brae Field's operations identified NF membrane as a possible means to solve the scaling problem. Since the Brae installation, more than 44 sulfate removal process (SRP) systems have been installed on offshore platforms, producing over 2,000,000 barrels of water per day (318,000 m3·d^{-1}) [6]. Recently, Bader [7,8] proposed innovative approaches to integrate pressure-driven membranes such as NF membrane in conjunction with liquid-phase precipitation or compressed-phase precipitation to solve the inherent sulfate scale problems in treating seawater for oilfield water injection operations.

Although NF softening seawater has been used for water flooding successfully for more than 30 years, however, not much research work was reported extensively on this subject, and to our knowledge, no investigation has been reported on the polymer flooding using NF membrane technology.

Integrated membrane system (IMS) is a kind of water treatment process which combines multiple classes of membranes [9]. It has been used recently for better treatment of seawater or wastewater. The novel concept of using NF as the pretreatment to RO process forms a kind of IMS by Saline Water Conversion Corporation (SWCC) and enhances the production of desalted water by more than 60% and reduces the cost by about 30% [10,11]. The IMS is also creatively used by Drioli [12,13] in a MF–NF–RO membrane system integrated with membrane distillation/crystallization units, and to increase the water recovery factor up to 92.8% without a significant increase of the costs.

In this work, investigation was carried out using a pilot ultrafiltration (UF)–NF integrated membrane system as the method of removing divalent ions from seawater and providing softened water for oilfield water injection and polymer flooding to enhance oil recovery in offshore oilfield production. The compatibility of NF softened seawater with reservoir fluid and formation cores has been investigated to evaluate the suitability of permeation water of the selected NF membrane in water flooding and polymer flooding of offshore oilfield. The viscosity stability has also been investigated to demonstrate that the prepared aqueous polymer solution using the NF softened water could reach the demand for polymer flooding.

2. Material and methods

2.1. Membranes

Commercial hollow fiber UF membrane module of polyether sulfone (PES) was used and the molecular weight cut-off (MWCO) of which was 80 K Dalton (Da). The characteristic and operation of the UF membrane can be seen elsewhere [14]. Four types of commercial NF membranes which numbered as NFI, NFII, NFIII, and NFIV, respectively, were used and their characteristics according to the membrane manufactures are shown in Table 1.

2.2. Experimental setup and procedure

A suitable seawater pretreatment system should provide feed water with low value of turbidity and SDI continuously and stably for NF membrane. In addition, for the purpose of application on offshore production platform, the process should be compact of space, simplicity of operation and ease of maintenance. UF is reliable and of great capacity compared with conventional pretreatment, which could save about 50% of the space [15]. Therefore, UF was selected as the pretreatment technology of NF, and the UF–NF integrated membrane system was investigated. The diagram of the pilot process and the photos of the actual device are shown in Figs. 1 and 2, respectively. The pilot test was carried out at Jiaozhou Bay, Qingdao, China.

Seawater was firstly pumped through a sand filter and a cartridge filter to the UF module, the UF filtrate was then filtered through a cartridge filter and was pumped into the NF module to obtain NF softening seawater.

Performance of the four NF membranes was evaluated with the operation pressure range of 1.4–3.8 MPa during summer time and the feed water temperature is in the range of 25–27.5 °C.

Long-term running was also carried out during the same summer time to evaluate the stability of the NF membrane system. The IMS setup was operated at NF trans-membrane pressure of 1.6 MPa. The NF membrane was flushed using UF filtrate every 12 h, and no chemical cleaning was performed. The samples of permeation and feed water were collected every 12 h and analyzed to evaluate the total salt rejection.

Table 1
Characteristics of NF membranes used in this pilot test.

Items	NFI	NFII	NFIII	NFIV
	NF90-2540	NF200-2540	NF270-2540	DL-2540
Membrane module	Spiral-wound	Spiral-wound	Spiral-wound	Spiral-wound
Separation layer material	Polyamide	Polypiperazine	Polypiperazine	Polypiperazine
Effective area/m^2	2.6	2.6	2.6	2.5
Rejection rate/%	>97%	>97%	>97%	96%
Highest inlet water temperature /°C	45	45	45	45
pH range	2–11	2–11	2–11	2–11
Highest operating pressure/MPa	4.14	4.14	4.14	4.14
Highest inlet water turbidity/NTU	1	1	1	1
Highest inlet water SDI	5	5	5	5