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Review Article

Recent Advance of Microbial Enhanced Oil Recovery (MEOR) in China

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Compared with other enhanced oil recovery (EOR) techniques like gas flooding, chemical flooding, and thermal production, the prominent advantages of microbial enhanced oil recovery (MEOR) include environment-friendliness and lowest cost. Recent progress of MEOR in laboratory studies and microbial flooding recovery (MFR) field tests in China are reviewed. High biotechnology is being used to investigate MFR mechanisms on the molecular level. Emulsification and wettability alternation due to microbial effects are the main interests at present. Application of a high-resolution mass spectrum (HRMS) on MEOR mechanism has revealed the change of polar compound structures before and after oil degradation by the microbial on the molecular level. MEOR could be divided into indigenous microorganism and exogenous microorganism flooding. The key of exogenous microorganism flooding was to develop effective production strains, and difficulty lies in the compatibility of the microorganism, performance degradation, and high cost. Indigenous microorganism flooding has good adaptation but no follow-up process on production strain development; thus, it represents the main development direction of MEOR in China. More than 4600 wells have been conducted for MEOR field tests in China, and about 500 wells are involved in MFR. 47 MFR field tests have been carried out in China, and 12 field tests are conducted in Daqing Oilfield. MFR field test's incremental oil recovery is as high as 4.95% OOIP, with a typical slug size less than 0.1 PV. The input-output ratio can be 1 : 6. All field tests have shown positive results in oil production increase and water cut reduction. MEOR screening criteria for reservoirs in China need to be improved. Reservoir fluid, temperature, and salinity were the most important three parameters. Microbial flooding technology is mature in reservoirs with temperature lower than 80°C, salinity less than 100,000 ppm, and permeability above 5 mD. MFR in China is very close to commercial application, while MFR as quaternary recovery like those in post-polymer flooding reservoirs needs further study.

Table 4: Chao 50 block microbial flooding field test in Daqing Oilfield [61–63].

Area of block (km^2)	2.43
OOIP (tons)	1667000
Reservoir depth (m)	989
Reservoir thickness (m)	7.9-9.5
Reservoir temperature (°C)	55
Injectors/producers	2/10
Formation brine salinity (ppm)	4450
Formation brine divalent (ppm)	14
Average permeability (mD)	25
Average porosity (%)	17
Dead oil viscosity (cP)	20.2
Formation oil viscosity (cP)	9.7
Original oil saturation (%)	57
Water cut	95%
Implementation time	June 2004-Sep 2005
Injection slug (PV)	0.005
Microbe concentration	5% (first slug), 2% (second slug)
Effective well ratio	74.2%
EOR (% OOIP)	3%
Water cut reduction (%)	30.3
Input-output ratio	1 : 6
Effective duration time	3 years
Expansion test	Yes

4.2.1. Daqing Oilfield. Up to present, more than 12 MFR field tests have been conducted in Daqing Oilfield. Some MFR tests are available in reference [54]. Among these field tests, Chao 50 in Chaoyanggou Oilfield is very prominent. Two microorganisms (Brevibacillus brevis and *Bacillus cereus*) were selected from indigenous microorganisms to conduct field tests of single well simulation and microbial flooding in ultra-low-permeability reservoirs in Daqing Oilfield [22, 61, 62]. From 2002 to 2003, 60 wells were put into CMR tests. The average formation permeability was 10 mD, and the formation temperature was 55°C. Among the 60 wells, formation permeability of 28 wells was 15-25 mD, and that of 22 wells was 5-15 mD, and formation permeability of 10 wells was below 5 mD. 71.7% wells were seen as having positive results, and the input-output ratio was 1 : 8. Based on previous single-well MEOR success, microbial flooding recovery (MFR) tests were carried out in 50 blocks with 2 injection wells and 10 production wells [61]. The reservoir data and field test performance are given in Table 4 [61–63]. Well patterns and field test performance are given in Figure 10 [63] and Figure 11 [63], respectively. The liquid-producing capacity increased from 43.6 to 79.6 tons, daily oil production increased from 24.7 t to 40.8 t, and water cut decreased by 30% and the incremental oil recovery was 3% OOIP with an effective duration of three years. Considering the low injection slug (0.005 PV) compared to chemical flooding slug, the incremental oil recovery is very prominent. Another very successful microbial flooding field test was reported to have an incremental oil recovery of 4.45% OOIP by 0.05

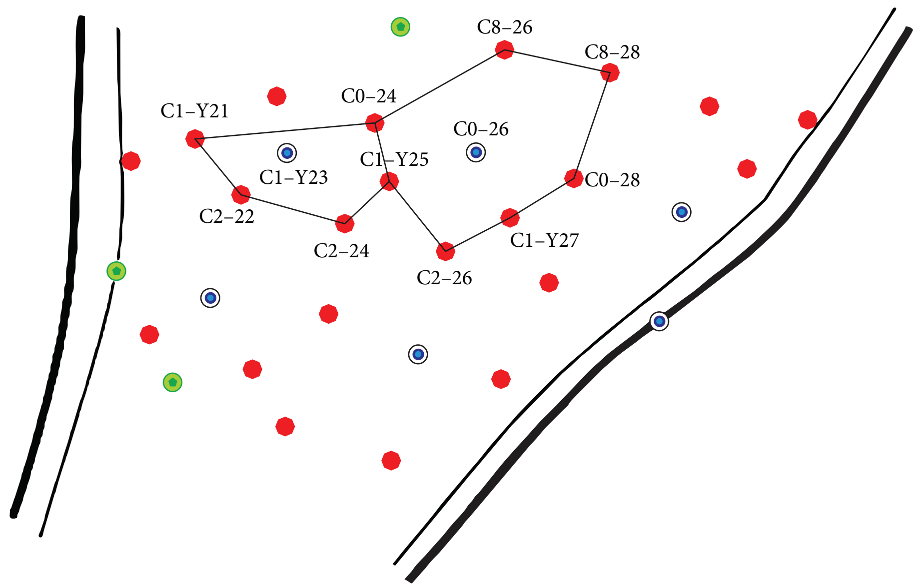

Figure 10: Chao 50 MFR field test well pattern in Daqing Oilfield [54].

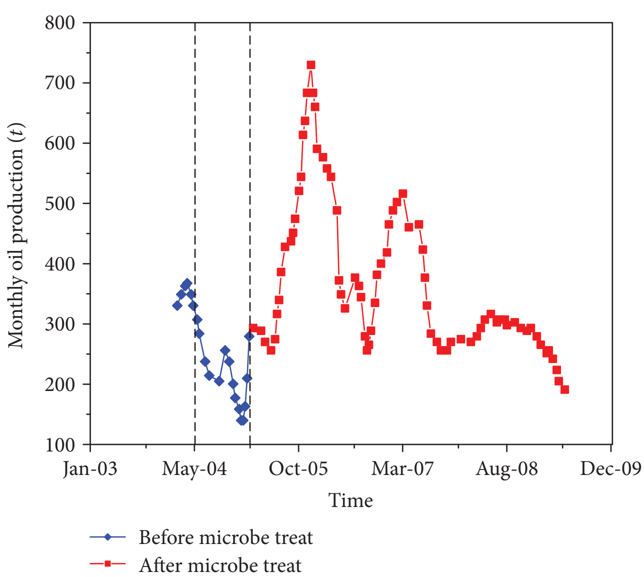

Figure 11: Chao 50 MFR field test production performance [54].

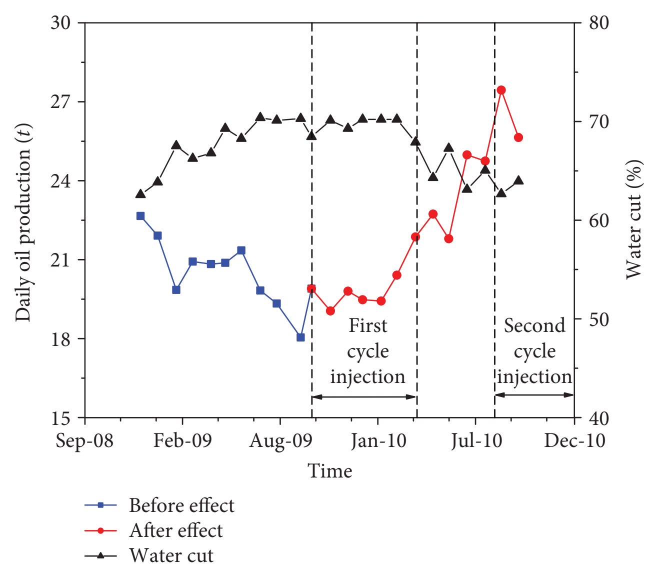

Figure 12: Chao 50 expansion MRF field test production performance [54].

PV bacteria slug [54]. The Chao 50 input/output ratio was 1 : 6. This successful pilot test indicated that MFR can succeed in the reservoir with permeability lower than present criteria at 50 mD, seen in Table 2 and Table 3. This test also showed that microbial flooding could set an effective displacement system which made the dead oil well remobilized. This field test verified that the injection-production relationship significantly affected microbial flooding effects. Based on the success of MRF in Chao 50, expansion microbial flooding tests with 9 injectors and 24 producers were conducted in 2009 [54]. The production performance of the expansion test can be seen in Figure 12 [54]. Detailed information of the expansion field test is not made public yet, but it is reported that microbial flooding makes the block production turn from decreasing to increasing.

4.2.2. Shengli Oilfield. Since Shengli Oilfield has been the second largest oil producer for a long time, MEOR in Shengli provides for the industry a valuable experience. MEOR research in Shengli Oilfield started since 1995, and MEOR field tests have been conducted since 1997 [14]. Although more than one thousand wells have been used in MWR and CMR in Shengli Oilfield, only 9 blocks have been conducted for MFR. Table 5 [14, 36, 64, 65] is a summary of 7 microbial flooding field tests in Shengli. The MRF test in Shan 12 is well introduced in a previous publication [30]. Among these field tests, only Guan 3 Block is not of fault block type, while the other 6 are all fault block reservoirs. And these 6 blocks are water flood reservoirs, while Guan 3 block is a post-polymer flood reservoir. In other words, the first 6 tests in Table 5 are all in tertiary recovery stage, while the last is in

Table 5: Recent microbial flooding recovery field tests in Shengli Oilfield.

Case	Block	Implement time	T (°C)	*Perm* (mD)	Salinity (ppm)	Dead oil viscosity at 50°C (mPa·s)	Inj./Pro	Area (km^2)	Type	Incremental oil (ton)	Water cut↓[1]	EOR↑[2] (%)
1	ZNXQ	1998.3-1999.09	54	477	1100	48	3/8	0.9	EMFR	5090	5	
2	Li 32	1998.06-2002.2	91	525	4600	88	4/7	1.8	EMFR	2001	slight	
3	Pan2-33	2000.08-2002.11	67	436	43900	1100	4/11	0.9	EMFR	7800	1.3	
4	Luo 801	1999.07-now	80	231	7790	353	5/13	1.25	Air EMFR	122800	7.3	4.95
5	Shan 12	2005.08-2008.06	66	263	20000	38	1/7	0.31	Air IMFR	8520	2	
6	Zhan 32	2011.11-now	63	682	9000	1885	3/12	0.69	Air IMFR	22855	5.5	*5.5*
7	Guan 3	2008.11-2012.12	69	2500	5920	1000	6/17	0.84	Air IMFR	21000	0.7	1.27

Note: T = reservoir temperature; Perm = permeability; Inj. = injectors; Pro = producers. [1]↓ means water cut reduction; [2]↑ means incremental oil recovery.

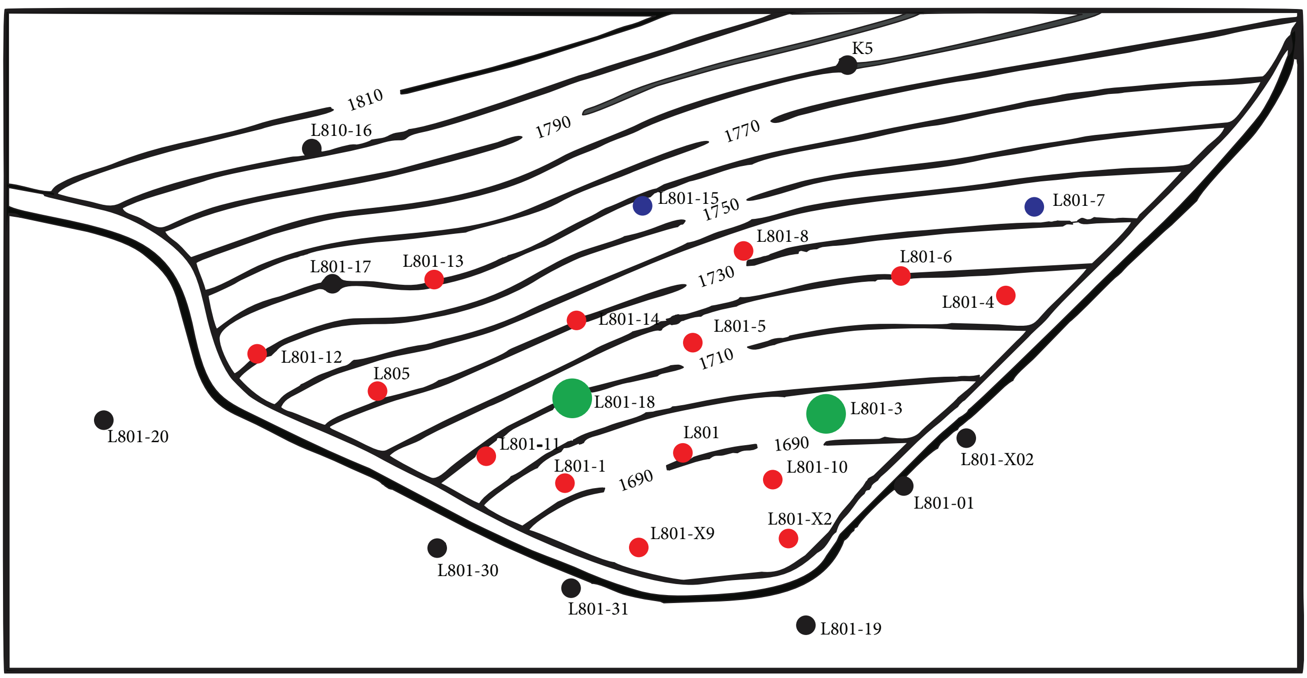

Figure 13: Luo 801 Block in Shengli Oilfield MEOR field test [65].

quaternary recovery stage. Since Shengli Oilfield has the second largest polymer flooding commercial use in China, the MFR test in Guan 3 is worthy of special attention. Polymer flooding in this block started in December 1994 and entered into the post-water flooding stage in April 1997 [14]. MFR started in November 2008. Although profile control measures have been taken before bacteria injection, injected bacteria broke through 4 days after injection in the latter stage. This test indicated the difficulty of MEOR in the post-polymer flooding reservoir with high heterogeneity. Among the 7 MFR field tests in Table 5, only three were reported with obvious enhanced oil recovery. In this block, MFR field tests have been enlarged from five wells (1 injector, 4 producers) in 2011 to 15 wells (3 injectors, 12 producers) in 2014 [14, 64]. In 2015, the field test has been enlarged, but the data has not been made public. Incremental oil recovery in Zhan 32 is a predicted recovery. Among all the blocks that are conducted for MEOR, Luo 801 deserves the most attention for several reasons. First, it has the longest MEOR application lasting time in China, probably in the world. Second, it has currently the highest field proven enhanced oil recovery in MEOR. The staged actual enhanced oil recovery is 4.95% OOIP, higher than the best one in Daqing Oilfield [54]. Finally, two kinds of microbial flooding (IMFR, EMFR) are both tested in the same block. The production history of Luo 801 is well introduced in reference [64, 65]. Figure 13 [65] shows the well pattern of MFR field tests. In Figure 13, green represents the two injectors from 2002 to 2011, while blue represents 3 injectors operated from July 1999 to August 2002, and red represents producers operated from 1999 to present [65]. The production performance of Luo 801 is shown in Figure 14 [65]. This data shows that microbial

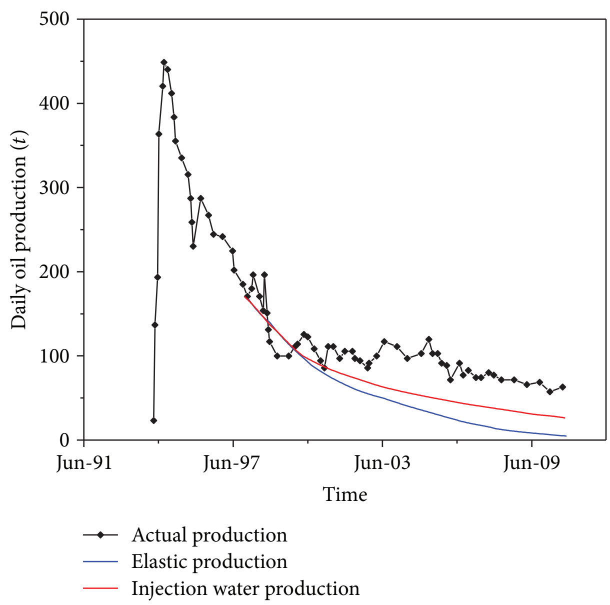

FIGURE 14: Luo 801 production curve and decline forecast [65].

flooding indeed improved oil recovery. For potential reservoir screening consideration, reservoir parameters and MFR field test performance are summarized in Table 6 from various references [30, 33, 60, 64, 65]. After air-assisted MFR, the annual water cut increase rate changed from 9% to 0.53%, and it has been maintained lower than 1.5% for 8 years [14]. The input/output ratio was not reported and is estimated to be 1 : 4 according to a comparison with some similar MRF projects in Shan 12. MFR success in Luo 801 paved a way towards enlarging MEOT tests in other blocks like Zhan 32 in Table 5. The cost for incremental oil from Luo 801 microbial flooding blocks is as low as 7 USD/bbl (339.56 yuan/ton) [65]. Some latest MEOR projects in Shengli Oilfield have not been made public.

4.2.3. Changqing Oilfield. Changqing Oilfield is the largest oilfield if judged by production oil equivalent. Almost all reserves of Changqing Oilfield are from low-permeability reservoirs, and more than half are of ultra-low-permeability formation. Since the reservoir permeability bound given by CNPC and Sinopec is 50 mD, whether ultra-low-permeabilityreservoirs are suitable to use MOER draws attention. A pilot in an ultra-low-permeability reservoir was conducted in 2009 in Ansai in Changqing Oilfield [31, 66–68]. The average permeability of Ansai Oilfield is 1.29 mD, and the average porosity is 12.4%. The pilot was conducted to check the microbial flooding effect, which contains one well group with 1 injector and 6 producers. Oil production in this block started from March 1990, and the daily oil production per well before MFR is 1.48 tons [31]. The well pattern is shown in Figure 15 [31, 68]. Oil production before and after MRF is given in Table 7 [31, 68] while reservoir parameters are given in Table 8 [31, 66–68]. Oil production indicates that microbial flooding can reduce water cut and increase oil production. The water cut increase rate was reduced from 10.86% to 4.42%, and the comprehensive production decline rate was changed from 2.34% to -2.58%, which means oil production was significantly increased [68]. This pilot also shows that production performance has a positive relation with microbe movement. This is in agreement with other field tests in Daqing and Shengli. MEOR is a water-enhanced improved oil technique. Only when an effective injection-production relationship is formed can effective oil production be attained. In other words, if water injection is difficult, MEOR is likely ineffective. The economic performance is very good, with an input-output ratio of 1 : 5.9. This indicated that the permeability ground should be lower.

TABLE 6: Luo 801 block microbial flooding field test in Shengli Oilfield.

Area of block (km^2)	1.25
OOIP (tons)	2910000
Reservoir depth (m)	1680-1800
Reservoir thickness (m)	15.5
Reservoir temperature (°C)	75-80
Injectors/producers	5/13
Formation brine salinity (ppm)	9794
Formation brine divalent (ppm)	NA
Average permeability (mD)	218
Average porosity (%)	23.4
Dead oil viscosity (cP)	221.7
Formation oil viscosity (cP)	12.8
Original oil saturation (%)	60
Water cut	86.5
Implementation time	July 1999-
Injection slug (PV)	0.25
Microbe concentration	NA
Effective wells ratio	NA
EOR (% OOIP)	4.95
Water cut reduction (%)	7.3
Input-output ratio	≈1 : 4
Effective duration time	>15 years
Expansion test	Yes

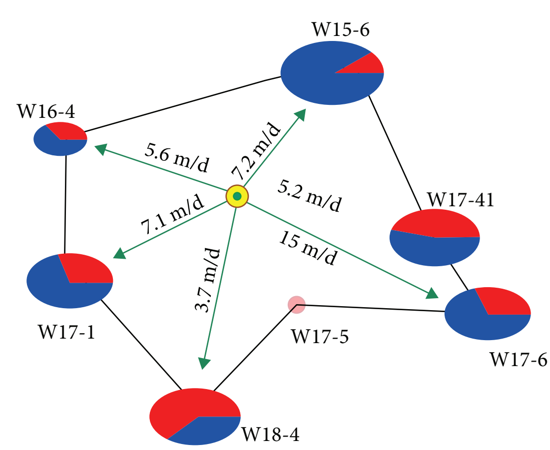

FIGURE 15: MRF pilot well pattern and bacteria flow velocity [31, 68].

Table 7: Well performance of Ansai MFR pilot [31, 68].

No	Before MFR Daily fluid (m^3)	Daily oil (ton)	Watercut (%)	After MFR (December 18, 2009) Daily fluid (m^3)	Daily oil (tons)	Watercut (%)	Daily oil increase (tons)	Cumulative incremental oil (tons)
1	2.13	0.67	62.7	4.02	2.2	34.9	1	169.7
2	5.37	1.43	68.2	4.28	1.86	48.4	0.45	57.93
3	5.73	1.59	67	5.19	12.17	50.2	0.46	34.37
4	5.01	1.04	75.6	4.65	0.52	86.6	0.5	33.56
5	7.54	1.1	82.6	5.45	0.92	80	0.07	2.09
6	5.36	3.04	32.6	3.53	2	32.5	0	0
Total	31.14	8.87	66.1	27.12	19.67	57.6	0.66	297.65

Table 8: Ansai MFR pilot in Changqing Oilfield [31, 67, 68].

Area of block (km^2)	NA
OOIP (tons)	NA
Reservoir depth (m)	1220-1241
Reservoir thickness (m)	15.8
Reservoir temperature (°C)	45
Injectors/producers	1/6
Formation brine salinity (ppm)	92600
Formation brine divalent (ppm)	NA
Average permeability (mD)	5.22
Average porosity (%)	14
Dead oil viscosity (cP)	10.5 at 20°C
Oil saturation (%)	60
Water cut before test (%)	67.1
Implementation time	June 28-August 21, 2009
Injection slug (PV)	0.003
Microbe concentration	3%
Effective well ratio	67
EOR (% OOIP)	NA
Water cut reduction (%)	8.5
Input-output ratio	1 : 5.9
Effective duration time	1 year
Expansion test	Yes

5. Conclusions

Compared with thermal production, gas flooding, and other enhanced oil recovery methods, the prominent advantages of MEOR are much lower costs and more environment friendliness compared to other EOR techniques. Field tests show that the input-output ratio of microbial flooding recovery is as high as 1 : 6, with a much lower total cost than all the other EOR techniques like polymer flooding, gas flooding, and thermal production.

Indigenous microorganism flooding is the development trend with the advantages of good adaptability and avoiding of microbes' culture development and production process compared with exogenous microbial flooding.

Both laboratory and field tests have verified that the crude oil composition changed remarkably as the saturated hydrocarbon proportion increased; aromatics, nonhydrocarbon, and asphaltene proportion decreased; and the acid value increased while wax and pectin proportion decreased.

The microbial metabolism produced surface active compounds including biosurfactants, alcohol, acid, and biogases. The most common and desired biosurfactant was rhamnolipid which could reduce interfacial tension. Biogases were mostly carbon dioxide and methane, and little ethane. The acid was mainly fatty acid like methanolic acid, acetic acid, and propanoic acid.

The crude became emulsified with different extents due to effects of microbes.

Microbial products could change the wettability toward more water being wet and also reduce formation permeability remarkably. The microbial profile control mechanism could be accounted into one or all the mechanisms including microbes forming a reticular biofilm in porous media, precipitation of the colony, and formation of a bridge plug due to absorption of other microbes, the biogas block effects.

The basis for microorganisms consuming crude oil to enhance oil recovery was its ability to automatically search for carbon source and directionally migrate. Microbial effects on remaining oil could be ordered ranked in a descending order as island remaining oil, membranaceous remaining oil, columnar remaining oil, blind end remaining oil, and cluster remaining oil.

Application of a high-resolution mass spectrum (HRMS) on MEOR mechanism has revealed the change of polar compound structures before and after oil degradation by the microbe on the molecular level.

The reservoir screening parameters include temperature, salinity, oil viscosity, permeability, porosity, wax content, water cut, and microorganism concentration in which production fluid, temperature, and salinity were the three most important parameters. It is possible to use MFR in a reservoir with permeability as low as 5 mD.

Microbial flooding recovery field tests in China show that MRF is close to commercial application, since a high incremental oil recovery of 4.95% OOIP was attained with a typical 0.1 PV slug. Three typical reservoirs with detailed MFR field tests data were reviewed for possible guide for similar reservoirs.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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