Research on the Mechanism of Decompression and Augmented Injection during Waterflooding Development in Low Permeability Reservoirs

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Abstract: Developing low permeability reservoirs becomes more and more important to the sustainable energy development in China and the waterflooding development is the common mode. But with the oilfield development, water injection well has exposed some problems gradually, such as the injection pressure increases, water injection rate decreases and so on. Based on this situation, scale inhibitor, corrosion inhibitor and other additives are added in injection water continually, which increases the development cost to a large extent.

In order to develop low permeability reservoirs better and more economical, we proposed a novel decompression and augmented injection technology by manufacturing a novel surfactant FS-01, which could change the wettability of the rock surface and has the features of low free surface energy, low interfacial tension, emulsifying and so on. The decompression and augmented injection mechanism is discussed by measuring the contact angle, SEM (scanning electron microscope), EDX (energy dispersive X-ray), oil-water relative permeability test and so on. After the core surface treated by FS-01, the contact angle of crude oil and the core surface increases from 35.35°to 85.7°, which has perfect wettability reversal function. After the successful application in well HJS112-21 in ShengLi oilfield, it is proved that the new technology has well decompression and augmented injection function.

Keywords: Waterflooding, decompression, augmented injection, surfactant, rock surface property, low permeability reservoir, wettability reversal, surfactant.

1. INTRODUCTION

Low and extra low permeability reservoirs are characterized by tiny pore throats, complicated structures, serious heterogeneity, large oil-water flow resistance and so on [1]. As the water flooding continues, the water injection well pressure increases quickly, water injection rate decreases and injection water is deficient, at the same time, hydration swelling happens, water blocking damage and jamin effect occur [2-4]. Conventional acidification de-blocking measures do not have remarkable results, and the valid period is short (some valid periods of the water injection wells are just one month).

The main mechanism of waterflooding in low permeability reservoirs is the imbibition of water [5, 6]. By changing the rock surface wettability, we could enhance the water phase permeability [7-9]. At present, the technology of decompression and augmented injection during the waterflooding development has been studied at home and abroad, at the same time, tests have been put on in some oil-fields and acquire certain results [10-13]. But for the particularity of low reservoirs, conventional surfactants can not attain the aim of well decompression and augmented injection.

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Based on the fact, we synthesize a novel surfactant FS-01 to change the wettability of low permeability reservoirs which could enhance the oleophobicity of the rock surface. In order to enhance the development in low permeability reservoirs, the decompression and augmented injection mechanism is studied. The surfactant could change the wettability of the rock surface, which could reduce the surface and interfacial tension, enhance the emulsifying ability and so on [14-17]. After the laboratory tests and field application, it is proved that the new surfactant could change the injection water property and rock surface wettability, which could attain the aim of well decompression and augmented injection.

2. MATERIALS AND APPROACHES

2.1. Instruments and Reagent

Spinning drop interfacial tensiometer, energy dispersive X-ray (EDX), Quanta 200F scanning electron microscopy (SEM), Three-neck flask, thermostatic water bath, contact angle measurement apparatus, shear mixer, Displacement experiment device.

Sulfobetaine type fluorocarbon surfactant (FS-01), perfluorooctanesulfonyl fluoride (PF), N,N-dimethyl-1,3-propanediamine (NNDP), isopropyl ether (IE), N-perfluorinated sulfonamide (NFA), sodium 2-hydroxy-3-chloro propanesulfate (SHCP), distilled water, epichlorohydrin (EN), isopropanol (IL), Sodium bisulfite (SB), methanol.

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2.2. Copolymer Synthesis

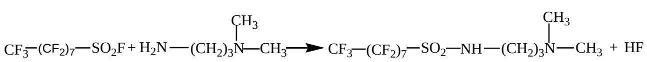
2.2.1. Synthesis Mechanism

Non-polar groups of the common surfactants are C-H chains, but the Non-polar groups of the fluorocarbon surfactants are F-C chains. The fluorocarbon surfactants are the surfactant whose C-H chains are replaced by F-C chains.

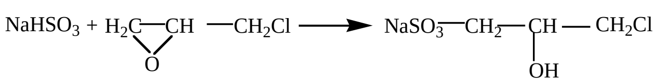
The bond energy of F-C chains is higher than that of C-H chains, so F-C chains are more stable than C-H chains and harder to be polarized. The fluorocarbon surfactant FS-01 have stronger hydro-oleophobicity than common surfactants because of the lower polarity.

2.2.2. Experimental Steps

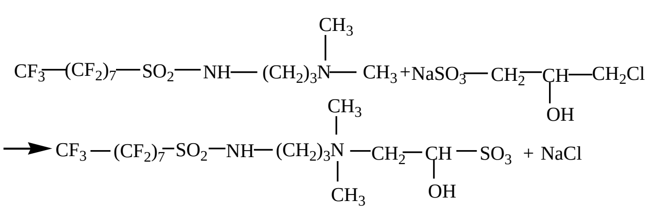
(1) The NNDP and IE are slowly added into a three-neck flask and the mixture is made to homogeneous emulsion, and then put the three-neck flask under water-bath of 10℃. The PF solution is dropped into the three-neck flask slowly, and then ascend the temperature to 60℃. Transfer the solution into the beaker after complete reaction, we would get the compound NFA and the chemical reaction equation is shown as follows:



(2) The SB and methanol are mixed and the mixture is made to homogeneous emulsion, and then the EN solution is dropped into the mixture. After the complete reaction under the condition of 85℃, we would get the compound SHCP and the chemical reaction equation is shown as follows:



(3) The NFA and IL are slowly added into a three-neck flask at 60℃, and then SHCP is dropped into the mixture. Ascend the temperature to 85℃ and the reaction time is 6 hours, transfer the emulsion into a beaker and dry it. At last, we would get the novel fluorocarbon surfactant FS-01 and the chemical reaction equation is shown as follows:



2.3. Core Surface Properties

2.3.1. Wettability

Clean and dry the natural core slice, then immerse it in FS-01 solution under different concentrations for hours and dried naturally. Measure the distilled water and oil contact angle respectively. The natural cores are derived from Shengli Oilfield HJS112-21 Well Shahejie strata (2589.53m~2667.28m).

2.3.2. Surface Free Energy

One end of the surfactant molecular is polar and the other end is non-polar. The water molecular has very strong polarity, and then the surfactant molecular will adsorb on the surface of the solution. As is shown in Fig. (**1**), the polar end of the surfactant molecular is toward water and the other end is toward oil or gas, which could decrease the oil-water interfacial tension. So the oil is washed from the rock surface more easily.

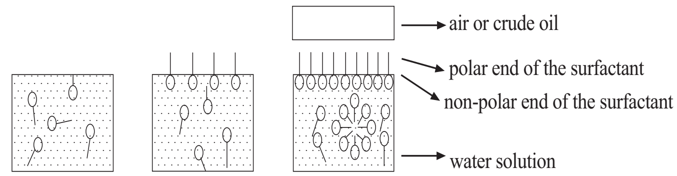


Fig. (1). Principle of low interfacial tension.

The solid surface free energy could be calculated with the Owens method, which needs two test reagents with known dispersion force and polar force. Distilled water and crude oil are chosen as test reagents. The dispersion force and polar force of distilled water are 21.8 and 51.0 mJ/m^2 respectively while those of oil are 27.6 and 0 mJ/m^2 respectively.

2.3.3. SEM Analysis

The natural core and the one treated by FS-01 are observed by Quanta 200F scanning electron microscopy and the energy spectrum is also analyzed.

2.4. Emulsification

As is shown in Fig. (**2**), the fluorocarbon surfactant will absorb at the water-oil interface, which will decrease the water-oil interfacial tension. The fluorocarbon surfactant could form stable oil-in-water emulsion and oil is hard to adhere to the rock surface during the waterflooding process.

Mix crude oil (100 ml) with FS-01 solution under different concentrations, stir for 10 minutes at 25℃ and observe the phenomenon.

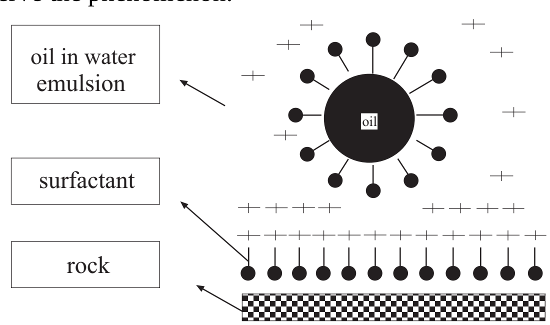


Fig. (2). Principle of emulsification.

2.5. Oil-water Relative Permeability

Oil-water relative permeability tests are taken by the distilled water and FS-01 solution (5%) respectively.

2.6. Oil Recovery Efficiency and Injection Pressure

Two oil saturated cores are displaced by the distilled water and FS-01 solution (5%), the recovery efficiency and injection pressure are measured.

3. RESULTS AND DISCUSSION

3.1. Wettability

Figs. (**3**) and (**4**) indicate that the contact angles of the rock surface become bigger after the core treated by FS-01.

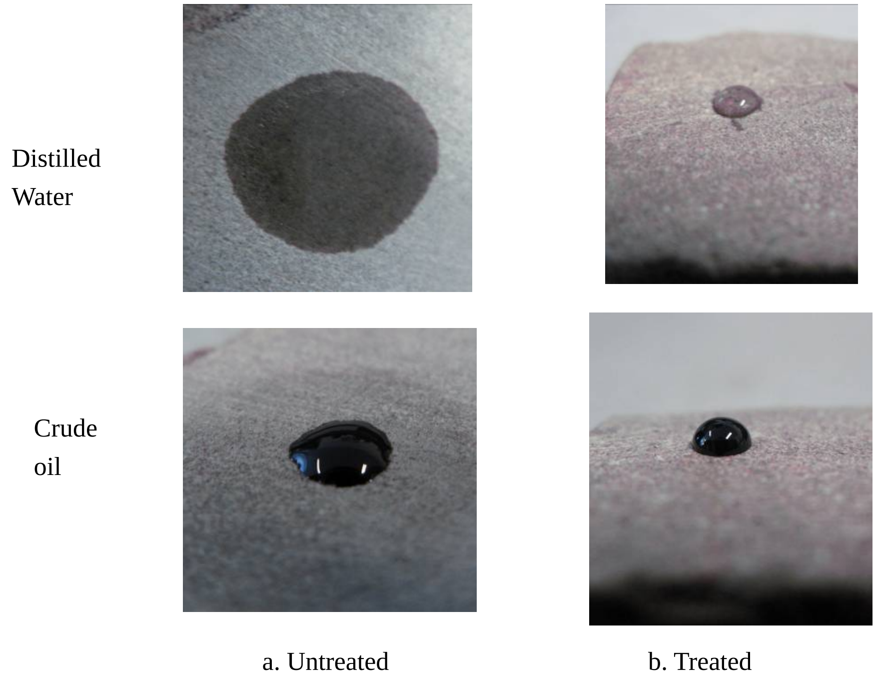


Fig. (3). Photos of the core slice.

The contact angle of water and the core surface increases from 2.2°to 35.5°, the contact angle of crude oil and the core surface increases from 35.3°to 85.7°. It is concluded that FS-01 has quite well wettability reversal function which could increase the oleophobicity of the core surface by a large extent.

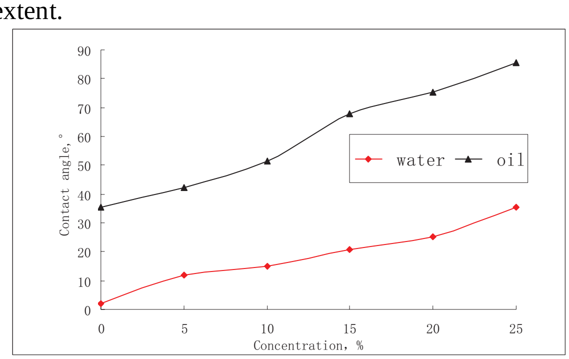


Fig. (4). Contact angle.

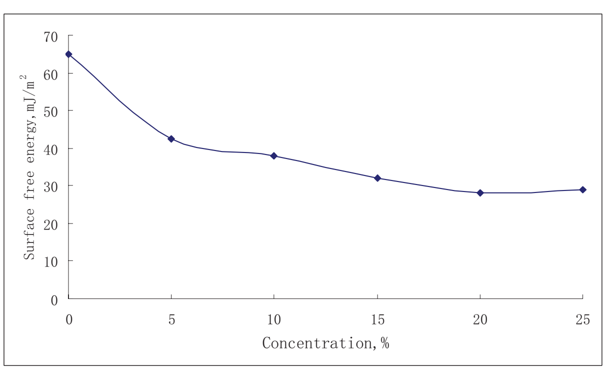


Fig. (5). Surface energy.

3.2. Surface Free Energy

Fig. (**5**) shows that, the surface free energy of core slices treated by FS-01 has a significant reducing trend as the concentration increases form 0 to 25%. Surface free energy of the cores treated by FS-01 reduces from 65.2 mJ/m^2 to 9.25341 mJ/m^2, which are far lower than the surface tension of distilled water (72.8 mN/m) and general oils (25 to 35 mN/m), thus, the core surface is hard to be wetted by general fluids and shows the character of low energy.

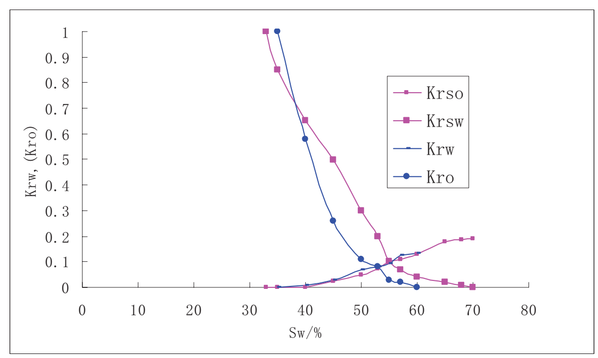


Fig. (6). Relative permeability.

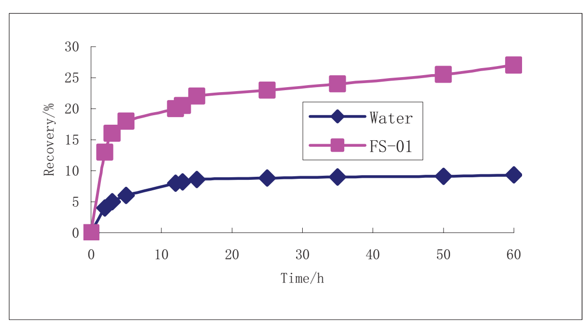


Fig.(7). Oil recovery.

3.3. Oil-water Relative Permeability

Fig. (**6**) indicates the changes of the relative permeability. When the core is displaced by distilled water, the residual oil saturation is 40.6%, the bound water saturation at the equivalent permeability point is 51.8% and the range of the

Table 1. Results of the Emulsion Tests

Sample NO. \ Density	0	0.1%	0.5%	1.0%	2.0%
1	sharp interface	Massive fusion	Massive fusion	Complete fusion	Complete fusion
2	sharp interface	Massive fusion	Complete fusion	Complete fusion	Complete fusion
3	sharp interface	Partial fusion	Complete fusion	Complete fusion	Complete fusion
4	sharp interface	Partial fusion	Massive fusion	Complete fusion	Complete fusion

oil water two-phase flow is narrow. When the core is displaced by FS-01 solution, the residual oil saturation is 31.4%, the bound water saturation at the equivalent permeability point is 55.1% and the range of the oil water two-phase flow is broader than the one displaced by distilled water. The oil-water equivalent permeability point moves to the right, which proves that the water phase relative penetration has improved and the wettability of the rock is reversed to the hydrophilicity. After the test it is proved that FS-01 could improve the water phase penetration and the water absorbing ability of the core.

3.4. Emulsion Test

We could see that FS-01 solution has well emulsifying capacity on crude oil from Table **1**. When the concentration of FS-01 reaches 0.1%, partial or massive fusion happens. The concentration reaches 1.0%, the FS-01 solution and the oil is on the state of complete fusion. It is proved that FS-01 has perfect emulsifying capacity which is good for oil migration.

3.5. Oil Recovery Efficiency and Injection Pressure

Fig. (**7**) indicates that the oil recovery efficiency (displaced by FS-01) is higher than the one (displaced by distilled water) by 15.06%. The injection pressure decreases from 7.68 MPa to 5.66 MPa and the pressure-drop rate is 26.3%. The distinction becomes conspicuous after 4 hours because adequate adsorption of FS-01 needs a period of time. The adsorption of FS-01 could improve the oil recovery efficiency and decrease the injection pressure.

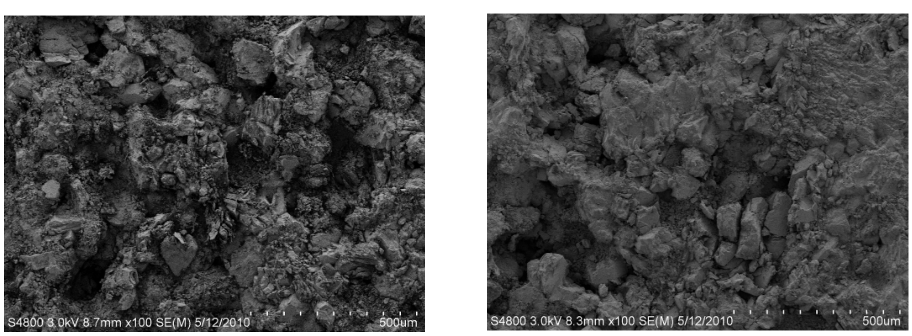
3.6. SEM

Fig. (**8**) indicates that the natural core surface is mainly composed of big particles and pores, the main element of the untreated core is silicon, and the quality percentage of silicon is 48.95% while fluorine is only 0.85%.

After the core surface treated by FS-01 solution, the core surface particles become smaller and the porosity decreases. The quality percentage of silicon decreases to 41.96%, while fluorine increases to 9.74%, which indicated that FS-01 had adsorbed on the core surface.

4. FIELD APPLICATION

We had the field application in ShengLi Oilfield HJS112-21 Well. The reservoir porosity distributes from 11.6% to 21.4%, the average porosity is 18.2%. The reservoir permeability distributes from 1.9×10^{-3} μm^2 to 26.4×10^{-3} μm^2, the average permeability is $9.2\times10^{-3} \mu m^2$. We could see that



A. Untreated

Element	Wt%	At %
F K	0.85	1.21
Si K	48.95	44.13

B. Treated

Element	Wt%	At%
F K	9.74	12.36
Si K	41.96	40.21

Fig. (8). SEM of core surface.

the reservoir has the feature of low porosity and low permeability, FS-01 solution (3%) is injected from the injection string in the field application.

By using the technology, the injection pressure reduced from 20.9 MPa to 15.2 MPa and daily water-injection rate increased from 4.5 m^3/d to 8.7 m^3/d. The valid period is more than half a year and the developing cost is reduced by 25.5%. It is demonstrated that the new fluorocarbon surfactant FS-01 has made a great effort in decompression and augmented injection during the waterflooding development in low permeability reservoirs.

5. CONCLUSION

1. The wettability is reversed to water-wet largely after the adsorption of FS-01 on the rock surface, contact angles of distilled water and crude oil increase to 35.5°and 85.7°respectively.
2. The technology could decrease the surface free energy and the interfacial tension, the surface free energy decreases to 8.25341 mJ/m^2. After the emulsion, oil-water relative permeability and oil recovery efficiency test, it is demonstrated that the technology could enhance the oil recovery efficiency, water phase penetration and the water absorbing ability.
3. After the field application, it is proved that the new technology is competent for decompression and augmented injection during the waterflooding development in low permeability reservoirs.

NOMENCLATURE

S_w	=	The bound water saturation, %
K_{rso}	=	The oil phase relative penetration (displaced by FS-01)
K_{rsw}	=	The water phase relative penetration (displaced by FS-01)
K_{rw}	=	The water phase relative penetration (displaced by distilled water)
K_{ro}	=	The oil phase relative penetration (displaced by distilled water)

CONFLICT OF INTEREST

None declared.

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