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Perspective

Fluid flow and efficient development technologies in unconventional reservoirs: State-of-the-art methods and future perspectives

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Abstract:
With the global energy consumption on the rise and the gradual decline in conventional oil production, unconventional reservoirs have received considerable attention in the last decade. However, due to the unique physical properties and a large number of micro/nanopores in unconventional reservoirs, fluid flow in these reservoirs is considerably different from conventional ones. Therefore, it is highly important to conduct research on elucidating these fluid flow mechanisms. Furthermore, to avoid problems associated with the rapid production decline and low recovery efficiency in such reservoirs, an enhanced oil recovery technology that can efficiently and economically develop unconventional reservoirs is urgently required. This paper systematically summarizes the current research on flow mechanisms, including capillary imbibition, molecular-scale fluid flow and productivity prediction in unconventional reservoirs, and introduces the enhanced oil recovery and application status of hydraulic fracturing assisted oil displacement technology, along with a brief analysis of their advantages and disadvantages. This study is intended to serve a reference for the efficient development of unconventional reservoirs.

1. Introduction

Unconventional reservoirs are characterized by strong heterogeneity, a large number of micro/nanopores, ultra-low porosity and permeability, and complex fluid flow behavior. The application of conventional reservoir seepage theory to unconventional reservoirs has required consideration of the changes in mechanism caused by scale effects. The lack of more effective production technology and development methods guided by a theoretical framework has limited the large-scale and efficient development of such oil and gas reservoirs. In unconventional reservoirs, the principal technology to enhanced oil recovery (EOR) is volumetric fracturing, which adds oil displacement agents to the fracturing fluid and relies on the imbibition effect to replace crude oil. However, a number of problems still remain such as low production, rapid decline and difficulty in stabilizing production. Therefore, for the efficient development and production of unconventional reservoirs, it is of great significance to deeply understand the fluid flow behavior and explore the economical and efficient EOR technologies.

This work discusses the latest research developments on fluid flow in unconventional reservoirs, including capillary imbibition, fluid flow at the molecular scale, and the produc-

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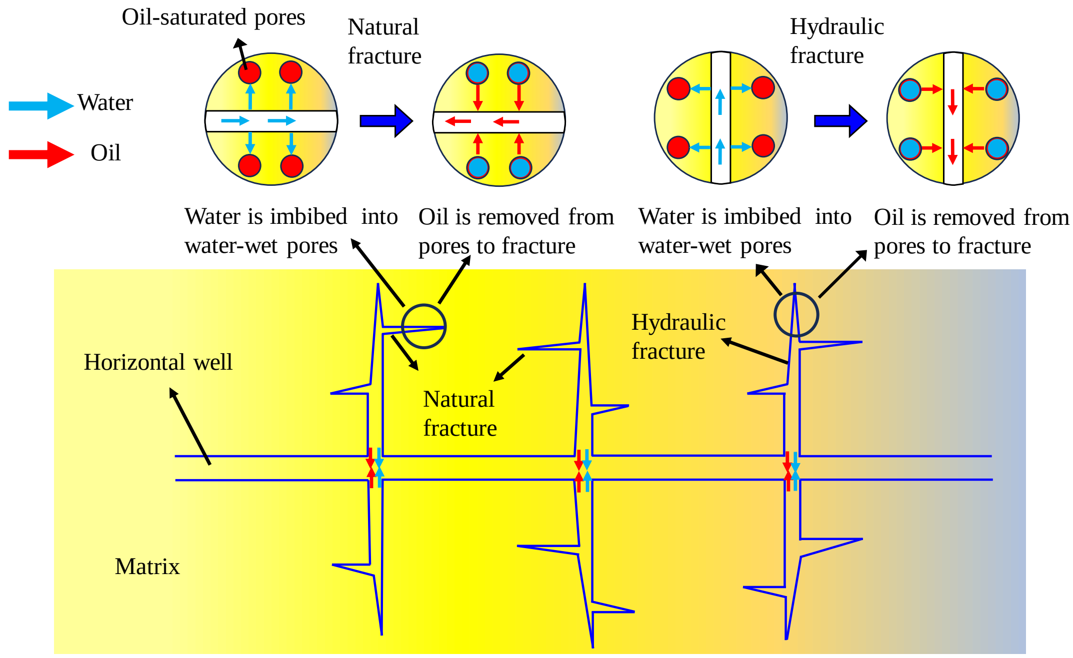

Fig. 1. Fluid flow during the hydraulic fracturing development of unconventional reservoirs.

tivity prediction model. In addition, the hydraulic fracturing-assisted oil displacement (HFAD) technology for high efficiency EOR is presented and the possibility of its application in unconventional reservoirs is analyzed. This paper aims to provide a valuable reference for the efficient development of unconventional reservoirs.

2. Fluid flow in unconventional reservoirs

2.1 Capillary imbibition

The poor porosity and permeability of unconventional reservoirs lead to the development of a large number of micro/nanopores. At present, the development of unconventional reservoirs is based primarily on the large-scale volume fracturing of horizontal wells. This process creates a large number of artificial fractures to enable effective utilization at the initial scale of unconventional reservoirs (Fig. 1). Capillary imbibition is an important mechanism that promotes material exchange between the reservoir matrix and fractures. The forced imbibition effect occurs near the main fracture, whereas spontaneous imbibition occurs away from it.

Wettability is a key factor affecting imbibition efficiency. A prerequisite for the occurrence of imbibition in unconventional reservoirs is the wettability of rocks, and the stronger the hydrophilicity, the higher the imbibition efficiency. In general, imbibition efficiency is positively correlated with temperature, pressure and permeability, and the better the pore-throat connectivity typically leads to higher imbibition recovery. Certainly, salinity also affects the spontaneous imbibition efficiency, as high salinity can restrain the expansion of typical minerals and decrease the maximum imbibed liquid volume (Cai et al., 2020). Additionally, imbibition occurs primarily in nanopores and micropores, followed by mesopores and macropores. However, for macropores and some mesopores, the forced imbibition effect is better than the spontaneous imbibition effect, whereas for micropores and other mesoporous pores, spontaneous imbibition is better than forced imbibition. Moreover, the imbibition process can be divided into concurrent and countercurrent types. During the countercurrent imbibition process, permeability is positively correlated with the degree of recovery (Wang et al., 2023c).

During the initial phase of imbibition, velocity depends primarily on the maximum pore size and the distribution of macropores. However, during the later stages, velocity depends mainly on mesopores. Moreover, after considering the dynamic contact angle effect, the three-phase contact line friction, fluid viscosity, interfacial tension, and reservoir wettability are all important factors influencing imbibition (Tian et al., 2023). Considering nanoconfinement, inertia and inlet end effects, the dynamic contact angle effect exerts the greatest influence on the imbibition process, followed by nanoconfinement (multilayer adhesion and slippage), inertia, and inlet end effects. As a next significant step, a multi-factor and multi-field coupling dynamic imbibition model considering the fluid-solid coupling effect in the nanoconfinement space could be developed to further elucidate the imbibition displacement mechanism of unconventional reservoirs. In addition, the application of the imbibition model from the nanoscale to the pore scale requires further investigation.

2.2 Molecular flow

Molecular simulation technology can compensate for the shortcomings of nanoscale research experiments and reduce

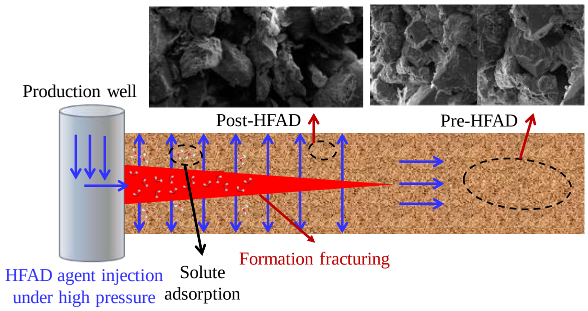

Fig. 2. Schematic of hydraulic fracturing-assisted oil displacement technology.

their costs. Moreover, it can reveal the dynamic behavior of oil and gas in confined spaces and their microscopic interaction with mineral rock walls. Molecular dynamics simulation methods have been used extensively to analyze the fluid flow in unconventional reservoirs.

Oil molecules in the pores are in adsorbed and free states according to their occurrence, and the proportion of these two states is considerably affected by the pore throat size. When oil is in a confined space or the pore size is less than a certain threshold value (for n-octane, this is approximately 3.6 nm), there is no free crude oil in the pores, the oil exists in the form of adsorbed crude oil, and the state of oil will directly affect the production efficiency (Wang et al., 2024). The composition of crude oil is also an important factor in the occurrence state in which it is found in the pores: the light hydrocarbon components of oil-phase molecules are more inclined to diffuse, whereas the heavy hydrocarbon components are more prone to slide near the wall. During this displacement process, the light hydrocarbon components near the wall are more likely to peel off, whereas the heavy hydrocarbon components remain in the pores (Jiang et al., 2024). Molecular stagnation time is regarded as a basis for determining the change of crude oil occurrence state. Light hydrocarbon components exhibit a shorter stagnation time in the adsorption layer, making it easier for them to transform into free crude oil, whereas heavy hydrocarbon components exhibit a stronger adsorption effect on the wall surface and longer stagnation time.

From the results of molecular dynamics simulations, the flow at the molecular scale cannot directly guide the macroscale flow mechanism. Consequently, it has become imperative to explore how the results from molecular dynamics simulations can be integrated into the macroscopic flow model.

2.3 Productivity forecasting

Unconventional oil considerably differs from conventional oil in terms of its flow behavior. In unconventional reservoirs, the seepage theory of conventional reservoirs is not applicable owing to the environment characterized by strong heterogeneity, complex fracture networks generated by fracturing, and the nonlinear characteristics of fluids. Currently, a multi-fracture horizontal well fluid flow model is commonly used to predict unconventional reservoir productivity, and factors such as initial pressure gradient, stress sensitivity, capillary force, and natural fractures can be considered to modify the model (Jiang et al., 2022). Meanwhile, the characteristics of oil and gas separation during production in unconventional reservoirs are also important factors affecting the accuracy of the model (Li et al., 2023).

Matrix capillary pressure, fracture-related parameters, formation pressure system, microfracture permeability, natural fracture density, horizontal well length, and differential production pressure are the main factors influencing productivity in unconventional reservoirs. Among them, matrix permeability, microfractures, fracture interval, natural fracture density, and matrix capillary pressure are the key parameters affecting the oil-well productivity. In the next research stage, based on the complexity of fluid flow in micro/nanopores, a corresponding fluid flow model should be developed. This should consider the coupling action, such as multi-scale, multi-medium, and multi-field coupled, and so on, and thus guide engineering practice and realize the large-scale economic development of unconventional reservoirs.

3. HFAD technology

HFAD is a new high-efficiency EOR method developed in recent years. In this technique, a low viscosity HFAD agent is used as the fracturing fluid and hydraulic fracturing is utilized to transport large quantities of the chemical agent along the fractures into the deep parts of the target reservoir. HFAD agents flow from the fractures into the upper and lower matrix, effectively flushing and displacing the crude oil (Fig. 2). The technical characteristics of HFAD technology are as follows: the traditional hydraulic fracturing "promote fracture extension" process is changed into a "slow fracture extension" process, which effectively inhibits the premature breakthrough of the displacement phase front caused by rapid fracture extension. Moreover, it can also change the fracturing fluid flow behavior from an "inhibiting filtration" process to a "promoting filtration" process, effectively expanding the displacement phase swept volume and improving the displacement efficiency.

3.1 Oil displacement mechanism

HFAD technology directly transports the chemical agent to the reservoir depths, which can quickly supplement the formation energy, expand the displacement phase swept volume, and improve the oil washing efficiency (Liu et al., 2022). The use of HFAD technology involving the high-pressure injection of the chemical agent can improve the porosity and permeability of reservoirs, increase the average pore radius, and reduce the adhesion of crude oil on the wall, ultimately reducing the fluid flow resistance and improving the displacement phase flow velocity (Wang et al., 2023a). Additionally, HFAD technology can reduce the adsorption loss of HFAD agents in reservoirs and increase their effective concentration, thereby enabling economical and efficient reservoir development (Wang et al., 2023b).

3.2 Application status and future prospects

HFAD technology is widely used in the Daqing Oilfield (medium-low permeability reservoir), Shengli Oilfield (low permeability/ultra-low permeability reservoir), Changqing Oilfield (tight reservoir), and an offshore oilfield (low permeability reservoir). Field results have demonstrated that this technology can effectively improve oil recovery. Moreover, the successful application of HFAD to tight reservoirs provides a new method for unconventional reservoir development. Under high injection and pressure conditions, HFAD technology can quickly supplement the formation energy, expand the displacing phase swept volume, and communicate natural fractures. It can improve the reservoir physical properties and enhance the imbibition effect, thereby improving the oil displacement efficiency. The above analysis indicates that HFAD has a high potential to become an EOR technology for the cost-effective development of unconventional reservoirs.

Future studies should focus on the application of HFAD technology in unconventional reservoirs and explore the corresponding fluid flow mechanism under HFAD conditions. Moreover, the EOR mechanisms of HFAD technology to develop unconventional reservoirs need to be analyzed to determine the suitable HFAD agents for a better enhancement of displacement efficiency. For unconventional reservoirs with widely developed nanopores, supercritical carbon dioxide can easily penetrate the micro/nanopores owing to its extremely strong solubility and diffusivity, which will expand the crude oil and reduce its viscosity and interfacial tension. Consequently, when HFAD technology is applied in unconventional reservoir development, supercritical carbon dioxide could be considered as an effective HFAD agent.

4. Conclusions

This paper underscores the importance of capillary imbibition, molecular flow and fluid flow behavior in unconventional reservoir development. Capillary imbibition plays a crucial role in oil displacement, influenced by factors such as wettability, temperature, pressure, interfacial tension, and permeability. The occurrence state of crude oil holds the key to the stimulation of unconventional reservoirs, primarily due to the fact that oil molecules in the free state are easier to strip. And it is strongly affected both by the radius of pore throat and the light and heavy fractions. Considering the initial pressure gradient, stress sensitivity, capillary pressure and natural fractures, the multi-fracture horizontal well fluid flow model can accurately predict the productivity of unconventional reservoirs. HFAD technology can effectively supplement the formation energy, communicate natural fractures, and improve the reservoir physical properties. Therefore, it could become one of the EOR technologies for the cost-effective development of unconventional reservoirs. Future research work should focus on the dynamic imbibition effect and fluid flow behavior under multi-scale, multi-media and multi-field coupling, and constantly explore more efficient development technologies.

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Conflict of interest

The authors declare no competing interest.

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