CHEMICAL ENGINEERING TRANSACTIONS
VOL. 66, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216
DOI: 10.3303/CET1866084

Experimental Study of Novel Reservoir Protection Agents for Low Permeability Reservoirs in Water-based Drilling Fluids

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The low permeability reservoirs in SL Oilfield are featured by large buried depth, poor physical properties, strong diagenesis and heterogeneity, and there exist serious water sensitivity damage and water lock during the drilling process, which significantly restricts the exploration efficiency and benefits of low permeability reservoirs. In order to solve the reservoir protection problems of low permeability reservoirs, novel polymer plugging agent and water lock prevention agent were optimized and characterized in detail, and the polymer plugging agent could work synergistically with water lock prevention agent to impart reservoir protection performance due to film-forming shielding effect and low surface tension. The low damage water-based drilling fluids were also established and evaluated, and the results indicated that low damage water-based drilling fluids exhibited excellent reservoir protection performance with permeability recovery of above 90%, and filtrate surface tension is 18.5mN/m. It could be concluded that the low damage water-based drilling fluids could be priority alternatives to low permeability reservoirs exploration in SL Oilfield.

1. Introduction

With the promotion of oil and gas development around the world, the exploration scope has been gradually extended to complicated geological reservoirs, such as deep or ultra-deep, unconventional, tough reservoirs, and low or ultra-low permeability reservoirs takes up the dominate positions (≥60%) of undeveloped reservoirs, which could constitute a secondary source of fossil energy to prolong the oil and gas supply in the future (Zhao et al., 2017; Motamedi, 2018). SL Oilfield, is abundant in low permeability reservoirs such as BN, ZX, SH, CH block, and it has a great potential of exploration and development. However, to date, production of these low permeability reservoirs has been hampered by the economic risks related to the uncertainties in their size, shape, spatial distribution and reservoir properties. Compared with similar reservoirs in China, the low permeability reservoirs in SL Oilfield is featured by large buried depth, poor physical properties, strong diagenesis and heterogeneity (Sulaiman and Yusof, 2017), and there exist serious water sensitivity damage and water lock during the drilling process and average oil and gas recovery efficiency is only 18.6%, which significantly restricts the exploitation efficiency and benefits of low permeability reservoirs (Li et al., 2017).

Reservoir protection is the constant subject of petroleum engineering technology, and reservoir damage would be inevitable throughout the whole development process of oilfield, especially the low permeability reservoirs (Wu et al., 2017). While pores and throats of low permeability reservoirs are very tiny, they have significant influence on flow behaviour in those reservoirs (Saboorian-Jooybari and Pourafshary, 2015). Stronger liquid-solid interaction within finer pore throats having a large interface area and abundant hydrophilic clay tends to be unfavourable to reservoir protection (Liu et al., 2017). If there are no effective reservoir protection measures, serious water sensitivity damage and water lock would be inevitable during the drilling process, which significantly restricts the exploitation efficiency and benefits of low permeability reservoirs.

In order to solve the reservoir protection problems of low permeability reservoirs in SL Oilfield, we attempted to optimize the novel polymer plugging agent (SLRP) and water lock prevention agent (SLWB), and they are introduced as potential low permeability reservoirs protection agents in water-based drilling fluids. The novel polymer plugging agent (SLRP) and water lock prevention agent (SLWB) could work synergistically to impart reservoir protection performance due to film-forming shielding effect and low surface tension. Furthermore, the

Please cite this article as: Su Z., Liu J., Wang R., Chen E., Li X., 2018, Experimental study of novel reservoir protection agents for low permeability reservoirs in water-based drilling fluids, Chemical Engineering Transactions, 66, 499-504 DOI:10.3303/CET1866084

low damage water-based drilling fluids were also established. It is concluded that the low damage water-based drilling fluids displayed excellent reservoir protection performance, and it could be priority alternatives to low permeability reservoirs exploration in SL Oilfield.

2. Low permeability reservoirs protection agents

Based on the potential damage analysis above, the water sensitivity, water lock and solid invasion damage take up the dominate positions of low permeability reservoir damage, and shield temporary plugging and low interfacial tension should be deployed to reduce the reservoir damage induced by solid or filtrate invasion (Zhao et al., 2018). Therefore, novel polymer plugging agent (SLRP) and water lock prevention agent (SLWB) were optimized and characterized in detail, and the polymer plugging agent (SLRP) could work synergistically with water lock prevention agent (SLWB) to impart reservoir protection performance due to film-forming shielding effect and low surface tension.

2.1 Polymer plugging agent

Polymer plugging agent (SLRP), a novel polymer plugging agent based on temporary shielding plugging theory, was developed by emulsifier polymerization of styrene (St), butyl acrylate (BA) and 2-acrylamide-2-methyl propane sulfonic acid (AMPS). Polymer plugging agent (SLRP) could work synergistically with superfine calcium carbonate to form a thin, plastic and compacted sealing film, thus preventing solid or filtrate invasion.

The reservoir protection performance of SLRP was investigated quantitatively based on the variation of permeability recovery by core flow experiment. The fully preserved rock samples used in this study was cored from ES2 formation of the Da 43 block of Yibei oilfield. The experimental fluids were 3% pre-hydrated bentonite slurry with 3% SLRP. It could be seen from Table 1 that SLRP exhibits good plugging ability with core plugging ratio (PR) of above 97%, and after core being cut off certain length, SLRP also exhibits good reservoir protection ability with core permeability recovery (R_d) of above 95%. As indicted in Fig. 1, compared with the bentonite slurry, adding SLRP is beneficial to forming a thin, plastic and compacted sealing film and protecting low permeability reservoir from solid or filtrate invasion damage.

Table 1: Core flow experiment results of SLRP

Core NO.	K_1 /10^{-3} μm^2	K_2 /10^{-3} μm^2	P_R /%	L_{CUT} /mm	K_3 /10^{-3} μm^2	R_d /%
1#	14.21	0.17	98.80	3.0	14.03	98.73
2#	22.52	0.43	98.09	3.1	21.94	97.42
3#	31.24	0.72	97.69	3.1	30.26	96.86

Note: K_1-original core permeability; K_2-core permeability after interacting with fluids; K_3-core permeability after cutting certain length.

Figure 1: Optical microscope photographs (100X) of API filter-cake: bentonite(left) and SLRP(right)

2.2 Water lock prevention agent

Due to tiny pores or throats and strong capillary effect, water lock damage would be inevitable during the exploitation and development of low permeability reservoirs (Merchan-Arenas et al., 2017). Based on the film-forming plugging of polymer plugging agent (SLRP), decreasing interfacial tension and altering rock wettability

is one of the most effective methods to reduce water lock damage. Therefore, novel water lock prevention agent (SLWB) was optimized, which consists of a fluorocarbon surfactant and a hydrocarbon surfactant.
Contact angle measurement was carried out to evaluate the effect of water lock prevention agent (SLWB) on the core rock wettability. The natural rock sample, cored from ES2 formation of the Da 43 block of Yibei oilfield, was immersed in the 10% SLWB solution for 4 h and air-dried for 24 h. The original core was adopted for comparison. Then, the drop images were taken with a high-resolution camera (HARKE-SPCA) and contact angles were calculated with specific software. The testing fluids consist of deionized water, oilfield wastewater, hexadecane and crude oil.

Table 2: Effect of SLWB on the core rock wettability

testing fluids	Contact angle/°	
	original	10% SLWB
deionized water	2.52	139.79
oilfield wastewater	10.62	122.31
hexadecane	2.20	65.46
crude oil	35.35	85.68

It could be seen from Table 2 that the contact angles of original cores using deionized water, oilfield wastewater, hexadecane and crude oil are 2.52°, 10.62°, 2.20° and 35.35°, indicating a favorable hydrophilicity. After immersed in 10% SLWB solution, contact angles was significantly increased no matter what testing fluids used in contact angle measurement, and the core rock wettability was altered from favorable hydrophilicity to hydrophobicity, thus preventing filtrate invasion into the low permeability reservoir and reducing the water lock damage and clay swelling.
Interfacial tension measurement was also carried out to evaluate the ability of water lock prevention agent (SLWB) to decrease interfacial tension of fluid filtrate. Six conventional surfactants were chosen for comparison. It could be seen from Table 3 that the compared with conventional surfactants with the same concentration, SLWB obtains the minimum interfacial tension, which is beneficial to reducing water lock damage and improving fluid filtrate backflow.

Table 3: Interfacial tension measurement of different surfactants

Surfactants	Concentration /%	Interfacial tension /mN.m^{-1}
SLWB	0.3	8.26
ABS	0.3	26.06
OP-10	0.3	26.59
Tween-40	0.3	30.25
Tween-80	0.3	41.36
Span-60	0.3	29.56
ABSN	0.3	25.50

3. Low damage water-based drilling fluids

Polymer water-based drilling fluids were widely used in the low permeability reservoirs development in SL Oilfield, but it could not meet the demand of reservoir protection for lack of effective polymer plugging agents. On the basis of conventional polymer water-based drilling fluids (CPWM), low damage water-based drilling fluids (LDWM) were established through adding novel polymer plugging agent (SLRP) and water lock prevention agent (SLWB). The rheological，filtration properties and reservoir protection performance of low damage water-based drilling fluids were evaluated in detail using conventional polymer water-based drilling fluids for comparison, and reservoir protection mechanism was also investigated in this study. The water-based drilling fluids tested were prepared using standard commercial additives, and the trade names of additives were replaced by generic description. The formulations of the tested drilling fluids are as follow.
Polymer water-based drilling fluids (CPWM): 3% bentonite + 0.2% Polyacrylamide + 2% Potassium humate + 3% Phenolaldehy resin + 2% Walchowite + 2% Sulfonated asphalt.
Low damage water-based drilling fluids (LDWM): 3% bentonite + 0.2% Polyacrylamide + 2% Potassium humate + 3% Phenolaldehy resin + 2% Walchowite + 2% Sulfonated asphalt + 2% Amino silicone glycol + 3% SLRP + 0.3% SLWB.

3.1 Rheological and filtration properties

Table 4 shows the rheological and filtration properties of CPWM and LDWM before and after hot rolling at 120 ℃ for 16 h. It could be concluded that compared with CPWM, adding SLRP and SLWB would not have adverse effect on rheological and filtration properties, and low damage water-based drilling fluids (LDWM) exhibits stable rheological and filtration properties before and after hot rolling, which could satisfy the field requirements. What's more, the interfacial tension of LDWM filtrate is much lower than that of CPWM due to usage of SLWB, and it is beneficial to reduce water lock damage.

Table 4: Rheological and filtration properties of drilling fluids

Fluids	Condition	AV /mPa·s	PV /mPa·s	YP /Pa	GEL /Pa	FL_{API} /mL	Interfacial tension /mN.m^{-1}
CPWM	Before aging	39.0	28.0	11.0	5.0/7.5	3.4	-
	After aging	34.5	25.5	9.0	2.5/5.0	4.2	57.8
LDWM	Before aging	41.5	30.0	11.5	5.5/9.5	3.4	-
	After aging	34.5	25.0	9.5	3.5/5.5	4.5	18.5

Note: AV-apparent viscosity; PV-plastic viscosity; YP-yield point; GEL- gel point; FL_{API}-fluid filterate.

3.2 Reservoir protection performance

The core flow tests, CT scan core analysis (CT), and formation water compatible tests were adopted to comparatively evaluate the reservoir protection performance of CPWM and LDWM fluids.
The reservoir protection performance of CPWM and LDWM fluids were investigated with the core plugging ratio (PR) and core permeability recovery (Rd) as evaluation parameters. The fully preserved rock samples used in core flow experiments was cored from ES2 formation of the Da 43 block in Yibei oilfield. The Core flow experiment results of CPWM and LDWM are reported in Table 5. The permeability of natural cores all decreased after interacting with CPWM and LDWM fluids, and the plugging ratio of LDWM, (above 90%) was much higher than CPWM fluids. After being cut a certain length, the permeability of natural cores all recovered to some extent, and the permeability recovery of LDWM, (above 95%) was also higher than CPWM fluids. It is concluded that low damage water-based drilling fluids (LDWM) could form a thin and tight sealing film near the wellbore to prevent solid deep invasion into the reservoirs and protect low permeability reservoir from solid plugging damage.

Table 5: Core flow experiment results of SLRP

Core NO.	Fluids	K_1 /10^{-3} μm^2	K_2 /10^{-3} μm^2	P_R /%	L_{CUT} /mm	K_3 /10^{-3} μm^2	R_d /%
1#	CPWM	117.27	45.58	61.13	3.0	55.98	47.74
2#		89.76	39.65	55.83	3.0	44.23	49.27
3#	LDWM	92.35	7.30	92.09	3.0	88.28	95.59
4#		95.78	9.46	90.12	3.0	90.99	95.01

Note: K_1-original core permeability; K_2-core permeability after interacting with fluids; K_3-core permeability after cutting certain length.

The pore structure of natural cores before and after core flow tests was quantitatively characterized by CT scan core analysis instrument, and porosity of two-dimensional slices extracted from the full three-dimensional digital cores interacting with CPWM or LDWM was calculated with specific software. Fig. 2 presents the core porosity measurement of different two-dimensional slices before and after tests. As indicted in Fig. 2, after interacting with CPWM, the porosity of natural cores significant decreased within the length of 30mm from polluted part, that is to say, the drilling fluid invasion depth or damage depth was much more than 30mm. On the contrary, after interacting with LDWM, the porosity of natural cores decreased only within the length of 15mm from polluted part, and the porosity was nearly the same within the length of 15mm to 30mm. It could be visually concluded from Fig. 3 and Fig. 4 that LDWM could effectively protect low permeability reservoir from solid or fluid invasion damage, and the core slice porosity at 30mm length remained nearly constant.

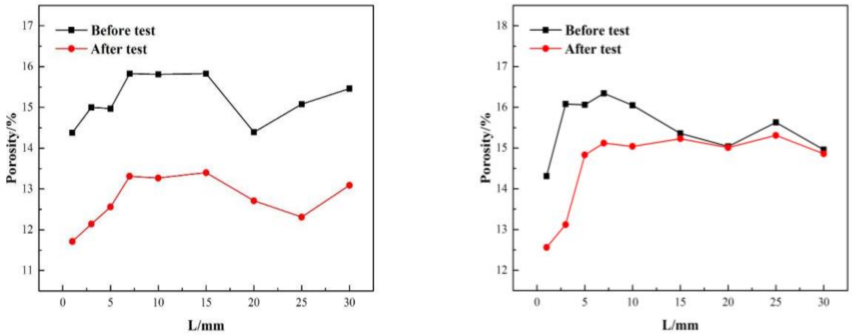

Figure 2: Porosity measurement of different three-dimensional core slices: CPWM (left), LDWM (right)

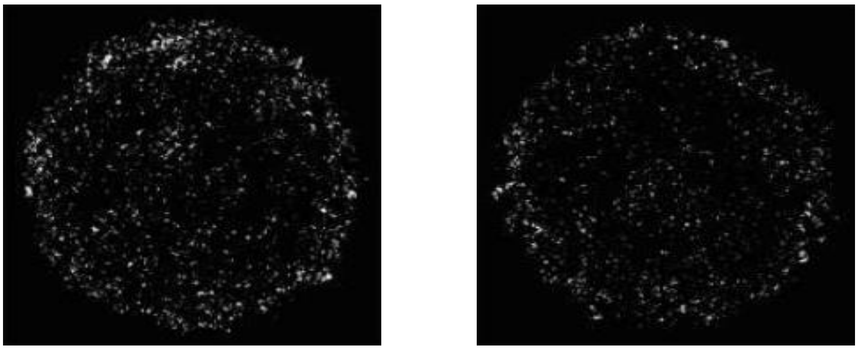

Figure 3: Core slices photographs: original (left), interacting with CPWM (right)

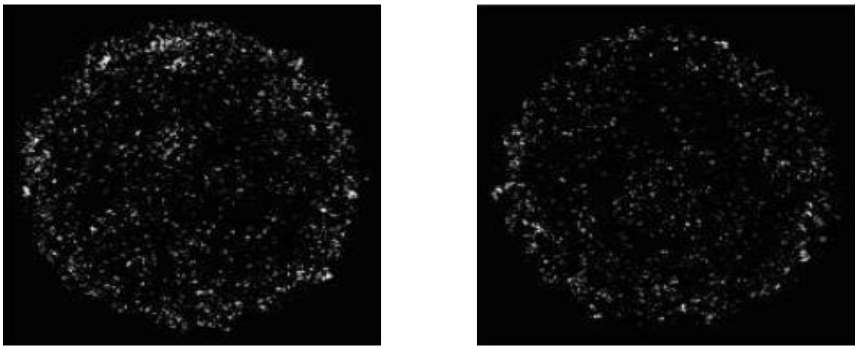

Figure 4: Core slices photographs: original (left), interacting with LDWM (right)

3.3 Reservoir protection mechanism

The action mechanism of low damage water-based drilling fluids (LDWM) was investigated based on the reservoir protection performance evaluation above. The results indicated that low damage water-based drilling fluids (LDWM) could form a thin and tight sealing film near the wellbore to prevent solid deep invasion, and alter rock wettability and decrease filtrate interfacial tension to reduce water lock damage to further improve the reservoir protection performance.

Film-forming shielding effect. Polymer plugging agent (SLRP), a novel polymer plugging agent, could be deformable to internally bridge and seal pore or pore-throats, and finally form a thin, plastic and compacted sealing film near the wellbore, which could prevent solid or filtrate invasion (Liu et al, 2017). Furthermore, the electrostatic interaction between SLRP and rock particles is also beneficial to film-forming sealing near the wellbore and reducing reservoir damage depth.

Rock wettability alteration. Novel water lock prevention agent (SLWB), a mixture of fluorocarbon surfactant and hydrocarbon surfactant, could adsorb on the rock surface, alter its wettability from favorable hydrophilicity to hydrophobic and oleophobic, and enhance the effective permeability, which could reduce water lock damage and decrease oil or gas flow resistance to increase oil or gas recovery (Li et al., 2017). What's more, SLWB could also decrease the filtrate interfacial tension of low damage water-based drilling fluids (LDWM) to further reduce water lock damage and improve fluid filtrate backflow.

Clay hydration inhibition. The abundant hydrophilic clay, such as kaolinite and mixed-layer illite/smectite, is developed in the pores (Zhong et al., 2017), which makes it possible for water sensitivity damage and fine particles migration (Hasannejada et al., 2017). Amino silicone glycol, used in the low damage water-based drilling fluids, could effectively inhibit clay hydration and swelling through chemical adsorption with clay and prevent low permeability reservoirs from water sensitivity damage.

4. Conclusions

The polymer plugging agent (SLRP) and water lock prevention agent (SLWB) were optimized and characterized in detail as low permeability reservoir protection agents in water-based drilling fluids. The polymer plugging agent (SLRP) could internally bridge and seal pore or pore-throats, and finally form a thin and tight sealing film near the wellbore, which could prevent solid or filtrate invasion. The water lock prevention agent (SLWB) could alter rock wettability and decrease interfacial tension to reduce water lock damage through chemical adsorption. Furthermore, the low damage water-based drilling fluids (LDWM) were established based on the cooperative reservoir protection performance of polymer plugging agent (SLRP) and water lock prevention agent (SLWB). The low damage water-based drilling fluids (LDWM) could be priority alternatives to low permeability reservoirs exploration in SL Oilfield.

Acknowledgments

We would like to thank the financial support from China Postdoctoral Science Foundation (2017M612344), Shandong province post-doctoral innovation projects (201703044), and National Science and Technology Major Project of China (2016ZX05040-005).

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