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Research Article

Asynchronous Injection-Production Process: A Method to Improve Water Flooding Recovery in Complex Fault Block Reservoirs

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The complex fault block reservoir has the characteristics of small area and many layers in vertical. Due to the influence of formation heterogeneity and well pattern, the situation that "water fingering is serious with water injection, on the contrary, driving energy is low" frequently occurs in water flooding, which makes it difficult to enhance oil recovery. Asynchronous injection-production (AIP) process divides the conventional continuous injection-production process into two independent processes: injection stage and production stage. In order to study oil recovery in the fault block reservoir by AIP technology, a triangle closed block reservoir is divided into 7 subareas. The result of numerical simulation indicates that all subareas have the characteristic of fluid diverting and remaining oil in the central area is also affected by injected water at injection stage of AIP technology. Remaining oil in the central area is driven to the included angle and border area by injected water and then produced at the production stage. Finally, the oil recovery in the central area rises by 5.2% and in the noncentral area is also increased in different levels. The AIP process can realize the alternative change of reservoir pressure, change the distribution of flow field, and enlarge the swept area by injected water. To sum it up, the AIP process is an effective method to improve the oil recovery in complex fault-block reservoir by water flooding.

1. Introduction

Due to the fault cutting, the complex fault block reservoir has characteristics of breaking block, numerous fault blocks, complicated structures, and complicated oil-water relationship [1–3]. The effect of water flooding is affected by the reservoir area, reservoir structure, and well pattern in complex fault block reservoirs. Especially in about 0.1 km^2 area of complex fault block reservoirs, the production contradiction that "if water injection is not applied, then reservoir pressure is low, else the producer with high water cut" is serious. But the remaining oil is widely distributed and enriched in local areas [1]. Economic factors limit the possibility of continuing drilling, so the effective utilization of remaining oil in complex fault block reservoirs at high water-cut stage is still a difficult problem.

In the process of water flooding, how to improve the sweep efficiency and the oil displacement efficiency is always the focus of research. Arab et al. studied the water flooding mechanism of the heavy oil reservoir based on the experimental results of heavy oil water flooding and the results showed that low injection rate can greatly improve oil recovery [4]. Cheng et al. aimed to optimize the scale of the stimulated reservoir volume (SRV) by conducting an experiment to verify the water injection capacity of the Chang 7 Formation, which is situated within a typical tight oilfield [5]. You et al. put forward the method of horizontal displacement of the reservoir for lateral displacement to improve the development effect of the bottom-water reservoir and the results of the physical model test showed that this method can effectively improve the recovery of the bottom-water reservoir [6]. Unstable water injection is an earlier proposed technique by hydrodynamic methods to improve water flooding recovery [7–13]. In the early field test, most of the low permeability reservoirs with strong heterogeneity have adopted the method of the changing water injection rate to realize the exchange of oil and water, which can achieve the purpose of enhanced oil recovery [5–11]. However, in mid-high permeability reservoirs, the capillary pressure is less effective and the dialysis is ineffective, so improving sweep efficiency of water flooding is the most effective way to enhance oil recovery.

In the process of heavy oil production by steam huff and puff, production and stop production are alternate. By injecting a certain amount of high-temperature saturated steam into the reservoir, the well simmers for a period of time to heat the crude oil in the reservoir and reduces the viscosity of the crude oil, and the well is opened. Venezuela in the north of Tia Juana oil field, the United States, in 1960, in Yorlba Linda oil field in California, and Canada in Cold Lake oil field all adopt large-scale steam huff and puff production, greatly improving the world's heavy oil production [14,15]. In water flooding production, AIP is a potential technology to improve oil recovery by alternative opening of the injector and producer to change the distribution of pressure and fluid saturation in the reservoir. AIP technology has achieved certain success in the complex fault block reservoir [16–18]. However, there are still some defects in AIP technology, which are mainly shown in the two respects: (1) the effectiveness is not clear and the degree of effectiveness is not unified. (2) The mechanism of action is not clear and the main effects are not clear.

Therefore, the author takes a triangle block reservoir as the research object and arranges one injector and two productors according to the shape of the block reservoir. Combined with its geological characteristics and remaining oil distribution, the pressure, remaining oil saturation, and fluid flow velocity of the injection and production process of AIP are studied by numerical simulation. The contributions of this paper lie in two aspects: (1) the subareas of the complex fault block reservoir are studied and the mechanism of AIP in different subareas is discussed; (2) the changes of pressure, oil saturation, and fluid flow direction are studied in the subareas by AIP, and the sweep efficiency, oil displacement efficiency, and recovery are compared with conventional water flooding for further comparative study. The remainder of this paper is organized as follows. In Section 4, AIP is implemented in X11XN80 block, which can reduce water-cut and stabilize oil production and increase the recovery rate by 10.9%. This paper is concluded in Section 5.

2. The Mechanism of AIP Process in Subarea

2.1. The Division of Subarea. The P436 block of LP oilfield is located in the Bohai Bay Basin of China, which is a typical triangle closed-fault block reservoir. The oil-bearing area is 0.11 km^2, and the reserve is 18.7×10^4 t. The reservoir is mainly composed of silty-silty fine sandstone with a median grain diameter of 0.07–0.12 mm. It is mainly composed of pore-contact cementation type, cementation is loose, average porosity is 28.7%, and average permeability is $188.7 \times 10^{-3}\,\mu m^2$. Under formation conditions, the viscosity of crude oil is 58.5 MPa·s and the density is 0.88 g/cm^3. The original formation pressure is 16.1 MPa, saturation pressure is 6.9 MPa, so the difference pressure is 9.2 MPa, the pressure coefficient is 1.01, the formation temperature is 69°C, and the geothermal gradient is 3.6°C/100 m. In 2014, the liquid rate was 31.8 t/day, oil rate was 4.9 t/day, the water cut was 84.6%, the dynamic liquid level was 1148 m, and accumulative oil production was 2.78×10^4 t. The oil recovery was only 14.8%, and the oil recovery rate was 0.07%.

Geological model of LP436 fault block reservoir is built by Petrel, which provides basis for reservoir numerical simulation, overall evaluation, and design of oilfield development project [19]. The numerical simulation is very stable and fast, which is widely used in oil, heat conduction, and other fields [20–24]. The numerical simulation model is established after importing the fluid and production history data and is operated with IMEX module. The mechanism of expanding water flooding sweep by AIP is studied after historical match. The remaining oil in triangle closed-fault block reservoir exhibits local enrichment characteristics: the remaining oil is mainly concentrated in the included angle area and the border area, and the remaining oil saturation is low in the central area.

In conventional injection-production (CIP) process, the injected water always flows along the formed fixed channel and will no longer affect other reservoir areas, so the oil in the unswept area is difficult to flow. The AIP process breaks the inherent flow mode of oil and water to displace the remaining oil by separating the CIP process into two stages: "injection" and "production." The causes of remaining oil is different in different regions. According to the characteristics of the fault block and the results of numerical simulation, the reservoir is divided into different subareas. The principle of division is as follows:

(1) Central area (CA): in the CIP method, the area is near the injector-producer line and the fluid velocity is within 30%, and the remaining oil saturation is less than 0.3.

(2) Border area (BA): an area is from the off-line to the area near the center section and the fluid velocity is low. In the CIP area, the producing degree is not high and the oil saturation is greater than 0.45.

(3) Included angle area (IAA): the area is made up of two sections: reservoir corner and wells near the corner. The characteristics of CIP are similar to BA.

According to the above principles, P436 block is divided into 7 subareas (Figure 1): central area (1#), border area (2#~4#), and included angle area (5#~7#).

2.2. The Mechanism of AIP Technology. In the CIP, the liquid flow rate is fast in CA, while very low in non-CA (Figure 2). The oil is difficult to effectively utilize in non-CA.

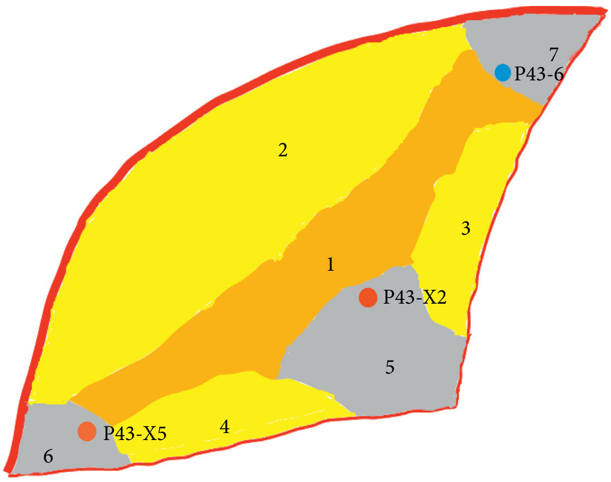

Figure 1: Division areas in triangular closed-fault block reservoirs by seepage characteristics.

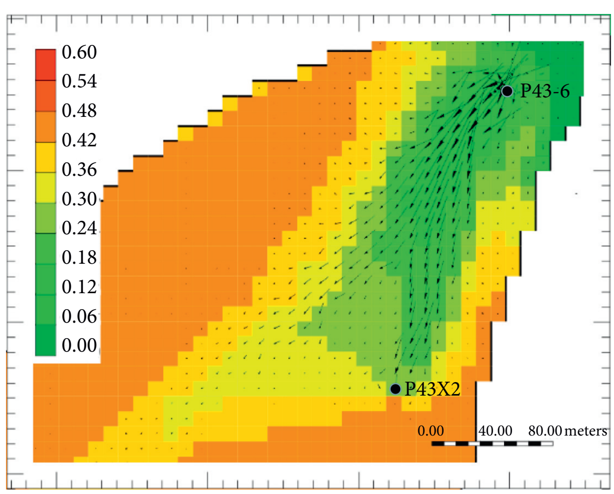

Figure 2: Flow direction of remaining oil in CA under CIP process.

AIP design has the following stages. (1) Injection stage: close producer and open injector. (2) Production stage: close injector and open producer.

In order to study the relationship between each subarea during the AIP process, the characteristic of liquid flow direction in the two different stages of "injection" and "production" is mainly analyzed.

(1) CA: only the injector opens at the injection stage of AIP, so the injected water accumulates continuously in the central area at first. With the increase of accumulated water volume, the pressure in CA continues to increase. When the pressure of CA is greater than that in the BA, the direction of liquid flow turns to BA and the seepage area increases (Figure 3(a)), which indicates that the sweep area of injected water is increasing. With injected water constantly driven to the interior of IAA, the previously nonflow of crude oil is swept to the interior of IAA; therefore, the oil saturation increases and the elastic energy is also continuously superimposed.

At the production stage, the liquid in the CA flows to the producer at first, and the pressure decreases in this area, while the IAA is still in the previous high-pressure state, so there is a pressure difference between CA and IAA. With the pressure difference increasing, oil and water in IAA overcome all kinds of resistance, flow into CA, and finally flow into the producer (Figure 3(a)).

(2) BA: with the stage of AIP changed from "injection" to "production," the oil saturation decreases in BA. At the injection stage, fluid in the CA flows towards the BA under high pressure, and the pressure in BA is gradually increasing. At the production stage, the flow direction in the BA turns to a producer. In the end, the remaining oil saturation in BA is obviously lower than that in the injection stage (Figure 3(b)), and the oil recovery increased by about 1% in the AIP process.

(3) IAA: due to the shelter effect of the fault, the flow direction is changed in IAA. At the injection stage, the oil saturation and reservoir pressure increase with the increase of injected water volume, but decrease at the production stage. At the early production stage, the liquid rate is high by elastic energy released. After one cycle, the remaining oil saturation is obviously lower in IAA, and the oil recovery increased about 1.9%.

3. Comprehensive Characteristics of Subarea and Effect of AIP

3.1. Comprehensive Characteristics in the Subarea. At the injection stage, the pressure and oil saturation have a downward trend in CA. At the production stage, the pressure and oil saturation are decreasing rapidly in CA (Figure 4(a)). Compared with the initial value, the oil saturation is up to 5.2%. By studying the flow direction at the injection stage, the oil in CA is driven to non-CA, and the oil saturation has a upward trend in non-CA (Figure 4(b)). At the production stage, the pressure and oil saturation decrease rapidly and the flow direction points to CA. Compared with the initial value, the oil recovery increases about 1.1%.

Two flow reverse occurred in IAA (Figures 4(c) and 4(d)) in the AIP process, and the pressure and oil saturation increase at the injection stage and decrease at the production stage. The variation of remaining oil saturation is small in IAA and total oil recovery is 0.5%, which is called nonwell control area. The liquid flow velocity in the IAA is very slow in the injection-production process, so the remaining oil enriches at the end of the injection stage, and the remaining oil saturation is almost consistent with the initial value. At the AIP process, the turning of liquid flow almost does not occur in IAA and the water cut and oil rate is almost unchanged.

According to the hydrodynamic analysis of the flow field, the direction of fluid flow in the IAA turns to the mainstream line by regional pressure difference, and then IAA becomes the main oil source area of the CA.

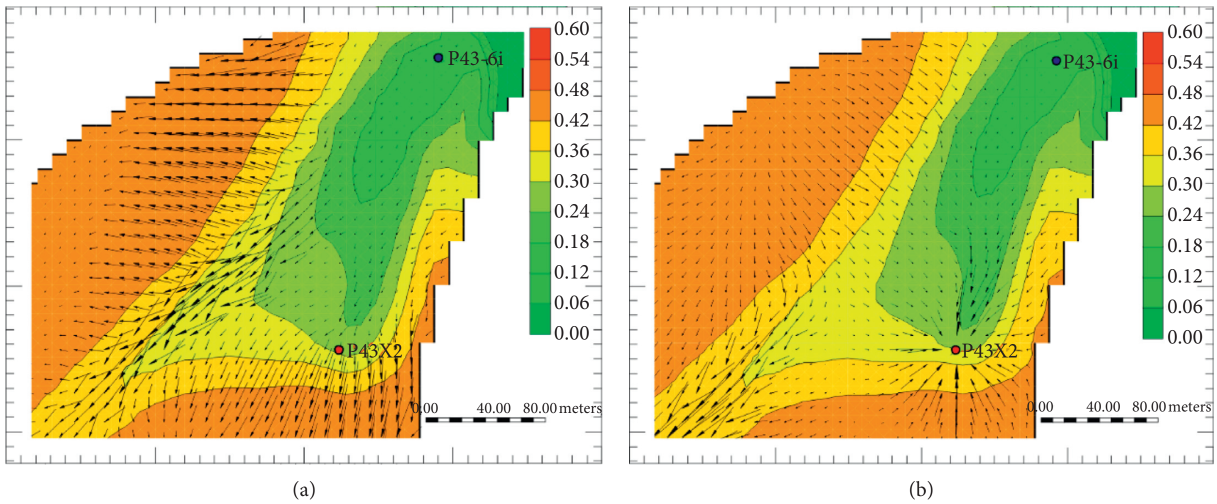

Figure 3: Dynamic characteristics of seepage in CA of remaining oil in different stages: (a) injection stage and (b) production stage.

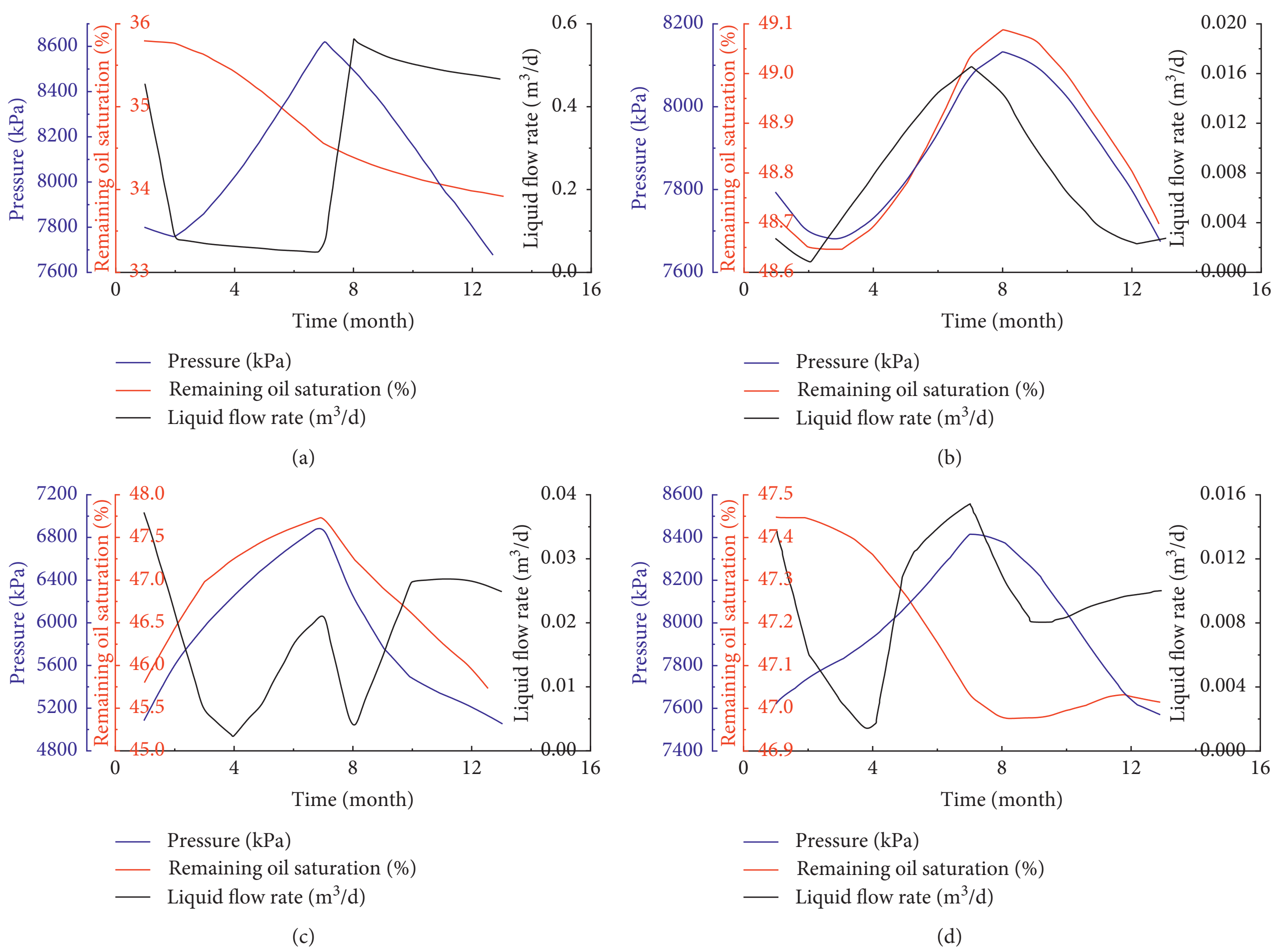

Figure 4: Dynamic characteristics in AIP: (a) central area, (b) border area, (c) high position angle area, and (d) low position angle area.

3.2. The Sweep Efficiency in Subarea. The difference value between oil saturation at any time and initial oil saturation is compared by formula (1). The establishment of formula (1) proves that both elastic volatilization and water injection decrease the oil saturation, which means water has swept into the grid area:

$$S_{oi} - S_{OI,J}^{t} - (C_w S_{wi})\left(P_i - P_{I,J}^{t}\right) > 0. \quad (1)$$

The $S^t_{OI,J}$ and $P^t_{I,J}$ in the formula are the oil saturation and pressure of the mesh at t time at the grid (I, J). $(C_w S_{wi})(P_i - P)$ is the expansion of bound water. The grid block that satisfies the above conditions is counted at each moment in each small layer, and the accumulation of pore volume in their reservoirs is divided by the total pore volume of the layer, which is the volumetric sweep efficiency of the layer.

Comparing the AIP and CIP process, the numerical simulation results show that the former sweep efficiency is larger than the latter (Figure 5). The total sweep efficiency of the AIP process is 0.77 and of the CIP process is less than 0.7. The former increases by 10% compared with the latter. The sweep efficiency in the AIP process is 1.11 times than that in the CIP process in CA (1#) and is 1.35 times in IAA (6#), even the minimum time is 1.05 in BA (2#).

In non-CA, the sweep efficiency increases with the increasing cycle number of the AIP process, which indicates AIP increases sweep efficiency by alternative pressure. The displacement of remaining oil in non-CA mainly depends on the release of elastic energy by large pressure difference.

3.3. Displacement Efficiency. In non-CA, which is near the injector and CA, the oil displacement efficiency by CIP is higher than AIP, but is slightly lower in non-CA which is far from the injector. The reason is the time of erosion and displacement of water is longer in non-CA in the CIP process (Figure 6).

3.4. Recovery Percent. In different subareas, the sweep efficiency and displacement efficiency are different under the two injection and production modes. The change of sweep efficiency and displacement efficiency finally changed the oil recovery. The comparison of oil recovery under two injection production methods indicates that it does not matter whether it is CIP or AIP, 1# and 3# are strong hydrodynamic affected areas with high oil recovery. Compared with the CIP method, the AIP method can not only supplement the formation pressure but also increase the porosity and permeability of the reservoir by hydraulic erosion, so as to improve the recovery in the non-CA area. With the method of AIP, the producing degree of IAA has increased, and the oil recovery of 1#, 3#, and 5# has greatly improved. Considering the different contribution of subareas to the overall oil recovery, the overall oil recovery is increased by about 5% (Figure 7).

Complex fault block reservoirs at high water-cut period accumulate large elastic energy at the water injection stage in the AIP process. The injector is closed at the production stage, so the streamline between the injector and producer is cut off. The release of pressure stimulates the remaining oil in the stagnant flow area to be effectively used, and the oil recovery is improved ultimately in non-CA.

In a production cycle (180 d) of AIP, compared with CIP (450 t), the output of AIP is higher (629 t), and the production costs such as water injection, water treatment cost, and electricity cost are lower. The cumulative oil production of CIP and AIP is counted, and the income under different oil prices is calculated (Figure 8). The results show that

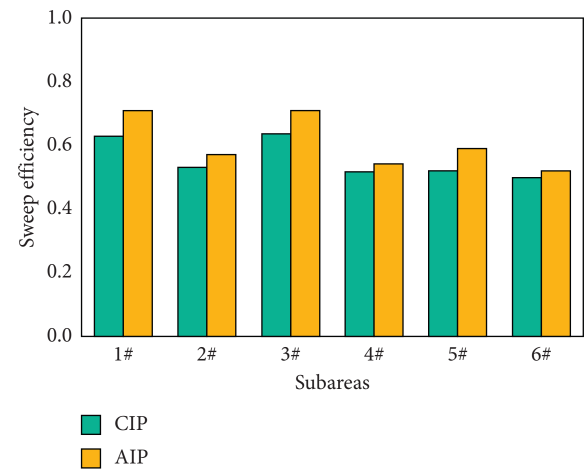

Figure 5: The sweep efficiency comparison of two different processes.

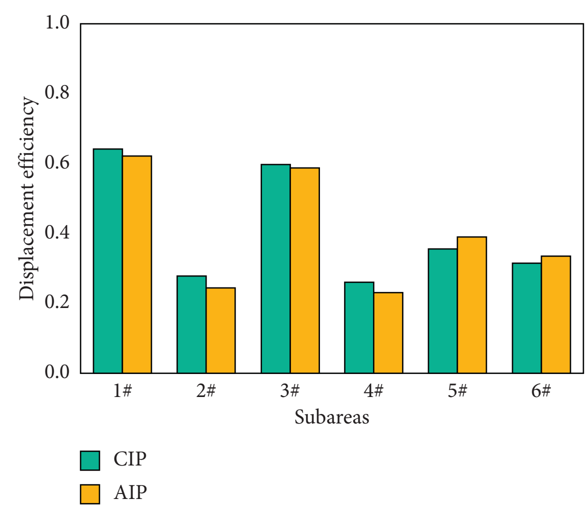

Figure 6: The displacement efficiency comparison of two different processes.

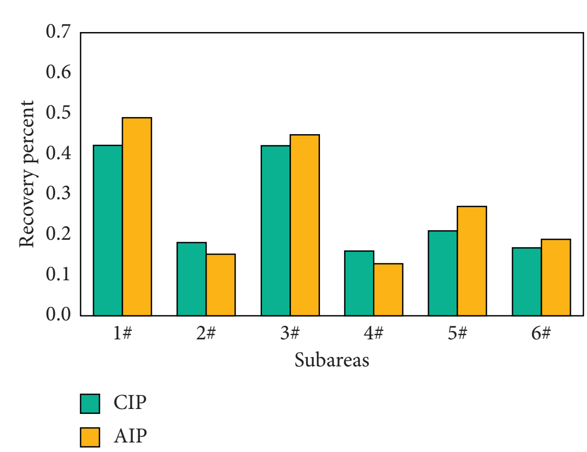

Figure 7: Comparison of recovery of two injection production methods.

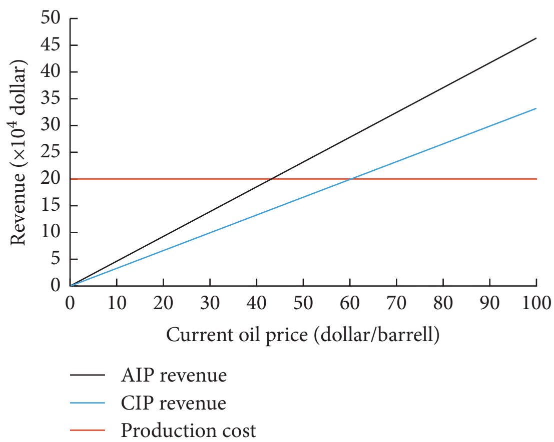

Figure 8: Comparison of economic benefits of two injection production methods.

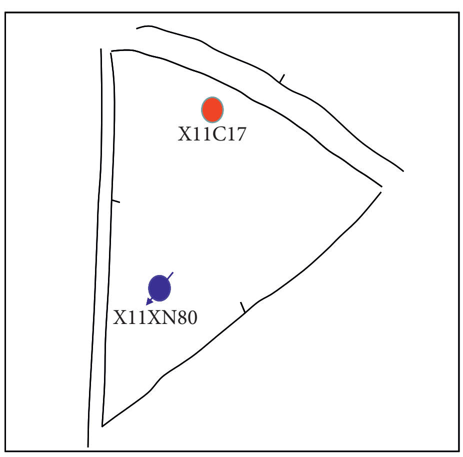

Figure 9: Well location map of X11XN80 reservoir.

compared with CIP, under the same production cost (20×10^4 dollar), the corresponding economic limit oil price of AIP is lower, and AIP can still maintain good economic benefits under low oil price.

4. Applications of AIP

X11XN80 (Figure 9) is located in the northern part of the X11 fault block reservoir, and it is a fault reservoir surrounded by 3 faults. The oil-bearing area is 0.03 km^2, and the geological reserves are 62000 t. The average permeability is $860 \times 10^{-3}\ \mu m^2$, the permeability variation coefficient is 0.593, and the porosity is 25%~35%. This fault reservoir belongs to a medium-high permeability fault block reservoir.

Based on the reservoir conditions, the technical limits of the AIP process are studied through numerical simulation. At the injection stage, the water rate is larger than 100 m^3/d; the injection cycle is about 30 d to 60 d. And at the production stage, the liquid production rate is about 15 m^3/d; the injection-production ratio is less than 1.2; and it is better to have a shut-in well segment. The production cycle is about 100 d to 180 d.

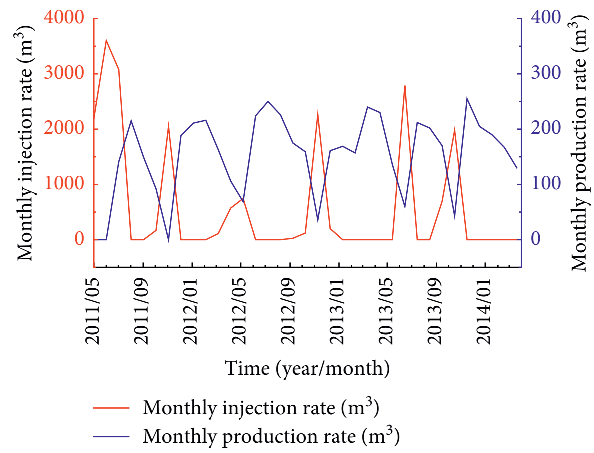

Figure 10: Oil production rate and injection rate of X11XN80 reservoir.

Before the implementation of AIP, one oil well in the fault block was intermittently opened, with daily liquid production of 2.5 m^3, daily oil production of 2.4 t, water cut of 4%, and recovery degree of 27.4%. After adopting the development mode as short injection and long production, the daily liquid production increases to 15 m^3 and the daily oil production is 5 t, which makes up for the production loss caused by short shut-in time. The technical scheme of AIP of the fault block is designed as short injection for 1–3 months, 80–100 m^3/d, and daily liquid production of about 15 m^3 is kept at the production stage. After the implementation of AIP, the daily oil increases to 5.9 t, the comprehensive water cut is 45%, and the recovery degree is increased by 10.9% (Figure 10).

5. Conclusions

(1) The oil recovery in subareas is different in the AIP process. When the permeability heterogeneity is not obvious, the recovery of remaining oil is higher near the line of the injector and producer (including IAA and BA) by the AIP process.

(2) AIP mainly uses residual elastic energy to displace remaining oil by improving sweep efficiency. According to the results of the X11XN80 reservoir, AIP can increase the recovery of the reservoir by 10.9% and can reduce water-cut and stabilize oil production without more drilling, which has high economic benefits. For the reservoir with high water cut and low recovery caused by heterogeneity, AIP technology can achieve better production results.

Data Availability

The data 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.

Acknowledgments

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