Study on mechanisms and influencing factors of the inter-fracture asynchronous huff-n-puff technology of horizontal well in the tight oil reservoir

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Abstract: Tight oil reservoirs have become an important alternative oil resource, and the geological reserve of tight oil reserves is abundant. Currently, the tight oil reservoir is mostly developed by volumetric fractured horizontal wells with the elastic drive of natural energy. However, because there is no energy supplement, the production of volumetric fractured horizontal well declines rapidly, and the final recovery ratio is low. The water huff-n-puff technology is the common method for the energy supplement of the horizontal well. In order to improve the oil recovery of the inter-fracture residual oil in the later stage of water huff-n-puff development of the volumetric fractured horizontal well, mechanisms and influencing factors of the inter-fracture asynchronous huff-n-puff technology of the horizontal well is studied in this paper. Results show that the inter-fracture displacement and the capillary imbibition are mechanisms of the inter-fracture asynchronous huff-n-puff technology of horizontal well. Moreover, The cumulative oil production of horizontal well of the inter-fracture asynchronous huff-n-puff technology decreases and tends to be stable gradually with the increase of the injection rate and increases approximately linearly with the increase of injection volume. With the increase of soaking time, the cumulative oil production of horizontal well of the inter-fracture asynchronous huff-n-puff technology increases and tends to be stable gradually. The increase of production rate leads to the decrease of the cumulative oil production of horizontal well of the inter-fracture asynchronous huff-n-puff technology. The inter-fracture asynchronous huff-n-puff technology of the horizontal well is an efficient method to improve the development effect of water huff-n-puff of horizontal wells, and the study provides a certain guidance for improving the development effect of water huff and puff.

Keywords: Tight oil reservoirs; volumetric fractured horizontal well; formation energy supply; the inter-fracture asynchronous huff-n-puff technology; influencing factors.
1. Introduction
The resource of tight oil reservoirs in China is rich, and the geological reserve is about $125 \times 10^8$ t. The tight oil reservoir is mainly distributed in the Ordos Basin, Tarim Basin, Sichuan Basin, Songliao Basin, Bohai Basin, and Jungar Basin [1-4]. Due to the extremely low permeability of tight oil reservoirs, the wells have no nature productivity, which needs special formation reconstruction to obtain industrial oil flow [3-8]. The popularization and application of horizontal well-drilling technology and staged fracturing technology promote the efficient development of the tight oil reservoir [9]. The tight oil reservoirs are mostly exploited by the volumetric fractured horizontal wells. However, because there is no energy supplement, the production of volumetric fractured horizontal wells declines rapidly, and the final recovery ratio is low [8,10]. Therefore, how to supply formation energy effectively is the key problem in the later development stage of the horizontal well.

Due to the extremely low permeability of tight oil reservoirs and the large-scale fracture network formed by volume fracturing in horizontal wells, the waterflooding method does not work well in the tight oil reservoir. The water huff-n-puff technology is the common method for the energy supplement of the horizontal well in the tight oil reservoir. For the water huff-n-puff of the multi-stage fractured horizontal well, there is a problem that the inter-fracture remaining oil is difficult to produce. In 2016, Lin et al. [11] carried out studies on the segmental water huff-n-puff of the horizontal well, and the result shows that the inter-fracture displacement can not be ignored in the process of the segmental water huff-n-puff of the horizontal well. Subsequently, Cheng et al. [12, 13] studied the inter-fracture asynchronous injection and production technology for the same horizontal well, and the result shows that the inter-fracture asynchronous injection and production technology can give full play to the role of inter-fracture displacement and the capillary imbibition. On this basis, in order to improve the development effect of the water huff-n-puff of horizontal well and the oil recovery of the inter-fracture remaining oil, the inter-fracture asynchronous huff-n-puff technology is studied in this paper. The inter-fracture asynchronous huff-n-puff technology refers to the technology that water injection in part of fractures and then oil production from all fractures after shut-in for a while. Based on the study on the mechanisms of the inter-fracture asynchronous huff-n-puff technology is studied in this paper. The inter-fracture asynchronous huff-n-puff technology refers to the technology that water injection in part of fractures and then oil production from all fractures after shut-in for a while. Based on the study on the mechanisms of the inter-fracture asynchronous huff-n-puff technology is analyzed, the influence of process parameters on the development effect of the inter-fracture asynchronous huff-n-puff technology of horizontal well is studied by the numerical simulation method, so as to provide certain theoretical guidance for improving the development effect of water huff-n-puff in multi-stage fractured horizontal wells in tight oil reservoirs.

2. Comparative experimental study of the water huff-n-puff with different huff-n-puff mode

2.1. Experimental apparatus
The experimental apparatus of the inter-fracture asynchronous huff-n-puff consists of a plunger pump, an intermediate container, and three parallel sand pack tubes (30cm×2.5cm). In order to simulate the inter-fracture displacement of the inter-fracture asynchronous huff-n-puff, the sand pack tubes are connected by pipelines through pressure monitoring ports. the experimental apparatus of the inter-fracture asynchronous huff-n-puff is shown in Fig. 1.
2.2. Experimental procedure

1) The 100 mesh quartz sand is filled into the sand pack tube, and the weight of the sand pack tube before and after filling is calculated to make clear the weight of the quartz sand which is filled into the sand pack tube, so as to ensure the similar porosity and permeability of the three sand pack tubes and the repeatability of the experiment;

2) Sand pack tubes are fully saturated with the formation water using the vacuum pump, and the porosity is measured by the weighting method. Furthermore, the permeability of sand pack tubes are measured respectively;

3) Sand pack tubes are saturated with the crude oil by displacement, and the initial oil saturation can be calculated;

4) Keeping the same injection volume, injection rate, and soaking time, the experiments of general water huff-n-puff and inter-fracture asynchronous huff-n-puff are carried out. In the injection stage of the general water huff-n-puff, three sand pack tubes are all opened. However, the middle sand pack tube is only opened in the injection stage of inter-fracture asynchronous huff-n-puff.

2.3. Results and discussion

Fig. 2 shows the results of the water huff-n-puff with different huff-n-puff modes. It can be seen that the oil recovery of the inter-fracture asynchronous huff-n-puff is higher than that of the general water huff-n-puff. The final oil recovery of the inter-fracture asynchronous huff-n-puff is 14.74%, which is 4.21% higher than the final oil recovery of the general water huff-n-puff. Therefore, the oil recovery of the horizontal well can efficiently be improved by the inter-fracture asynchronous huff-n-puff, and the inter-fracture asynchronous huff-n-puff is an effective method for the development of tight oil reservoirs.
Fig. 2. Comparison of the oil recovery of the water huff-n-puff with different huff-n-puff mode

3. Oil recovery mechanisms of the inter-fracture asynchronous huff-n-puff

The capillary imbibition is the main oil recovery mechanism of the water huff-n-puff in the tight oil reservoir. For the capillary imbibition, the oil in the matrix is replaced into fractures and macro-pores by the imbibition effect of capillary force, which reduces the flow resistance of crude oil, and leads to the redistribution of oil and water in the reservoirs. In addition to the capillary imbibition, the inter-fracture displacement is formed due to the pressure difference between fractures in the process of the inter-fracture asynchronous huff-n-puff, which displaces the inter-fracture remaining oil to fractures with lower pressure and reduces the seepage resistance of crude oil, so as to improve the oil recovery of the water huff-n-puff. It can be seen from Fig.2 that the final oil recovery of the inter-fracture asynchronous huff-n-puff is 14.74%, which is 4.21% higher than the final oil recovery of the general water huff-n-puff. Therefore, the inter-fracture displacement can not be ignored in the process of the inter-fracture asynchronous huff-n-puff. The inter-fracture asynchronous huff-n-puff can give full play to the role of inter-fracture displacement and the capillary imbibition, thus improving the oil recovery of the inter-fracture remaining oil and improving the development effect of the water huff-n-puff.

Fig. 3. Schematic of oil recovery mechanisms of the inter-fracture asynchronous huff-n-puff
4. Influencing factors of the inter-fracture asynchronous huff-n-puff

Influencing factors of the inter-fracture asynchronous huff-n-puff are the injection mode, the injection rate, the injection volume, the soaking time, and the production rate. In order to study the influence of process parameters on the development effect of the inter-fracture asynchronous huff-n-puff, the process of the inter-fracture asynchronous huff-n-puff is simulated by the numerical simulation software (ECLIPSE). The basic parameters of the geological model are shown in Table 1, and the schematic of the reservoir model based on the parameters is shown in Fig. 4.

Table 1. Basic parameters of the geological model

| Parameter                          | Value     | Parameter                          | Value     |
|------------------------------------|-----------|------------------------------------|-----------|
| Number of fractures                | 6         | Half-length of fractures, m         | 260       |
| The conductivity of fractures, $10^{-3}$ $\mu$m$^2$ m | 2250      | Spacing of fractures, m            | 100       |
| Porosity                           | 0.08      | The viscosity of crude oil, mPa$\text{s}^{-1}$ | 17.42     |
| The effective thickness, m         | 15        | Volume coefficient of crude oil    | 1.02      |
| Well radius, m                     | 0.1       | Compression coefficient of formation water, mPa$^{-1}$ | 4.1       |
| Permeability of the matrix         | 0.8       | The viscosity of formation water, mPa$\text{s}$ | 0.3       |
| Oil saturation, %                  | 50        | Volume coefficient of formation water | 1.02      |
| Compression coefficient of crude oil, mPa$^{-1}$ | 7.5       | Initial reservoir pressure, MPa    | 5.4       |

Fig. 4. Schematic of the reservoir model

1) The injection mode

In order to study the influence of the injection mode on the development effect of the inter-fracture asynchronous huff-n-puff, the development effect of the inter-fracture asynchronous huff-n-puff with different injection modes is simulated under the same injection rate, injection volume, soaking time, and production rate. The injection mode can be divided into I$_1$, I$_2$, I$_3$, I$_4$, and I$_5$ five categories, which are the general injection mode, the injection mode with the odd number of fractures open and the even number of fractures close (injection in fracture 1, 3, and 5), the injection mode with the odd number of fractures close and the even number of fractures open (injection in fracture 2, 4, and 6), the injection mode with
the front fractures open and the back fractures close (injection in fracture 1, 2, and 3), and the injection mode with the front fractures close and the back fractures open (injection in fracture 4, 5, and 6). The cumulative oil production of the horizontal well in three cycles is taken as the evaluation index.

Fig. 5. The cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff with different injection modes

Fig. 5 shows that the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff with different injection modes. It can be seen that the development effect of the water huff-n-puff with the injection mode with the odd number of fractures open and even number of fractures close and the injection mode with the odd number of fractures close and even number of fractures open is the best, and the development effect of the water huff-n-puff with the general injection mode is the worst. The development effect of the inter-fracture asynchronous huff-n-puff is all better than that of general water huff-n-puff. That is because that in addition to the capillary imbibition, the inter-fracture displacement can be formed in the process of the inter-fracture asynchronous huff-n-puff, and the combination of the two effects can further improve the development effect of water huff and puff. Given the uneven fluid production in different fractures of horizontal wells, the production of fractures at both ends of the horizontal well is more due to the weak fractures interference, and the production of the middle fracture is less due to the strong fractures interference. Therefore, the development effect of the water huff-n-puff with the injection mode with the odd number of fractures open and even number of fractures close is slightly better than that with the injection mode with the odd number of fractures close and the even number of fractures open.

(2) The injection rate

In order to study the influence of the injection rate on the development effect of the inter-fracture asynchronous huff-n-puff, a series of schemes are designed. Under the condition of the same injection volume, soaking time, production rate, and production time, the cumulative oil production of the horizontal well in three cycles with the injection mode of with the odd number of fractures close and the even number of fractures open at different injection rate is simulated, and the result shows in Fig. 6.
Fig. 6 shows that the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff at different injection rates. It can be seen from Fig. 6 that the cumulative oil production of the horizontal well decreases gradually with the increase of the injection rate, and finally tends to be stable. That is because that the increase of the injection rate will not only lead to the decrease of the time for imbibition but also leads to the inter-fracture water channeling, thus resulting in the decrease of the cumulative oil production of the horizontal well. With the further increase of the injection rate, the inter-fracture water channeling becomes more obvious, so the inter-fracture displacement can be ignored, and the capillary imbibition plays a dominant role in the process of the inter-fracture asynchronous huff-n-puff. Moreover, when the injection rate is high, the time of injection stage can be ignored compared with the soaking time, the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff is only related to the soaking time, and the increase of injection rate has little effect on the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff, so the cumulative oil production of the horizontal well keep stable.

(3) The injection volume

In order to study the influence of the injection volume on the development effect of the inter-fracture asynchronous huff-n-puff, a series of schemes are designed. Under the condition of the same injection rate, soaking time, production rate, and production time, the cumulative oil production of the horizontal well in three cycles with the injection mode of with the odd number of fractures close and the even number of fractures open at different injection volumes is simulated, and the result shows in Fig. 7.
Fig. 7. The cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff at different injection volumes

Fig. 7 shows the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff at different injection volumes. It can be seen that the cumulative oil production of the horizontal well almost shows a linear increasing trend with the increase of the injection rate. With the increase of the injection volume, the formation pressure gets increased, and the volume of fractures and pores swept by the injected water increases, thereby increasing the probability of imbibition and improving the imbibition production. Moreover, with the increase of the injection volume, the inter-fracture displacement gets more sufficient and the displacement efficiency gets improved. The combined effect of the two aspects leads to the increase of cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff.

(4) The soaking time

In order to study the influence of the soaking time on the development effect of the inter-fracture asynchronous huff-n-puff, a series of schemes are designed. Under the condition of the same injection rate, injection volume, production rate, and production time, the cumulative oil production of the horizontal well in three cycles with the injection mode of with the odd number of fractures close and the even number of fractures open at different soaking times is simulated, and the result shows in Fig. 8.
Fig. 8 shows the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff at different soaking times. It can be seen that the cumulative oil production of the horizontal well increases gradually with the increase of soaking time, but the increase of oil production gradually slows down and tends to be stable with the increase of soaking time. The reason is that, with the increase of soaking time, the capillary imbibition is getting more and more sufficient, which increases the oil recovery of the horizontal well of the inter-fracture asynchronous huff-n-puff. Moreover, with the further increase of soaking time, the fracture surface is covered by the oil replaced by imbibition, which has an inhibitory effect on the subsequent imbibition, so the imbibition rate gradually decreases, and the oil recovery of the inter-fracture asynchronous huff-n-puff gradually slows down and tends to be stable.

(5) The production rate

In order to study the influence of the production rate on the development effect of the inter-fracture asynchronous huff-n-puff, a series of schemes are designed. Under the condition of the same injection rate, injection volume, soaking time, and production time, the cumulative oil production of the horizontal well in three cycles with the injection mode of with the odd number of fractures close and the even number of fractures open at different production rates is simulated, and the result shows in Fig. 9.
Fig. 9 shows the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff at different production rates. It can be seen that the cumulative oil production of the horizontal well decreases with the increase of production rate, and finally tends to be stable. Due to the viscosity difference of oil and water, the viscous fingering becomes more and more obvious with the increase of the injection rate, which will lead to the decrease of the displacement efficiency. Although the crude oil in the matrix is imbibed and displaced into the fracture by the injected water, and the seepage resistance of the crude oil is reduced, the displacement efficiency of the injected water is reduced due to the viscous fingering of the injected water, which will lead to the decrease the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff. Therefore, the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff decreases with the increase of the production rate.

5. Conclusion
(1) The inter-fracture displacement and the capillary imbibition are mechanisms of the inter-fracture asynchronous huff-n-puff technology of horizontal well.

(2) Compared with other injection modes, the development effect of the inter-fracture asynchronous huff-n-puff with the injection mode with the odd number of fractures open is the best.

(3) The oil recovery of the horizontal well of the inter-fracture asynchronous huff-n-puff technology decreases with the increase of the injection rate and increases approximately linearly with the increase of injection volume. The increase of the injection rate will not only lead to the decrease of the time for imbibition but also leads to the inter-fracture water channeling, thus resulting in the decrease of cumulative oil production. Moreover, with the increase of the injection volume, the volume of fractures and pores swept by the injected water increases, thereby increasing the probability of imbibition and improving the imbibition production.

(4) With the increase of the soaking time, the capillary imbibition is become more and more sufficient, so the cumulative oil production of the horizontal well of the inter-fracture asynchronous huff-n-puff technology increases. Furthermore, due to the existence of adsorbed oil on the fracture surface, the capillary imbibition gets inhibited, so the increase of cumulative oil production slows down and tends to be stable. Given the viscous fingering, the cumulative oil production of the horizontal well decreases with the increase of production rate and finally tends to be stable.
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