Kinetic Model and Numerical Simulation of Microbial Growth, Migration, and Oil Displacement in Reservoir Porous Media

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ABSTRACT: Microbial enhanced oil recovery (MEOR) is a potential tertiary oil recovery method. However, past research has failed to describe microbial growth and metabolism reasonably, especially quantification of reaction equations and operating parameters is still not clear. The present study investigated the ability of bacteria extracted from Ansai Oilfield for MEOR. Through core flooding experiments, bacteria-treated experiments produced approximately 6.28−9.81% higher oil recovery than control experiments. Then, the microbial reaction kinetic model was established based on laboratory experimental data and mass conservation. Furthermore, the proposed model was validated by matching core flooding experiment results. Lastly, the effects of different injection parameters on bacteria growth, bacteria migration, metabolite migration, residual oil distribution, and oil recovery were studied by establishing a field-scale model. The results indicate that the injected bacteria concentration and nutrient concentration have a great influence on bacteria growth in a reservoir and the low nutrient concentration seriously restricts bacteria growth. Compared with the injected bacteria concentration, nutrient concentration has a decisive effect on bacteria and metabolite migration. The injected bacteria concentration has little effect on oil recovery, while nutrient concentration and slug volume have a significant effect on oil recovery.
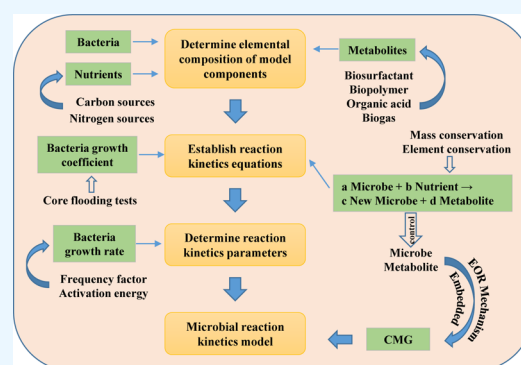
1. INTRODUCTION

Primary oil recovery, the process in which simple drilling and pressure differences are used to capture the gushing oil,

Table 1. Functions of Bacteria and Its Products in EOR

bacteria and products	example microbes	functions
bacteria	*Pseudomonas*	wettability alteration and oil degradation
biomass	*Bacillus, Leuconostoc, Xanthomonas*	selective plugging and wettability alteration
biosurfactants	*Acinetobacter, Arthrobacter, Bacillus, Pseudomonas*	emulsification and de-emulsification through reduction of IFT
biopolymers	*Bacillus, Brevibacterium, Leuconostoc, Xanthomonas*	viscosity enhancement
organic acids	*Clostridium, Enterobacter, mixed acidogens*	permeability increase and emulsification
biogases	*Clostridium, Enterobacter, Methanobacterium*	increased pressure, oil swelling and viscosity reduction

harvests only 5−10% of the original oil in place (OOIP), and the secondary oil recovery through water injection recoups about 10−40% of the OOIP (Patel et al.).[1] It is estimated that 50−85% of crude oil remains untouched. Microbial enhanced

oil recovery (MEOR) is one of the traditional tertiary oil recovery methods that are easy to be applied in oil fields and has a comparably low environmental impact (Kobayashi et al.; Song et al.; Alkan et al.).[2−4] Furthermore, MEOR has a further economic benefit because it requires only little investments in surface facilities and allows the use of cheap industrial byproducts such as molasses, which are independent of the price of crude (Sen; Kaster et al.; Simpson et al.).[5−7] However, MEOR processes can be quite complex and involve multiple biochemical process steps. Bacteria in the reservoir can produce biomass, biosurfactants, biopolymers, organic acids, and biogases (Sen).[5] The specific functions of bacteria and its products in enhancing oil recovery are shown in Table 1.

Research on MEOR simulation and modeling began in the 1980s. Updegraff used a filtration model to describe the relationship between bacteria migration and pore entrance size.[8] Jenneman et al. established the relationship between
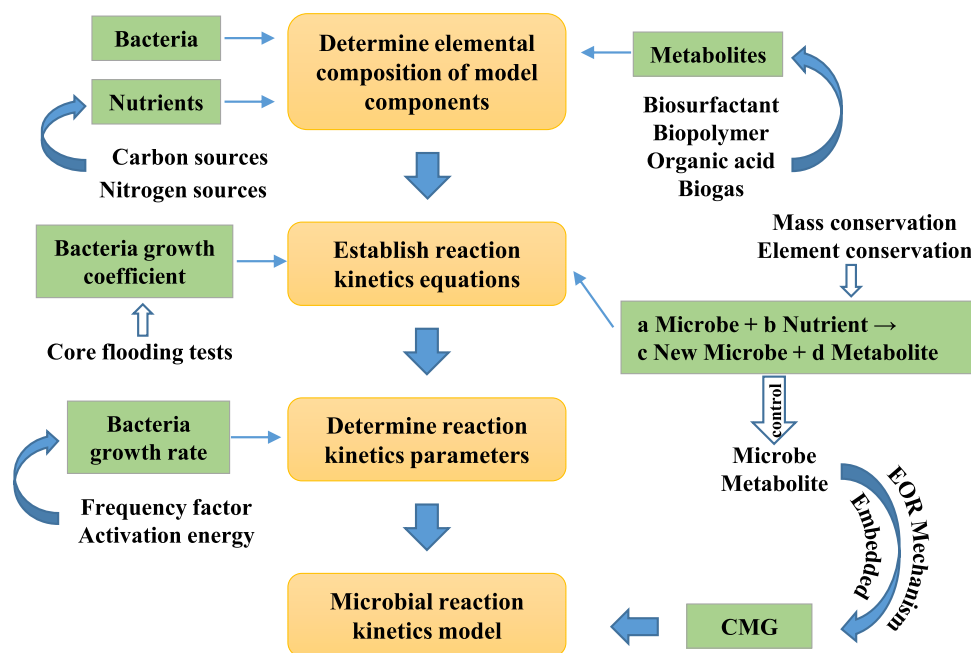
Figure 1. Flow chart of the MEOR numerical simulation model.

permeability and bacteria penetration using modified filtration theory.[9] Knapp et al. modeled the growth and migration of bacteria in porous formations.[10] Islam et al. described bacteria migration in a multidimensional porous medium by developing formulations including bacteria plugging and reduction of oil viscosity and interfacial tension.[11] Chang et al. developed a three-dimensional, three-phase, and multiple-component numerical model to describe the bacteria migration phenomenon.[12] Desouky et al. developed a five-component (oil, water, bacteria, nutrients, and metabolites) model considering adsorption, chemotaxis, diffusion, growth, and decay of bacteria, permeability damage, nutrient consumption, and porosity reduction effects.[13] Lei et al. established a three-dimensional three-phase and multicomponent numerical model including microbial growth, reproduction and migration, substrate consumption, product generation, and fluid and rock properties changes.[14] Lacerda et al. established a one-dimensional isothermal model with more comprehensive factors and performed the sensitivity analysis.[15] With the development of computers, the focus has been geared toward combining these mathematical models with commercial simulators such as CMG, ECLIPSE, MRST, and UTCHEM. For instance, Spirov et al. used ECLIPSE to simulate the ability of anaerobic gas-producing bacteria in MEOR, and the best results showed that the increase in oil recovery was 21%.[16] Bueltemeier et al. used CMG software to model the MEOR process, considering the effects of reducing interfacial tension by biosurfactant, increasing water viscosity by biopolymer, selective plugging of biomass, and reducing crude oil viscosity by biogas on enhanced oil recovery.[17] Ansah et al. investigated the ability of a thermophilic microbe for MEOR with CMG-Stars and matched the laboratory data using artificial intelligence.[18] Moreover, Ghasemi et al. simulated a two-phase system using MRST, focusing on the role of biopolymers in MEOR.[19] Numerous studies have shown that it is feasible to use commercial reservoir simulators to predict the MEOR process. Unfortunately, the previously established numerical model failed to describe microbial growth and metabolism

reasonably, and especially the quantification of reaction equations and operating parameters is still not clear.

Thus, the aim of this study is to qualify reaction equations and operating parameters in the MEOR process. Based on the principle of environmental engineering and science, laboratory experimental data, and numerical simulation, the MEOR process was modeled. Also, we analyzed bacteria growth and each component migration mechanism in the MEOR model and simulated the effect of various injection parameters on bacteria growth, metabolite migration, residual oil distribution, and oil recovery with the hope to provide a reference for the application of MEOR in the field.

2. METHODS AND MATERIALS

2.1. Numerical Simulation Model. Figure 1 shows the microbial reaction kinetics modeling process, which includes determining the elemental composition of model components, establishing reaction kinetics equations, and determining the

Table 2. Elemental and Macromolecular Composition of Bacteria

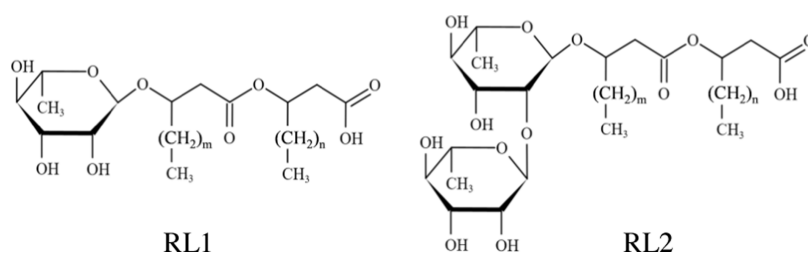| components	value (%)	macromolecular	value (%) (dry cell)
H_2O	75	protein	50−60
dry matter	25	carbohydrate	10−15
organic matter	90	phospholipid	6−8
C	45−55	nucleic acid	
O	22−28	DNA	3
H	5−7	RNA	15−20
N	8−13		
inorganic matter	10		
P_2O_5	50		
K_2O	6.5		
Na_2O	10		
MgO	8.5		
CaO	10		
SO_3	15		

Figure 2. Generalized structures of monorhamnolipids and dirhamnolipids.
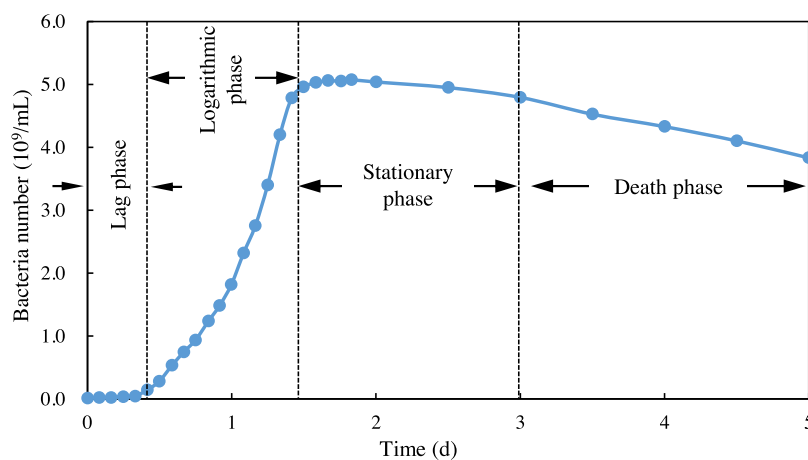

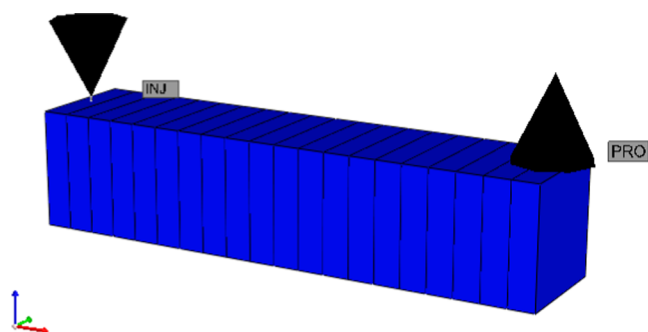**Figure 3.** Bacteria growth curve.

Figure 4. One-dimensional homogeneous geological model.

reaction kinetics parameters and the microbial reaction kinetics model. Moreover, the following model assumptions are made.

- Bacteria growth is not affected by temperature, only controlled by the bacteria growth rate constant.
- Considering bacteria adsorption but neglecting the plugging porous medium by bacteria.
- The lag phase of bacteria growth is not considered.
- There is no volume change upon mixing.
- The reservoir fluid is slightly compressible.

2.1.1. Bacteria Reaction Model. During the core flooding experiments, the injected nutrients are used for the reproduction of new bacteria, and the other parts are used for the synthesis of metabolites (Liu).[20] Then, this process is represented in CMG-Stars by eq 1.

$$a \text{ microbe} + b \text{ nutrient} \rightarrow c \text{ new microbe} + d \text{ metabolite} \tag{1}$$
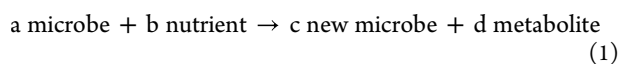
To quantify the component partition coefficient, the elemental composition of the components (microbe, nutrient, metabolite) must be determined. The elemental composition

Table 3. Simulation Model Data

	A	B	C	D (control)
core properties				
reservoir size (cm)		10 × 2.215 × 2.215		
number of grid blocks		20 × 1 × 1		
grid block size (cm)		0.5 × 2.215 × 2.215		
porosity		0.23		
pore volume (mL)		11.28		
permeability (mD)		75.5		
oil viscosity (mPa·s)		1.91		
initial oil saturation (%)		73.85		
initial water saturation (%)		26.15		
reservoir temperature (°C)		45		
injection data				
injection rate (mL/min)		0.2		
water flooding		water content reached 70%		until no oil
bacteria flooding	0.3PV	0.45PV	0.6PV	
shut-in (days)	3	3	3	
water flooding	until no oil			

of bacteria is complex and difficult to describe. To simplify the bacteria reaction, the elemental composition of bacteria is usually represented by C, H, O, and N. The empirical molecular formula of bacteria is very effective in mass balance calculation and the classical form of the empirical molecular formula of bacteria is $C_5H_7O_2N$ (Eckenfelder et al.).[21] The elemental and macromolecular compositions of bacteria are shown in Table 2.

Table 4. Blast Result of the Tested Bacteria Strains 16S rDNA

tested bacteria Strain		reference strain			
strain name	accession no.	genus species	accession no.	homology (%)	identification result
Cq-1	KJ782614	*Pseudomonas veronii*	CIP 104663	99.93	*Pseudomonas*
Cq-2	KJ782615	*Enterobacter xiangfangensis*	10−17	99.78	*Enterobacter*
Cq-3	KJ782616	*Bacillus licheniformis*	ATCC 14580	98.86	*Bacillus*

Table 5. Composition of the Formation Water

	composition (mg/L)					
pH	HCO_3^-	Cl^-	Ba^{2+}	Ca^{2+}	Mg^{2+}	$K^+ + Na^+$
6.8	80	56 380	650	21 000	80	13 000

Table 6. Data of the Core Flooding Experiments

	A	B	C	D (control)
core properties				
core length (cm)	10.02	10.00	10.03	10.02
core diameter (cm)	2.50	2.52	2.51	2.51
porosity	0.23	0.22	0.24	0.21
pore volume (mL)	11.31	10.97	11.91	10.41
permeability (mD)	75.5	96.7	96.7	80.4
oil viscosity (mPa·s)	1.91 at 45 °C			
initial oil saturation (%)	73.85	67.16	78.30	73.24
flooding experiments				
injection rate (mL/min)	0.2			0.2
water flooding	water content reached 70%			until no oil
bacteria flooding	0.3PV	0.45PV	0.6PV	
shut-in (days)	3			
water flooding	until no oil			

Nutrients include carbon sources and nitrogen sources. To simplify the reaction process, glucose ($C_6H_{12}O_6$) is assumed to be the carbon source and ammonia (NH_5O) is assumed to be the nitrogen source (Ashish et al.; Darvishi et al.).[22,23]

Three strains Cq-1 (*Pseudomonas*), Cq-2 (*Enterobacter*), and Cq-3 (*Bacillus*) were isolated from soil samples contaminated by crude oil in Ansai Oilfield. The main metabolites of *Pseudomonas*, *Enterobacter*, and *Bacillus* are biosurfactants and organic acids (Santos et al.; Ke et al.).[24,25] Rhamnolipid (RL1) is assumed to be a biosurfactant. The structure of RL1 with the classic molecular formula of $C_{32}H_{58}O_{13}$ is shown in Figure 2 (Muller et al.; Maier et al.).[26,27] Formic acid is assumed to be an organic acid, and the molecular formula is CH_2O_2 (Kogler et al.; Kraan et al.; Magot et al.).[28−30] According to mass and element conservation, bacteria growth is represented by the following equations after injection of the bacteria and nutrients.

$$C_5H_7O_2N + C_6H_{12}O_6 + a\ NH_5O$$
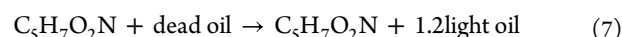$$\rightarrow \left(1 + \frac{6}{5}Y'\right)C_5H_7O_2N + \frac{6}{32}Y''\ C_{32}H_{58}O_{13} + 6Y''$$
$$CH_2O_2 + b\ H_2O \tag{2}$$
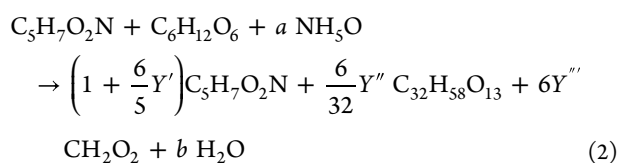
$$a = 1.2Y' \tag{3}$$

$$b = 4.425Y' + 0.375 \tag{4}$$

$$Y'' = \frac{2(1 - Y')}{3} \tag{5}$$

$$Y''' = \frac{1 - Y'}{3} \tag{6}$$

where a is the reaction coefficient of nitrogen sources, Y' is the bacteria growth coefficient, Y'' is the biosurfactant production coefficient, Y''' is the organic acid production coefficient, and b is the reaction coefficient of water.

The crude oil is degraded by bacteria following eq 7 and the death of bacteria is represented by eq 8. The molecular weights of dead oil and light oil in eq 7 are 600 and 500 g/mol, respectively.

$$C_5H_7O_2N + \text{dead oil} \rightarrow C_5H_7O_2N + 1.2\text{light oil} \tag{7}$$

$$C_5H_7O_2N \rightarrow 6.278H_2O \tag{8}$$

2.1.2. Determining Reaction Parameters. Arrhenius equation was used to describe the growth rate of bacteria (Huang et al.) as shown in eq 9.[31] In this study, the influence of temperature changes on bacteria growth was not considered (temperature is constant), and the reaction frequency factor was used to describe the bacteria growth rate.

$$\mu_{max} = A\ e^{-E_a/RT} \tag{9}$$

where μ_{max} is the bacteria maximum growth rate (day^{-1}), A is the frequency factor, R is the molar gas constant ($J\cdot mol^{-1}\cdot K^{-1}$), T is the reaction temperature (K), and E_a is the activation energy ($kJ\cdot mol^{-1}$).

To determine the bacteria growth rate, bacteria culture experiments were carried out. Also, the bacteria growth curve is shown in Figure 3.

During the logarithmic phase of bacteria, bacteria culture follows a first-order chemical reaction. The bacteria growth rate is proportional to the number of bacteria present at that time, which can be described by the following equation.

$$dN/dt = \mu N \tag{10}$$

After integration

$$\ln N_t - \ln N_0 = \mu t \tag{11}$$

where N is the bacteria number, t is the time (day), μ is the bacteria growth rate (day^{-1}), N_t is the bacteria number at time t, and N_0 is the bacteria number at the beginning.

According to the matching of the bacteria logarithmic phase, the bacteria growth rate was 2.60 day^{-1} ($R^2 = 0.9937$).

2.1.3. EOR Mechanism. Due to the complex oil recovery mechanism of bacteria and reservoir uncertainty, it is very difficult to describe the whole MEOR process. In this paper, MEOR modeling of bacteria from Ansai Oilfield was carried out. First, the bacteria in Ansai Oilfield were identified, mainly composed of *Pseudomonas*, *Enterobacter*, and *Bacillus*, whose main metabolites were biosurfactants and organic acids. Then, according to the mass and element conservation, the bacteria growth and metabolism were established. In this paper's model, the mechanism of bacteria oil recovery included the viscosity reduction of oil by bacteria, the reduction of oil−
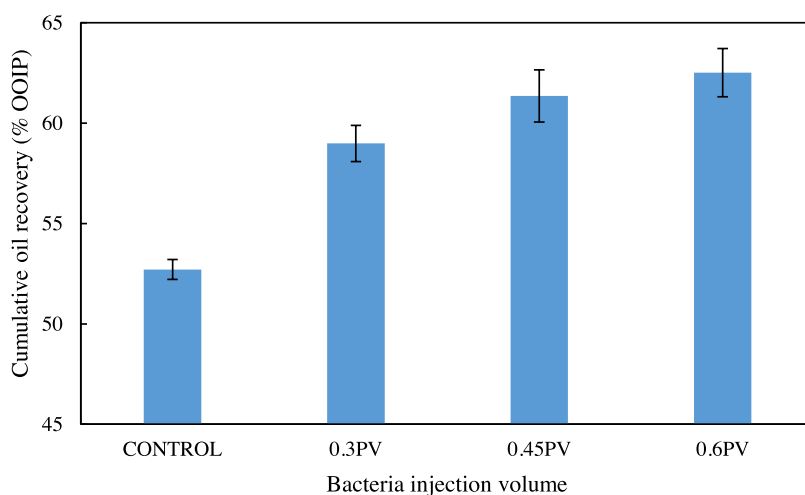
Figure 5. Cumulative oil recovery of core flooding experiments.
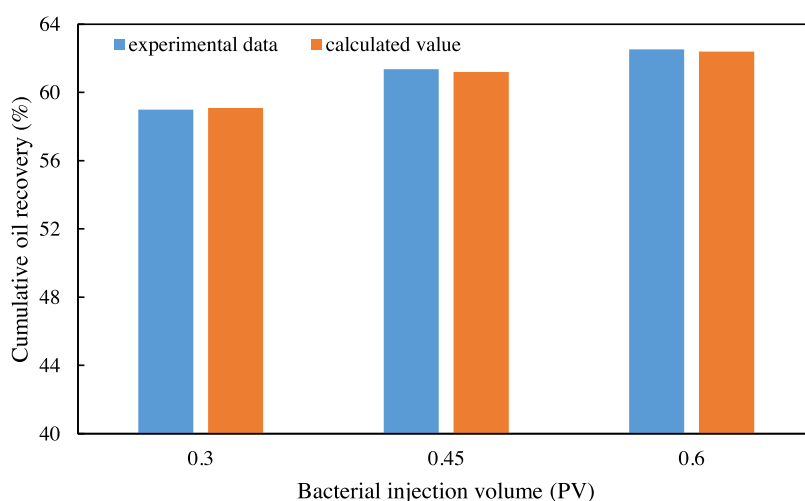

Figure 6. History matching of laboratory data.

water interfacial tension by biosurfactant, and the improvement in permeability by organic acid. The EOR mechanisms used in the model were embedded in the CMG based on laboratory data. Moreover, changing the bacteria growth coefficient and metabolites production coefficient could control the yield of bacteria and metabolites. Also, combined with CMG-related modules, the oil recovery was influenced.

2.1.4. Core-Scale Model. In this study, according to the core model data (equal cross-sectional area), a one-dimensional reservoir model was established with a scale of 10 cm × 2.215 cm × 2.215 cm and the grid system was 20 × 1 × 1 with a total of 20 grids, as shown in Figure 4. An injection well was in the first grid and the injection rate was 0.2 mL/min (both the mass fraction of bacteria and nutrients is 3%); a production well was in the last grid and produced at atmospheric pressure. The production properties and other reservoir properties of the simulation model were derived from the core flooding model (Table 3).

2.2. Experimental Section. *2.2.1. Bacteria Strain Type and Petroleum Fluids.* Three strains (Cq-1, Cq-2, Cq-3) were isolated from soil samples contaminated by crude oil in Ansai Oilfield. As shown in Table 4, through 16S rDNA analysis, the three strains were identified as *Pseudomonas*, *Enterobacter*, and *Bacillus*. The 16S rDNA analysis was performed at GenScript

Company in Nanjing. The crude oil sample from Ansai Oilfield was used for core flooding experiments (viscosity 1.91 mPa·s, measured at 45 °C).

2.2.2. Bacteria Cultivation. Bacteria strains were inoculated into a medium and incubated with shaking at 150 rmp and 45 °C for 48 h. Unless otherwise specified, the composition of the medium is canola oil (0.8%, w/v), yeast extract (0.2%, w/v), glucose (1.5%, w/v), and ammonium (0.5%, w/v). The composition of the formation water is shown in Table 5.

2.2.3. Core Flooding Experiments. The specific methods of core flooding experiments are as follows: (1) The core samples were dried and then saturated by formation water to establish the water wettability, and their porosity was measured. (2) The core samples were mounted in a Hassler-type core holder to measure their permeability. (3) The core samples were flooded with crude oil until there was no residual water, and the initial oil saturation and irreducible water saturation were calculated. (4) The core samples were flooded with formation water (the rates were set at 0.2 mL/min), and oil production and water production were recorded. Moreover, when the outlet water content was about 70%, the formation water flooding was stopped. (5) 0.3PV, 0.45PV, and 0.6PV of bacteria colonies cultivated (the contents of bacteria and nutrients were 3%) were injected into the core. Afterward, the production well was

shut-in for 3 days at 45 °C to allow bacteria reproduction and metabolite production. (6) Then, formation water flooding was performed until no more oil was produced, and oil production and water production were recorded. The data of the core flooding experiments are listed in Table 6.

3. RESULTS AND DISCUSSION

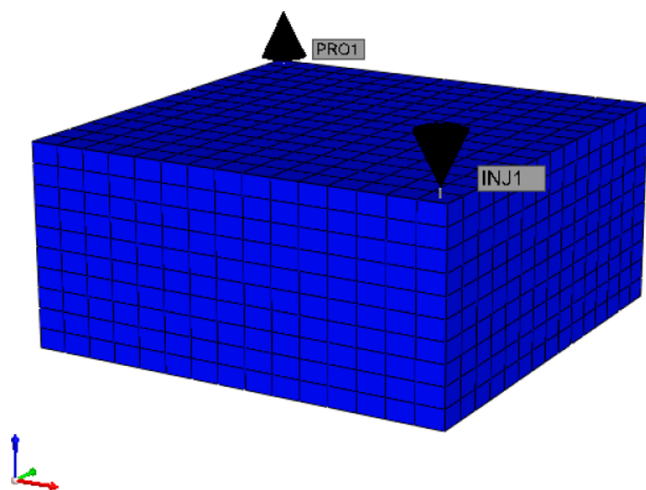**3.1. Core Flooding Experiments.** The core flooding experiments were designed to evaluate the effectiveness of

Figure 7. Three-dimensional field-scale geological model.

Table 7. Three-Dimensional Field-Scale Geological Model Data

reservoir properties	
reservoir size (m)	$150 \times 150 \times 10$
number of grid blocks	$15 \times 15 \times 10$
grid block size (m)	$10 \times 10 \times 1$
porosity	0.23
permeability (mD)	75.5
oil viscosity (mPa·s)	1.91
initial oil saturation (%)	73.85
initial water saturation (%)	26.15
reservoir temperature (°C)	45
bacteria properties	
maximum growth rate of bacteria (day^{-1})	2.52
bacteria growth coefficient	0.775
biosurfactants production coefficient	0.15
organic acid production coefficient	0.075
injection data	
injection rate (m^3/day)	20
mass fraction of bacteria (%)	3
mass fraction of nutrients (%)	3
water flooding	water content reached 90%
bacteria flooding	0.075PV
water flooding	until no oil

bacteria flooding extracted from Ansai Oilfield and provide experimental data for the numerical simulation model. As shown in Figure 5, the water flooding (control) experiment resulted in 52.71% of recovered oil, which meant that 47.29% of the oil remained trapped inside the core. Compared with the control, the core flooding experiments of bacteria (0.3PV,

0.45PV, 0.6PV) can result in 58.99, 61.63, and 62.52% oil recovery.

3.2. Model Verification. Equation 2 describes the bacteria growth model; moreover, the bacteria growth coefficient needs to be determined to further quantify the model. The water flooding (control) has a fairly good match by adjusting the relative permeability and residual oil saturation. Then, CMG-Stars with CMOST is used to simulate oil recovery of different bacteria growth coefficients, biosurfactant production coefficient, and organic acid production coefficient. According to the bacteria growth and metabolism equation, changing the bacteria growth coefficient and metabolite production coefficient can control the yield of bacteria and metabolites. Also, combined with CMG-related modules, oil recovery is influenced. As shown in Figure 6, when the bacteria growth coefficient, biosurfactant production coefficient, and organic acid production coefficient were 0.775, 0.15, and 0.075, respectively, the simulated oil recovery matched the core flooding experiments best ($R^2 = 0.9994$).

3.3. Field-Scale Model. The MEOR mechanisms are created as a result of a reaction of bacteria with nutrients (Alkan et al.).[4] To describe the growth and migration of bacteria, nutrients, and metabolites (biosurfactant and organic acid) within the reservoir, a five-point model (field scale) was developed, as shown in Figure 7. A summary of all parameters used to simulate the process can be found in Table 7 (basic model data). For the three-dimensional field-scale geological model, first, water flooding was processed until the production well reached 90% (water content). Then, 0.075PV of bacteria slug was injected into the reservoir. Finally, water flooding was performed until no more oil was produced.

3.4. Bacteria Growth Characteristics and Influence Factors. To have a detailed understanding of the growth characteristics of bacteria in a reservoir during the MEOR process, the mass fraction of bacteria in formation water was taken as an evaluation index to study the effects of injected bacteria concentration, injected nutrients concentration, and injection volume on the growth of bacteria.

3.4.1. Effect of Injected Bacteria Concentration. Figure 8 shows the bacteria growth in a reservoir at different injected bacteria concentrations. The concentration of injected bacteria is changed from 1 to 5% (mass fraction) and other parameters are the same as the basic model. After the injection of bacteria and nutrients, the bacteria begin to reproduce rapidly. Also, the bacteria growth curve is similar to the shake-flask cultivation (Ke et al.).[25] During the process of bacteria flooding, the bacteria growth rate gradually decreases and the total bacteria amount in the reservoir reaches the maximum at the end of bacteria flooding. When the injected bacteria concentrations are 1, 3, and 5%, the maximum bacteria mass fractions in the reservoir are 0.072, 0.099, and 0.124%, respectively. During the second water flooding, the bacteria mass fraction decreases rapidly due to adsorption and death (half-life control). The results indicate that the higher concentration of the injected bacteria leads to higher bacteria mass fraction in the formation water. Song et al. obtained similar experimental results in a core flooding experiment.[32]

3.4.2. Effect of Injected Nutrient Concentration. In this part, the effect of injected nutrient concentration on bacteria growth was studied (changing the injected nutrient concentration and keeping other parameters consistent with the basic model). It can be observed from Figure 9 that when the injected nutrient concentration is 1, 3, and 5%, the maximum
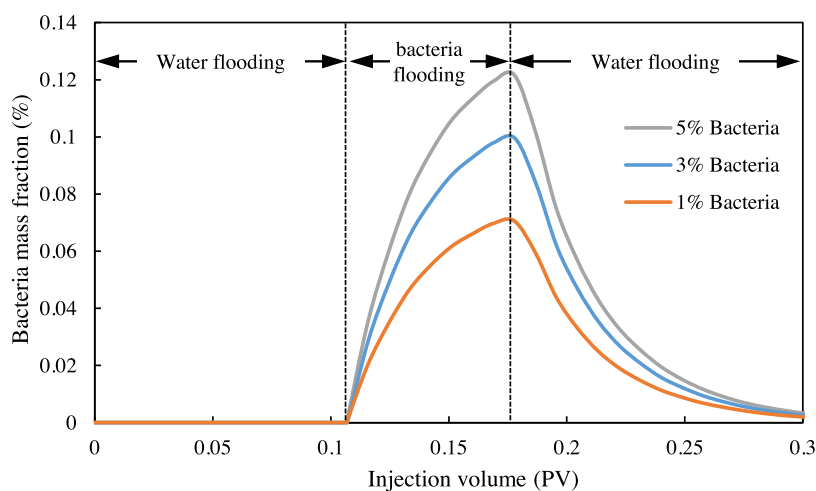
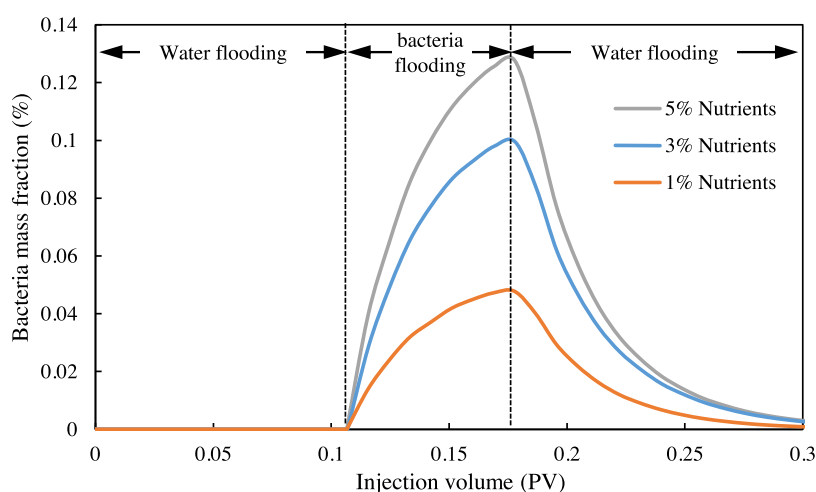**Figure 8.** Effects of injected bacteria concentration on bacteria growth.

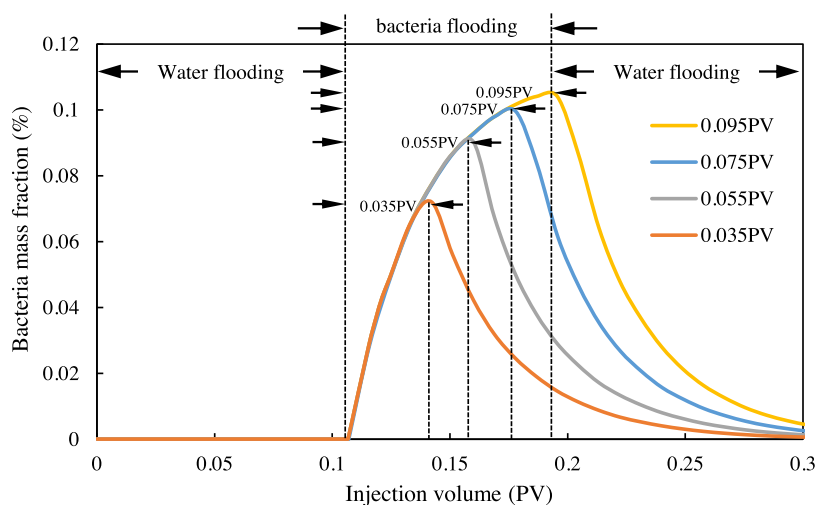**Figure 9.** Effects of injected nutrient concentration on bacteria growth.

Figure 10. Effects of injected bacteria and nutrient volume on bacteria growth.

bacteria mass fraction in the reservoir is 0.049, 0.099, and 0.129%, respectively. Compared with Figure 8, the injected nutrient concentration has a greater impact on bacteria growth than the injected bacteria concentration (Ghasemi et al.).[19] When the nutrient content is 1%, the growth of bacteria is severely restricted (Sugai et al.).[33] In other words, simply injecting high bacteria concentration cannot maintain a high level of bacteria in a reservoir.

3.4.3. Effect of Injected Bacteria and Nutrient Volume. In this part, the effect of different injection slug volumes on
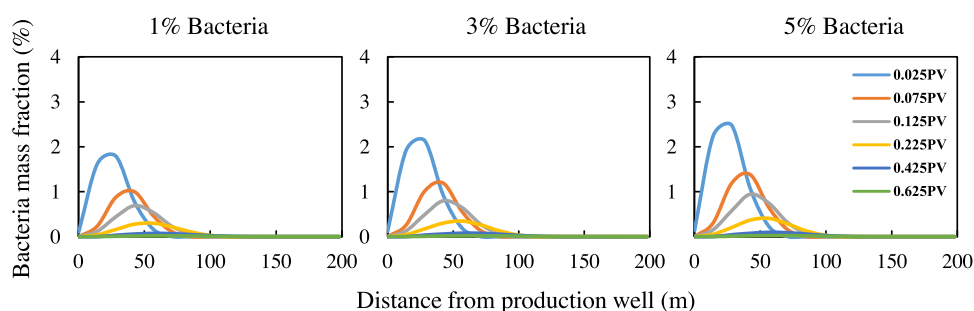
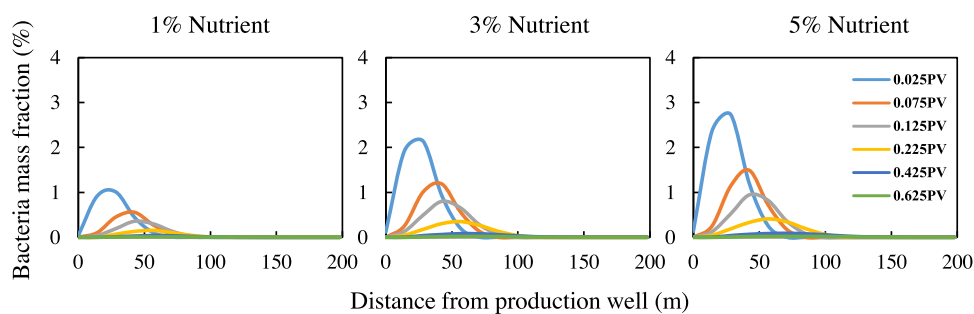**Figure 11.** Effects of injected bacteria concentration on bacteria migration.

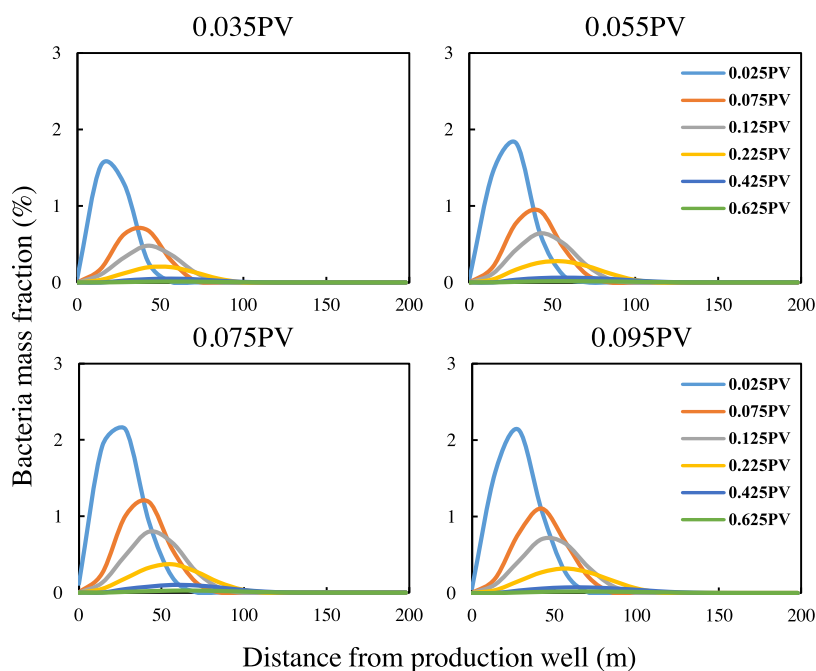**Figure 12.** Effects of injected nutrient concentration on bacteria migration.

Figure 13. Effects of injected slug volume on bacteria migration.

bacteria growth in the reservoir was studied. The injected slug volume of bacteria and nutrients in the basic model is 0.075PV. As shown in Figure 10, higher injected slug volume leads to higher bacteria mass fraction in the reservoir, but the growth trend has slowed. When the injected slug volume is 0.035PV, 0.055PV, 0.075PV, and 0.095PV, the maximum bacteria mass fraction in the reservoir is 0.072, 0.091, 0.099, and 0.104%, respectively. This is due to the fact that the bacteria death rate increases at higher bacteria concentrations in the reservoir. When the bacteria death rate is equal to the growth rate, the bacteria mass fraction in the reservoir does not increase.

3.5. Migration of Bacteria and Metabolites and Its Influence Factors. Various bioproducts can be produced due to bacteria growth and reproduction, such as biosurfactants, biopolymers, gases, solvents, and acids (Sen).[5] The main influencing mechanism of MEOR can be attributed to the interaction of bacteria and metabolites with crude oil (Patel et al.; Ansah et al.).[1,18] Therefore, in this part, we have studied the migration characteristics of bacteria and metabolites and their influencing factors.

3.5.1. Bacteria Migration Characteristics and Its Influencing Factors. In this part, the effects of the injected bacteria concentration, injected nutrients concentration, and injected
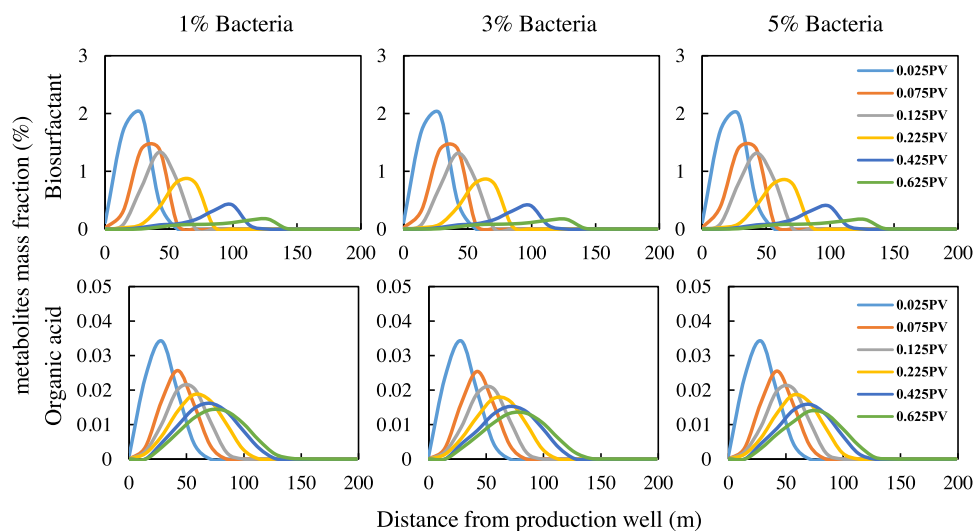
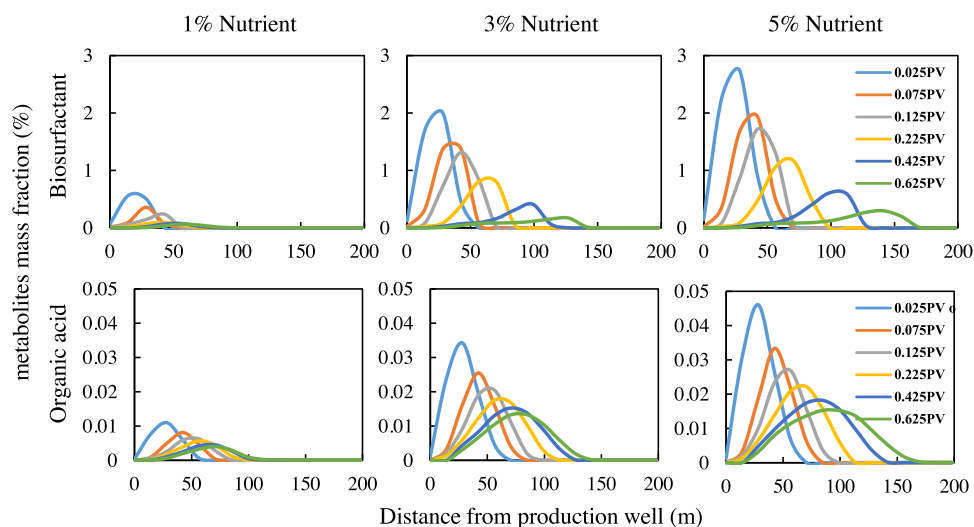**Figure 14.** Effects of injected bacteria concentration on metabolite migration.

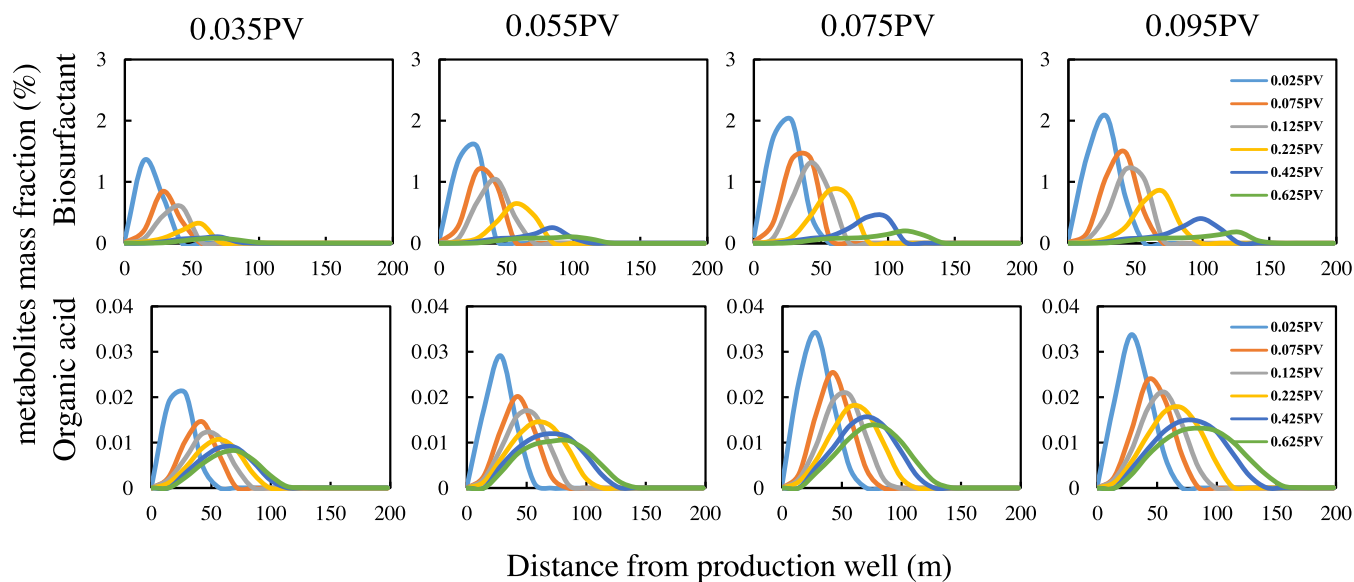**Figure 15.** Effects of injected nutrient concentration on metabolite migration.

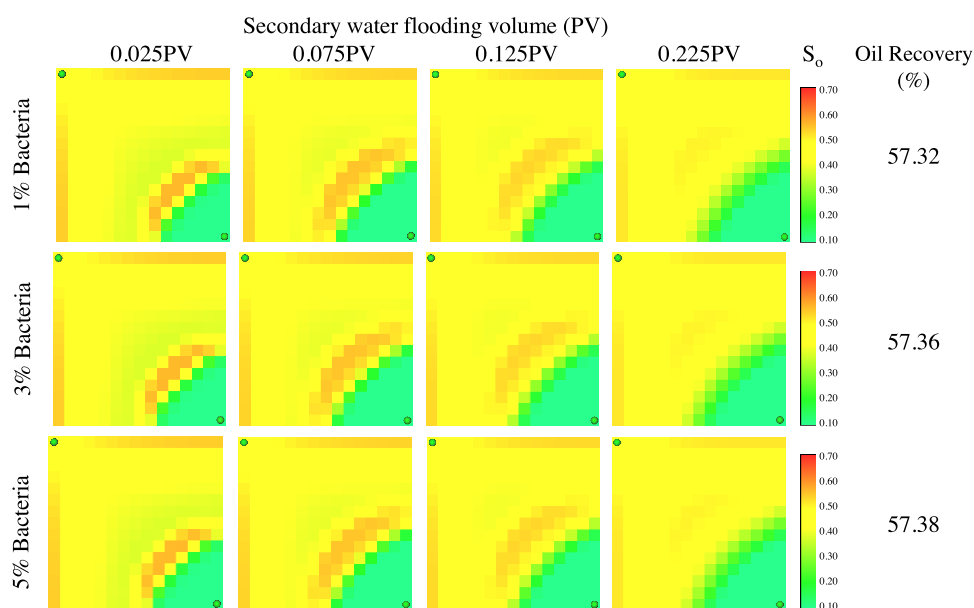**Figure 16.** Effects of injected slug volume on metabolite migration.

Figure 17. Effects of injected bacteria concentration on residual oil distribution.
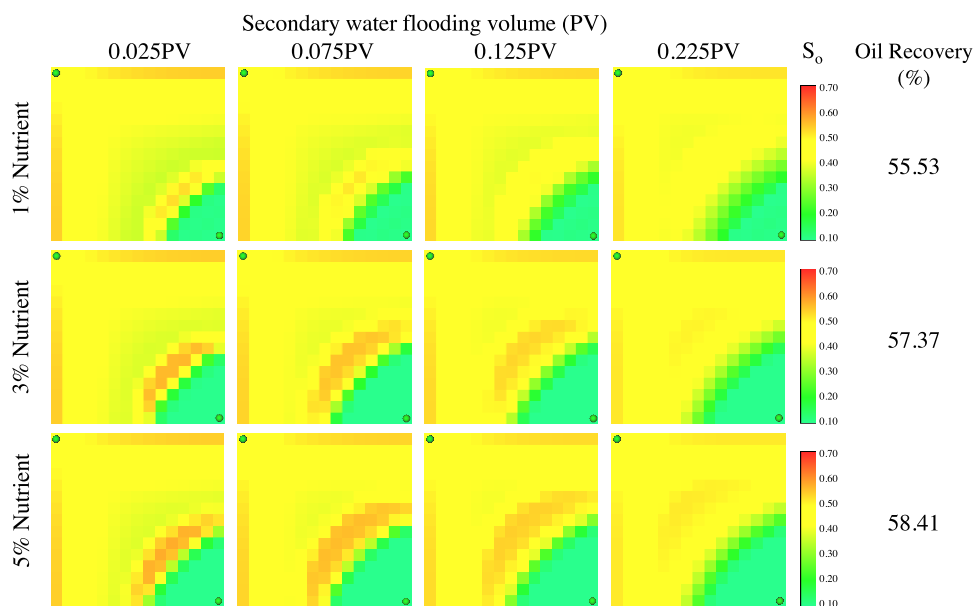

Figure 18. Effects of injected nutrient concentration on residual oil distribution.

slug volume on bacteria migration were studied. Figure 11 shows the relation between injected bacteria concentration and bacteria migration. As the injected bacteria concentration increases, the maximum bacteria concentration near the injection well increases. With the second water flooding, bacteria are pushed deeper into the formation, but the maximum concentration decreases rapidly (Ghasemi et al.).[19] This is due to the adsorption and death of bacteria. Chakraborty et al. observed a similar phenomenon by plotting the spatial and temporal distribution of bacteria.[34] Wang et al. also obtained a similar conclusion by simulating the distribution of bacteria concentration under different death rates.[35] The effect of the injected nutrient concentration on bacteria migration is shown in Figure 12. Compared with Figure 11, nutrient concentration has a greater impact on the maximum concentration of bacteria in the formation. At low

nutrient concentrations, not only is the bacteria peak concentration small but also the migration distance is short. Figure 13 shows the effect of injected slug volume on bacteria migration in the reservoir. When the injected slug increases from 0.035PV to 0.075PV, the bacteria peak concentration and migration distance in the reservoir increase evidently. However, when the injected slug increases from 0.075PV to 0.095PV, the bacteria peak concentration and migration distance are basically identical. This indicates that there is an optimal bacteria slug volume after considering economic factors.

3.5.2. Metabolite Migration Characteristics and Its Influencing Factors. The interaction between bacteria metabolites and oil has a great impact on enhanced oil recovery (Nielsen et al.).[36] In this part, the effects of bacteria concentration, nutrient concentration, and slug volume on
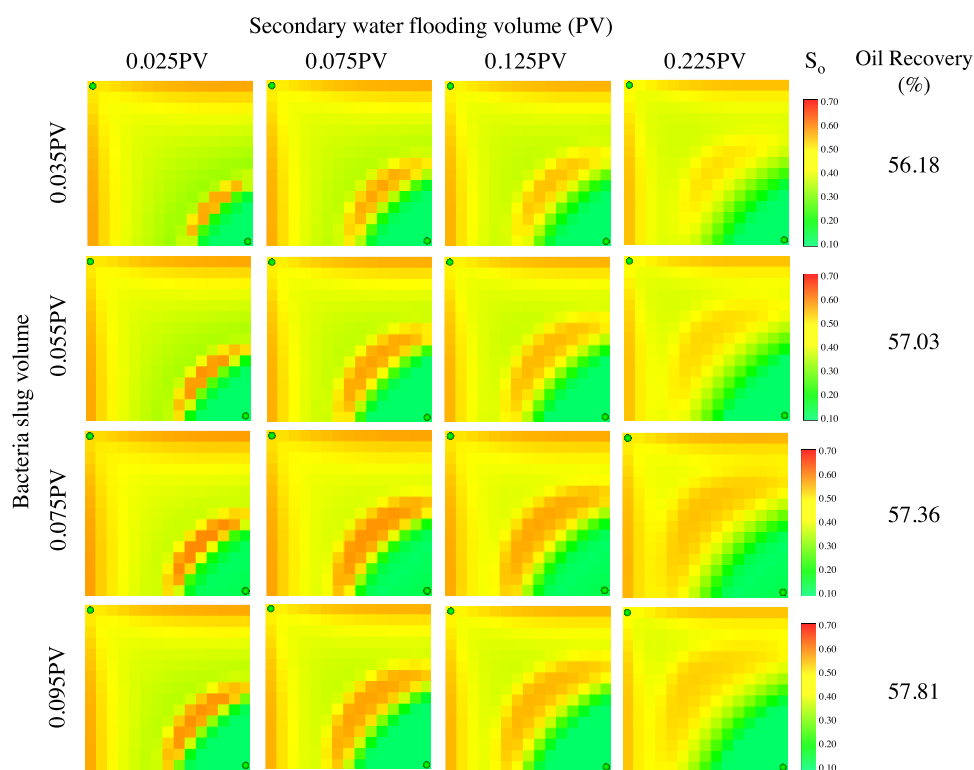
Figure 19. Effects of injected slug volume on residual oil distribution.

metabolite migration were studied. The injected bacteria concentration has no effect on metabolite migration (Figure 14). This is because the model assumes that metabolites are produced only during bacteria reproduction. Figure 15 shows the relation between injected nutrient concentration and metabolite migration. When the injected nutrients mass fraction increases from 1 to 5%, the metabolite peak concentration and the migration distance in the reservoir increase evidently. Figure 16 shows the relation between injected slug volume and metabolite migration. As the slug volume increases from 0.035PV to 0.075PV, the bacteria peak concentration and the migration distance increase obviously. However, as the slug volume increases from 0.075PV to 0.095PV, the peak concentration and the migration range keep unchanged. This indicates that the bacteria peak concentration and the migration range are limited when considering bacteria death and adsorption.

3.6 Effects of Injection Parameters on Residual Oil Distribution and Recovery Efficiency. *3.6.1. Effect of Injected Bacteria and Nutrient Concentrations.* Figures 17 and 18 show the effects of injected bacteria and nutrient concentrations on residual oil distribution and oil recovery. Increasing the nutrient concentration can obviously enlarge the residual oil zone and enhance the oil recovery compared to increasing bacteria concentration. Ghasemi et al. (2021) obtained the same conclusion by studying the sensitivity of MEOR.[19]

3.6.2. Effect of Injected Slug Volume. Figure 19 shows the relation between injected slug volume and residual oil zone and oil recovery. It can be seen that as the injection slug volume increases from 0.035PV to 0.095PV, the range and saturation of the residual oil zone increase explicitly, which means higher oil recovery.

4. CONCLUSIONS

In the present study, the MEOR model is quantified according to the principles of environmental engineering and science, laboratory experimental data, and mass conservation. The accuracy of the model is verified by the history matching core flooding experiments. Finally, a three-dimensional conceptual model of mine scale is established, and the growth and migration mechanism and sensitivity parameters of the MEOR model are studied. The following results were obtained:

(1) The results of bacteria core flooding experiments contribute to understanding the effect of *Pseudomonas*, *Enterobacter*, and *Bacillus* (extracted from Ansai Oilfield) on MEOR. Through core flooding experiments, bacteria-treated experiments produced approximately 6.28−9.81% higher oil recovery than control experiments.

(2) The injected bacteria concentration and nutrient concentration have a great influence on bacteria growth in the reservoir, and the low nutrient concentration seriously restricts bacteria growth.

(3) Compared with the injected bacteria concentration, nutrient concentration has a decisive effect on bacteria and metabolite migration.

(4) The injected bacteria concentration has little effect on oil recovery, while the nutrient concentration and slug volume have a significant effect on oil recovery.

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