Research Article

The Impact of Plane Heterogeneity on Steam Flooding Development in Heavy Oil Reservoirs

Yaguang Qu,1,2 YiPing Ye,3 Shichang Ju,4 Jiawen Liu,5 and Meng Lei1

1Petroleum Engineering College, Yangtze University, Wuhan 430100, China
2Ministry of Education Key Laboratory of Oil & Gas Resources and Exploration Technology, Wuhan 430100, China
3PetroChina Xinjiang Oilfield Company, Karamay 834000, China
4Heavy Oil Company, PetroChina Xinjiang Oilfield Company, Karamay 834000, China
5Research Institute of Petroleum Exploration and Development of Changqing Oilfield Company, CNPC, Xi’an 710018, China

Correspondence should be addressed to Yaguang Qu; qyg52122@126.com

Received 11 August 2021; Accepted 11 September 2021; Published 8 October 2021

Academic Editor: Hao Liu

Copyright © 2021 Yaguang Qu et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

Steam flooding is proven to be an effective method to improve the development effect of heavy oil reservoirs. And steam flooding is the most common oil recovery technology for heavy oil reservoirs in China. However, because of the various reservoir physical properties, bring great challenges to successful steam flooding development. According to the previous research and development practice, we know that reservoir heterogeneity has a great influence on the development effect of water flooding. Due to the heterogeneity of reservoirs, the development of different injection-production well patterns will be affected. However, it is uncertain whether reservoir heterogeneity has an impact on steam flooding development effect. In order to clarify the above scientific issues, we take Xinjiang steam flooding oilfield as the research object to carry out relevant research. According to the reservoir distribution characteristics of Xinjiang Oilfield, three conceptual heterogeneity models representing permeability, thickness, and geometric plane heterogeneity are firstly proposed. Then, mathematic models with different plane heterogeneity of reservoir sand were built. Based on the mathematic model, initial conditions, boundary condition, and geological parameters of conceptual models, different steam flooding patterns were studied by applying numerical calculation. It is found that heterogeneity is an important geological factor affecting the development of steam flooding of heavy oil reservoir. And the results showed that cumulative oil production was different of different flood pattern at the same production condition. It can be concluded that the development effect of steam flooding of heavy reservoirs is strongly influenced by flood pattern. In order to improve development effectiveness of steam flooding of heavy oil reservoirs, flood pattern should be optimized. For each type of plane heterogeneity reservoir, a reasonable flood pattern was proposed. For plane heterogeneity of permeability, thickness, and geometry form, under the conditions of that as the producer was deployed in high permeability, thick, wide sand body and injector was deployed in low permeability, thin, narrow sand body, the recovery of steam flooding in heavy oil reservoir was better. Finally, how the three types of plane heterogeneity influence steam flooding of heavy reservoirs was discussed by adopting a sensitivity analysis method. The results show that the influence of permeability heterogeneity is the largest, thickness heterogeneity is the second, and geometric heterogeneity is the least. This conclusion can help us improve the development of this reservoir. And also, the findings of this study can help for better understanding of properly deployed well pattern and how to effective develop the heavy oil reservoirs of strong plane heterogeneity for other heavy oil reservoirs.

1. Introduction

Water injection is still the most extensive and effective oilfield development method, and it is a widely used secondary oil recovery technology in the world [1]. Injected water has dual functions of oil displacement and formation energy supplement [2]. Water injection and pressure maintaining is the basic measure to ensure long-term stable production and improve oilfield development effect [3].

Therefore, people have done a lot of research on the factors that hinder and promote oil and gas production. One of the most important factors is the heterogeneity of strata,
which refers to the spatial heterogeneity changes of lithology and rock physical properties under the comprehensive action of geological processes such as sedimentation and diagenesis. Strong heterogeneity will bring considerable difficulties to oil and gas production and may lead to production loss [4, 5].

Heterogeneous reservoirs are widely distributed all over the world with low recovery. In the stage of water injection development, the injected water mainly percolates in the high permeability area. A large amount of oil left in low permeability areas cannot be effectively utilized. In addition, the long-term scouring of injected water intensifies the heterogeneity of the reservoir and greatly restricts the development performance of the oilfield [6]. According to the previous research and development practice [7–9], we know that reservoir heterogeneity has a great influence on the development effect of water flooding [10–13].

The heterogeneity of reservoirs is the key factor restricting the development performance of oilfields. Effectively improving the recovery of heterogeneous reservoirs is a common topic that people in the industry have been looking for a breakthrough. Many experts and scholars have put forward a series of technologies to further develop heterogeneous reservoirs [14].

At present, the development and utilization of heavy oil, which accounts for a large proportion of global oil resources, have attracted extensive attention [15]. Because of the high viscosity and poor fluidity of heavy oil, it is difficult to recover and requires high technology. According to the temperature-sensitive characteristics of heavy oil, a variety of heavy oil thermal recovery methods such as steam huff and puff, steam flooding, in situ combustion, and steam-assisted gravity drainage are proposed [16, 17]. The advantage of this technique over other methods is its high operability and high recovery rate. Steam injection technologies such as steam huff and puff and steam drive have been widely used in heavy oil reservoirs. And steam flooding is an effective way to improve oil recovery after steam stimulation in heavy oil reservoirs [18, 19].

It is well-known that reservoir heterogeneity has great effect for various EOR processes. This also applies to steam flooding in heavy oil reservoirs. Most heavy oil reservoirs have heterogeneity. These characteristics bring technical difficulties and cost challenges to the development of heavy oil [20, 21]. The formation heterogeneity and the mobility difference between heavy oil and steam are the main reasons for steam channeling in high permeability formation [22]. In addition, long-term steam injection will lead to the formation of steam channel, aggravate the heterogeneity of heavy oil reservoir, and significantly increase the permeability of heavy oil reservoir and poor steam injection effect [23].

In China, most heavy oil reservoirs are characterized by continental clastic deposition. Reservoir heterogeneity of continental sedimentary reservoir was very strong [24]. Reservoir heterogeneity includes plane and vertical heterogeneity. Plane heterogeneity was resulted from fast variations of fluvial facies, which mainly includes permeability, thickness, and geometric form of reservoir sand.

Based on previous researches, steam flooding was proven to be an effective method to improve recovery of heavy oil reservoirs [25]. Steam flooding was the method in which high pressure wet steam with suitable dryness fraction was injected into heavy oil reservoir. The temperature of reservoir increased after steam injection. The viscosity of crude oil would decline [26]. So the mobility ratio of water and oil can be effectively improved. The displacement efficiency and sweep efficiency are greatly increased [27]. Previous studies on steam flooding development of heavy oil reservoirs mostly focused on the mechanism of steam flooding to enhance oil recovery [28, 29]. And why can steam flooding greatly improve the recovery of heavy oil reservoir? At the same time, experts also show greater interest in the optimization of injection and production parameters of heavy oil steam flooding [30]. Some heavy oil recovery technologies with higher recovery efficiency have also been developed in combination with steam flooding [31–33].

Thus, the influence of reservoir heterogeneity on the development effect of heavy oil steam flooding is ignored. But due to the plane heterogeneity of reservoir sand, the recovery of steam flooding would be affected. Previous studies mainly focused on the plane heterogeneity of permeability for water flooding sandstone reservoirs. But the impact of plane heterogeneity reservoir sand for steam flooding heavy oil reservoir was less discussed. In this paper, we mainly focus on the development of reservoir heterogeneity on heavy oil. In order to clarify the above scientific issues, we take Xinjiang steam flooding oilfield as the research object to carry out relevant research. Firstly, according to the reservoir distribution characteristics of Xinjiang Oilfield, three conceptual heterogeneity models representing permeability, thickness, and geometric plane heterogeneity are firstly proposed. Secondly, mathematic models with different plane heterogeneity of reservoir sand were built. Based on the mathematic model, initial conditions, boundary condition, and geological parameters of conceptual models, the development effects of different injection production well patterns under different heterogeneous conditions are studied by reservoir numerical simulation method. Then, reasonable injection-production well pattern deployment scheme is proposed. Finally, based on sensitivity analysis, it is clear which kind of heterogeneity has the greatest influence on the development effect of heavy oil steam flooding.

2. Plane Heterogeneity and Conceptual Model

2.1. Plane Heterogeneity of Permeability, Geometry Form, and Thickness of Reservoir Sand. In general, the plane heterogeneity refers to the change of geometry form, scale, continuity, porosity, and permeability of reservoir sand in the plane. Although residual oil distribution and development efficiency of reservoir were constrained by well deployment and layer division criterion, the plane heterogeneity was the main internal factors. Regarding continental sedimentation reservoirs in China, especially the complicated fault-block reservoir, the plane and vertical heterogeneity were serious. Heterogeneity of reservoir sand has a rather great effect on its exploitation. And there have so many
methods to study the heterogeneity of reservoir sand. For example, the lamination factor, the sandstone density, and the overlap coefficient describe the sand body growth and the distribution. And also, reservoir heterogeneity was studied by using log data and digital pressing achievement, size analyses, cast sections, water injection profile data, and SEM. In this paper, plane heterogeneity of permeability, geometry form, and thickness of reservoir sand were discussed.

2.2. The Conceptual Model of Plane Heterogeneity. The heavy oil reservoir in Xinjiang Oilfield is delta front subfacies depositional system. According to the results of single well logging interpretation of the reservoir, it was found that the difference of reservoir’s property of different sedimentary microfacies was great. Due to the complicated geological condition, the permeability, geometry form, and thickness of reservoir sand were complicated. So it is difficult to do theoretical research. Based on the distribution characteristics of microfacies of Xinjiang Oilfield in China, the plane heterogeneity of reservoir was simplified. And the simplified distributed modes were proposed to indicate plane heterogeneity which including permeability, geometry form, and thickness of reservoir sand. The distribution of reservoir sand can be simplified as the concept model shown in Figure 1, for which to study the impact of permeability, geometry form, and thickness of reservoir sand on the law of fluid flow. The conceptual model assumed that reservoir sand consisted of two sands of different permeability, width, and thickness.

Conceptual model (a) represented permeability heterogeneity of reservoir. In the model, gray and white quadrangles indicated the sand bodies which formed in different sedimentary microfacies. And the area and thickness of the two sand bodies were the same. But permeability of the two sand bodies was different. It can be assumed that the permeability of the right sand was high and that of the left sand was low. If the permeability difference of two sand bodies was high, it showed serious heterogeneity of permeability in the reservoir. Conceptual model (b) represented geometry form heterogeneity of reservoir. In this model, gray and white quadrangles also depicted the sand bodies which formed in different sedimentary microfacies. And the thickness and permeability of the two sand bodies were the same. But the width of the two sand bodies was different. The difference of the sand’s width showed geometry form heterogeneity. And if the width difference of two sand bodies was high, it showed serious heterogeneity of geometry form in the reservoir. At last, conceptual model (c) indicated thickness plane heterogeneity of reservoir. In this model, gray and white quadrangles also represented the sand bodies which formed in different sedimentary microfacies. And the area and permeability of the two sand bodies were the same. The thickness of two sand bodies was different. As the thickness difference of two sand bodies was high, it showed serious heterogeneity of thickness in the reservoir. On the basis of the conceptual model, univariate and multivariate analyses of reservoir plane heterogeneity were conducted.

3. The Mathematical Model of Steam Flooding

Based on the above conceptual model of permeability, geometry form, and thickness of reservoir sand, the mathematical model of steam flooding was built. The mechanism of steam flooding in heavy oil reservoir was complicated. So in order to establish mathematical models, there were several assumptions. They were described as follows: (1) there were oil, gas, and water phase flow in reservoir; (2) thermal and phase equilibrium achieve instantaneously; (3) compressibility and thermal expansion of rock can be neglected; (4) there was no dissolved gas separated from crude oil; (5) mass transferring and heat transferring which were caused by molecular diffusion and heat diffusion can be neglected; and (6) enthalpy of oil, gas, and water phase is equal to internal energy, respectively.

(1) Mass conservation equation:

\[ \nabla \cdot \sum_{j=1}^{3} \rho_j x_j = \nabla P + \nabla \frac{P c_j}{\mu_j} - q_i = \sum_{j=1}^{3} \frac{\partial}{\partial t} \left( \varnothing \rho_j S_j x_j \right) \]  

(2) Energy conservation equations:

\[ \nabla \cdot \sum_{j=1}^{3} \rho_j x_j \left( \nabla P + \nabla \frac{P c_j}{\mu_j} - \gamma_j \nabla \frac{\mu_j}{\gamma_j} \right) + \nabla \cdot (\theta R T) + \nabla \cdot (\theta R T^4) - Q_i + Q_{HIL} \]

\[ = \frac{\partial}{\partial t} \left( \varnothing \sum_{j=1}^{3} \rho_j S_j U_j + (1-\varnothing) M_j (T - T_j) \right) \]

(3) Saturation equation:

\[ \sum_{j=1}^{3} S_j = 1 \]
4. Plane Heterogeneity of Reservoir Sand

4.1. Plane Heterogeneity of Permeability of Reservoir Sand. In general, there are significant differences of reservoir permeability in different microfacies. In the conceptual model, there are two sand bodies which were the same area. The length of the side is 500 meters. And the thickness of sand body is 10 meters. But the permeability of the two sand bodies is different. Three geological models were designed: (1) model 1—the permeabilities of the right and left sand were 2400 mD and 400 mD, (2) model 2—the permeabilities of the right and left sand were 2400 mD and 800 mD, and (3) model 3—the permeabilities of the right and left sand were 2400 mD and 1200 mD. For the same model, there were two different cases: (1) case 1—producer was deployed in high permeability sand body and injector was deployed in low permeability zone, and (2) case 2—producing well was deployed in low permeability sand body and injection well was deployed in high permeability sand body. The corresponding cases of permeability heterogeneity are shown in Figure 2.

For the three models, the permeability differential of two sand bodies was 6, 3, and 2, respectively. The fluid flow in the vertical direction was uniform and means that the velocity of fluid was identical in the same vertical plane. So the model can be further simplified as the 2-D model. And the bottom hole pressures of producer and injector were fixed. The injection pressure was 9 MPa, and producing well was 6 MPa. Based on the above mathematic model, initial conditions, boundary condition, and geological parameters of conceptual models, cumulative oil production of each case could be obtained by numerical simulation computing. For model 1, the cumulative oil production was $9.59 \times 10^4$ m$^3$. For model 2, the cumulative oil production was $8.04 \times 10^4$ m$^3$. In the other two models, the cumulative oil production of case 1 was also more than that of case 2. It can be concluded that cumulative production as producer was deployed in high permeability sand body and injector was deployed in low permeability zone was higher.

For the same conceptual model, the difference of cumulative oil production of two cases can be calculated. Then, three differences of cumulative oil production values of three geologic models can be figured out all. Then, the relationship of difference of cumulative production and permeability differential was further obtained, as shown in Figure 3. The larger permeability differential was, the bigger the difference of oil cumulative production was. For example, when the permeability differential was six, the difference of cumulative production of different flooding direction was $3.53 \times 10^4$ m$^3$.

The formation temperature and pressure of two cases in different conceptual model also can be obtained by numerical calculation. The distribution of formation pressure and temperature of two cases in model 1 is shown in Figures 4 and 5. The formation pressure around injector was higher than producing well. The left of the figure was the producer which was deployed in high permeability sand body and injector which was deployed in low permeability sand body. The right of the figure was the producing well which was deployed in low permeability sand body and injector which was deployed in high permeability sand body.

And the average pressure of formation was also higher. When the fluid flows from high permeability to low permeability zone, the flow resistance was higher. So the formation pressure around injector increased quickly. And the steam was hard to inject. It needs more injection pressure. While injection pressure was fixed, the volume of steam injection was more as the producer was deployed in high permeability sand body and injector was deployed in low permeability sand body.

Also, in the analysis of distribution of temperature in reservoir, the recovery of steam flooding as the producer was deployed in high permeability sand body and injector was deployed in low permeability sand body was better as seen in Figure 4.

4.2. Plane Heterogeneity of Thickness of Reservoir Sand. Also, the conceptual model of plane heterogeneity of thickness was designed, as shown in Figure 1. In the conceptual model, there are two sand bodies which were the same area. The length of the side is 500 meters. And the permeability of sand body is 800 mD. But the thickness of the two sand

(4) Capillary pressure equation:

$$P_{cw} = P_o - P_w, \quad P_{cg} = P_g - P_o$$

(5) Constituent constraint equations:

$$\sum_{i=1}^{3} X_{ij} = 1, \quad j = 1, 2, 3$$

And the boundary and initial conditions of the model were given. Initial pressure and oil saturation are known. For the above conceptual models, the boundary conditions were sealed boundary. The bottom hole pressure of the producer and injector were fixed. Analytical solution of the flow equation was hard to get, but its numerical solution can be solved by adopting discrete and differential numerical method. Its calculation process can be done by programming. According to the numerical simulation method, oil production and water production rate can be calculated. And cumulative oil production can be also calculated.

Figure 2: Injection and production pattern for the same conceptual model.
bodies is different. Three geological models were designed: (1) model 1—the thicknesses of the right and left sand were 12 meters and 2 meters, (2) model 2—the thicknesses of the right and left sand were 12 meters and 4 meters, and (3) model 3—the thicknesses of the right and left sand were 12 meters and 6 meters.

In the conceptual model, a horizontal producer and a horizontal injector were deployed. Ignoring well bore friction, the fluid flow in the Y direction was uniform and means that the velocity of fluid was identical. So the model can be further simplified as the 2-D model as seen in Figure 5. For the same model, there were two different cases: (1) case 1—horizontal producer was deployed in thick sand body, and horizontal injector was deployed in thin sand body; and (2) case 2—horizontal producer was deployed in thin sand body, and horizontal injector was deployed in thick sand body as seen in Figure 6. And injection pressure is 8 MPa, and bottom hole pressure of producer is 6 MPa.

Based on the above mathematic model, initial conditions, boundary condition, and geological parameters of conceptual models, cumulative oil production of each case could be obtained by numerical simulation computing. For model 1, the cumulative oil production was \( 5.70 \times 10^4 \) m³. For model 2, the cumulative oil production was \( 2.91 \times 10^4 \) m³. In the other two models, the cumulative oil production of case 1 was also more than that of case 2. It can be concluded that cumulative production as producer was deployed in thick sand body and injector was deployed in thin sand body was higher.

For the same conceptual model, the difference of cumulative oil production of two simulation cases can be calculated. Then, three differences of cumulative oil production values of three models can be figured out. And the thickness differential of the model was 6, 3, and 2, respectively. Then, the relationship of difference of cumulative production and thickness differential was further obtained, as shown in Figure 7. The larger the thickness differential of sand body was, the bigger the difference of oil cumulative production was. The formation pressure and temperature also can be figured out by numerical calculating. For case 2, when the fluid flows from thick sand body to thin sand body, the flow resistance was higher. So the formation pressure around injector increased quickly. And the steam was hard to inject. It needs more injection pressure. While injection pressure of well was fixed, the volume of steam injection was more as the producer was deployed in thick sand body and injector was deployed in thin sand body.

4.3. Plane Heterogeneity of Geometry Form of Reservoir Sand. The conceptual model of plane heterogeneity of geometry form was designed, as shown in Figure 1. The length is 500 meters. The permeability of sand body is 800 mD. But the width of the two sand bodies is different. Three geological models were designed: (1) model 1—the widths of the right and left sand were 500 meters and 83 meters, (2) model 2—the widths of the right and left sand were 500 meters and 167 meters, and (3) model 3—the widths of the right and left sand were 500 meters and 250 meters.

The fluid flow in the vertical direction was uniform and means that the velocity of fluid was identical in the same vertical plane. So the model can be further simplified as the 2-D model. And for the same model, two flooding patterns including vertical well and horizontal well were designed as seen in Figures 8 and 9. There were two different cases for the same model: (1) case 1—producer or horizontal producer was deployed in wide sand body, and injector or horizontal injector was deployed in narrow sand body; and (2)
producer or horizontal producer was deployed in narrow sand body, and injector or horizontal injector was deployed in wide sand body. The bottom hole pressure of producer and injector was fixed. The injection pressure was 8 MPa, and the producing well is 6 MPa. Based on the above mathematic model, initial conditions, boundary condition, and geological parameters of conceptual models, cumulative oil production of each case could be obtained by numerical simulation computing. For model 1 of pattern a, the cumulative oil production was 7.62 × 10^4 m^3. For model 2 of pattern b, the cumulative oil production was 6.12 × 10^4 m^3. In the other two models, the cumulative oil production of case 1 was also more than that of case 2. For pattern b, it can reach the similar conclusion. So it can be concluded that cumulative production as producer was deployed in wide sand body and injector was deployed in narrow sand body was higher.

For the same conceptual model, the difference of cumulative oil production of two simulation cases can be calculated. Then, three differences of cumulative oil production values of three models can be figured out. For three models of pattern a, the ratio of the width of two sand bodies was 6, 3, and 2, respectively. Then, the relationship of difference of cumulative production and thickness differential was further obtained as seen in Figure 10. The larger the ratio of width was, the bigger the difference of oil cumulative production was.

5. Sensitivity Analysis of Plane Heterogeneity

Through the above analysis, all of the plane heterogeneity of permeability, thickness, and geometry form had great impact on the development recovery of steam flooding in heavy oil reservoir. But which factor played more important role for steam flooding in heavy oil reservoir was still a problem. So in order to figure out the impact of three types of plane heterogeneity on flooding recovery, six more geologic models were put forward. For the model of plane heterogeneity of permeability, two models in which the permeabilities of the right and left sand were 2400 mD and 600 mD and 2400 mD and 240 mD were added. For the model of plane heterogeneity of thickness, two models in which the thicknesses of the right and left sand were 12 meters and 3 meters and 12 meters and 1.2 meters were added. For the model of plane heterogeneity of geometry form, two models in which the widths of the right and left sand were 500 meters and 125 meters and 500 meters and 50 meters. With the addition of the six new models, a total of fifteen models were built. And the differential of each type of plane heterogeneity can be numerical computed. Firstly, a variation coefficient was defined to explain the impact degree of the three types
of plane heterogeneity. For the same geologic model, cumulative oil production of two flooding patterns can be obtained. And the equation of variation coefficient can be expressed as

$$VC = \frac{N_{p1} - N_{p2}}{N_{p1}}.$$  \(6\)

The variation coefficient of all models was figured out as shown in Figure 11. It can be concluded that the variation coefficient of permeability heterogeneity was the maximum. The variation coefficient of heterogeneity of geometry form was the minimum. So for the impact of the three types of plane heterogeneity on development effect of steam flooding in heavy oil reservoir, the impact of permeability heterogeneity ranked the first, thickness ranked the second, and geometry form ranked the third.

6. Summary and Conclusions

From the above discussion, we can see that the development effect of steam flooding in heavy oil reservoirs is strongly influenced by flooding pattern. Based on the distribution characteristics of microfacies of Xinjiang Oilfield in China, three types of conceptual heterogeneous models which represent plane heterogeneity of permeability, thickness, and geometric form were proposed.

For plane heterogeneity of permeability, thickness, and geometry form of sand, under the conditions of that as the producer was deployed in high permeability, thick, wide sand body and injector was deployed in low permeability, thin, narrow sand body better, the recovery of steam flooding in heavy oil reservoir was better.

It can be concluded that the variation coefficient of permeability heterogeneity was the maximum. The variation coefficient of heterogeneity of geometry form was the minimum. So for the impact of the three types of plane heterogeneity on development effect of steam flooding in heavy oil reservoir, the impact of permeability heterogeneity ranked the first, thickness ranked the second, and geometry form ranked the third.

This conclusion can help us improve the development of this reservoir. And also the findings of this study can help for better understanding of how to effectively develop the heavy oil reservoirs of strong plane heterogeneity for other heavy oil reservoirs.

The research work of this paper is based on the model of ideal reservoir, and some qualitative conclusions and understandings are obtained, which plays a very important guiding role in the well pattern deployment of heavy oil reservoirs with strong plane heterogeneity. However, the real heterogeneity distribution of heavy oil reservoir is more complex, and the quantitative understanding, such as EOR amplitude and injection production parameter design, needs to be further studied.

Nomenclature

- \(\rho_j\): Density of phase \(j\)
- \(x_{ij}\): Mole fraction of constituent \(i\) in phase \(j\)
- \(K\): Permeability of reservoir
- \(K_{ij}\): Relative permeability of phase \(j\)
- \(\mu_i\): Viscosity of phase \(j\)
- \(\gamma_j\): Gravity of phase \(j\)
- \(Z\): Depth of reservoir
- \(q_i\): Production of constituent \(i\)
- \(P_{cj}\): Capillary pressure
- \(P\): Pressure of reservoir
- \(S_j\): Saturation of phase \(j\)
- \(\Phi\): Porosity of reservoir
- \(H_j\): Enthalpy of phase \(j\)
- \(U_j\): Internal energy of phase \(j\)
- \(\theta_c\): Thermal conductivity of reservoir
- \(\theta_R\): Thermal emissivity
- \(T\): Temperature of reservoir
- \(T_i\): Initial temperature of reservoir
- \(Q_H\): Enthalpy variation due to the fluid injection or output
- \(M_j\): Heat capacity of rock
$P_{cwo}$: Oil-water interfacial tension  
$P_{cgo}$: Gas-oil interfacial tension.  
VC: Variation coefficient  
$N_{p1}$: Maximum cumulative oil production  
$N_{p2}$: Minimum cumulative oil production.

**Data Availability**

Individual well production data from these fields cannot be publicly released due to confidentiality reasons. The individual well production data used to support the findings of this study were supplied by Research Institute of Exploration and Development Xinjiang Oilfield Company of PetroChina under license and so cannot be made freely available. Requests for access to these data should be made to Xinjiang Oilfield Company of PetroChina. The data required for the model comes from seismic data, single well logging data, and imaging logging data, and the high pressure physical properties of fluids and rocks required for reservoir numerical simulation used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**References**

[1] C. Z. Sun, H. Q. Jiang, J. J. Li, and S. J. Ye, “Pore network modeling of a polymer flooding microscopic seepage mechanism,” *Petroleum Science and Technology*, vol. 29, no. 17, pp. 1803–1810, 2011.

[2] M. M. Salehi, M. A. Safarzadeh, E. Sahraei, and S. A. T. Nejad, “Comparison of oil removal in surfactant alternating gas with water alternating gas, water flooding and gas flooding in secondary oil recovery process,” *Journal of Petroleum Science and Engineering*, vol. 120, pp. 86–93, 2014.

[3] E. Robertson, “Low-salinity waterflooding to improve oil recovery-historical field evidence,” in *Paper Presented at the SPE Annual Technical Conference and Exhibition*, Anaheim, CA, USA, November 2007.

[4] Z. Xiao, W. Ding, S. Hao et al., “Quantitative analysis of tight sandstone reservoir heterogeneity based on rescaled range analysis and empirical mode decomposition: a case study of the Chang 7 reservoir in the Dingbian oilfield,” *Journal of Petroleum Science and Engineering*, vol. 182, article 106326, 2019.

[5] J. Yao, Z. Xiao, G. Liu, and M. Han, “Source of crude oil in chang-8 member of wuqi oil-field, Ordos basin, China,” *Petroleum Science and Technology*, vol. 37, no. 22, pp. 2288–2294, 2019.

[6] A. Imqam, Z. Wang, and B. Bai, “Preformed-particle-gel transport through heterogeneous void-space conduits,” *SPE Journal*, vol. 22, no. 5, pp. 1437–1447, 2017.

[7] K. S. Hasan-Al-Ibadi and E. Mackay, “Heterogeneity effects on low salinity water flooding,” in *SPE Euro-Pec Featured at 82nd EAGE Conference and Exhibition*, pp. 8–11, Amsterdam, Netherlands, 2020.

[8] K. W. Li, C. W. Liu, Q. L. Zhang et al., “A new method for estimating the production performance of water flooding,” in *Paper Presented at the SPE Asia Pacific Oil & Gas Conference and Exhibition*, Perth, Australia, October 2016.

[9] J. Moghadasi, H. Müller-Steinhagen, M. Jamialahmadi, and A. Sharif, “Theoretical and experimental study of particle movement and deposition in porous media during water injection,” *Journal of Petroleum Science and Engineering*, vol. 43, no. 3–4, pp. 163–181, 2004.

[10] R. Baker, C. Fong, and T. Li, “Practical consideration of reservoir heterogeneities on SAGD projects,” in *Paper SPE 117525 presented at the SPE International Thermal Operations and Heavy Oil Symposium held in Calgary, Alberta, Canada*, 2008.

[11] Q. Chen, M. G. Gerritsen, and A. R. Kowscek, “Effects of reservoir heterogeneities on the steam assisted gravity - drainage process,” in *SPE Reservoir Evaluation & Engineering*, 2008.

[12] A. K. Pernadi, I. P. Yuwono, and A. J. S. Simanjuntak, “Effects of vertical heterogeneity on waterflooding performance in stratified reservoirs: a case study in Bangko Field, Indonesia,” in *Paper Presented at the SPE Asia Pacific Conference on Integrated Modelling for Asset Management*, Kuala Lumpur, Malaysia, March 2004.

[13] Y. G. Qu and Y. T. Liu, “The impact of sandstone’s geometry form on water flooding efficiency in heterogeneous reservoirs,” *Petroleum Science and Technology*, vol. 30, no. 17, pp. 1813–1822, 2012.

[14] X. Nie, J. Chen, Y. Cao et al., “Investigation on plugging and profile control of polymer microspheres as a displacement fluid in enhanced oil recovery,” *Polymers*, vol. 11, no. 12, pp. 1–14, 2019.

[15] L. Hao, C. Yegin, J. K. Oh et al., “Solid-shelled microemulsion with capabilities of confinement-induced release for improving permeability of reservoirs,” *Chemical Engineering Journal*, vol. 323, pp. 243–251, 2017.

[16] K. Guo, H. Li, and Z. Yu, “In-situ heavy and extra-heavy oil recovery: A review,” *Fuel*, vol. 185, pp. 886–902, 2016.

[17] A. Sadeghi, H. Hassanzadeh, and T. Harding, “Modeling of desiccated zone development during electromagnetic heating of oil sands,” *Journal of Petroleum Science and Engineering*, vol. 154, pp. 163–171, 2017.

[18] L. S. Cheng, L. Liang, Z. X. Lang, and X. S. Li, “Mechanistic simulation studies on the steam-foam drive in superviscous oil reservoirs,” *Journal of Petroleum Science and Engineering*, vol. 41, no. 1–3, pp. 199–212, 2004.

[19] P. Shen, *Thermal Technology for EOR*, Petroleum Industrial Press, Beijing, China, 2005.

[20] S. W. Hasan, M. T. Ghannam, and N. Esmail, “Heavy crude oil viscosity reduction and rheology for pipeline transportation,” *Fuel*, vol. 89, no. 5, pp. 1095–1100, 2010.

[21] S. I. Im, S. Shin, J. W. Park et al., “Selective separation of solvent from deasphalted oil using CO$_2$ for heavy oil upgrading process based on solvent deasphalting,” *Chemical Engineering Journal*, vol. 331, pp. 389–394, 2018.

[22] V. Shvets, V. Sapunov, R. Kozlovskiy et al., “Cracking of heavy oil residues in a continuous flow reactor, initiated by atmospheric oxygen,” *Chemical Engineering Journal*, vol. 329, pp. 275–282, 2017.

[23] Y. Chu, C. Fan, Q. Zhang et al., “The oxidation of heavy oil to enhance oil recovery: the numerical model and the criteria to describe the low and high temperature oxidation,” *Chemical Engineering Journal*, vol. 248, pp. 422–429, 2014.
[24] W. Z. Liu, Status, Progression, Review and the Prospect of Thermal Recovery Of Heavy Oil in China, Petroleum Industry Press, 2014.

[25] X. Dong, H. Liu, Z. Chen, K. Wu, N. Lu, and Q. Zhang, "Enhanced oil recovery techniques for heavy oil and oilsands reservoirs after steam injection," Applied Energy, vol. 239, pp. 1190–1211, 2019.

[26] A. M. Al-Bahlani and T. Babadagli, "Visual analysis of diffusion process during oil recovery using a Hele-Shaw model with hydrocarbon solvents and thermal methods," Chemical Engineering Journal, vol. 181-182, pp. 557–569, 2012.

[27] J. M. Alvarez and S. Han, "Current overview of cyclic steam injection process," Journal of Petroleum Science Research, vol. 2, no. 3, pp. 116–127, 2013.

[28] C. I. Beattie, T. C. Boberg, and G. S. McNab, "Reservoir simulation of cyclic steam stimulation in the cold lake oil sands," SPE Reservoir Engineering, vol. 6, no. 2, pp. 200–206, 1991.

[29] A. R. Kovscek, "Emerging challenges and potential futures for thermally enhanced oil recovery," Journal of Petroleum Science and Engineering, vol. 98-99, pp. 130–143, 2012.

[30] Y. Zhao, "Laboratory experiment and field application of high pressure and high quality steam flooding," Journal of Petroleum Science and Engineering, vol. 189, p. 107016, 2020.

[31] A. Shah, R. Fishwick, J. Wood, G. Leeke, S. Rigby, and M. Greaves, "A review of novel techniques for heavy oil and bitumen extraction and upgrading," Energy & Environmental Science, vol. 3, no. 6, pp. 700–714, 2010.

[32] Y. Wang, S. Ren, and L. Zhang, "Mechanistic simulation study of air injection assisted cyclic steam stimulation through horizontal wells for ultra heavy oil reservoirs," Journal of Petroleum Science and Engineering, vol. 172, pp. 209–216, 2019.

[33] Z. Yuan, P. Liu, S. Zhang, X. Li, L. Shi, and R. Jin, "Experimental study and numerical simulation of nitrogen-assisted SAGD in developing heavy oil reservoirs," Journal of Petroleum Science and Engineering, vol. 162, pp. 325–332, 2018.