Analysis of improving oil recovery in polymer area by expanding swept volume

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Abstract. In order to realize the development effect of the new K1 polymer flooding block in T oilfield, meet the recovery ratio not lower than that of the old test area and the small well spacing area, and reach or exceed the established development goal of the salt-resistant test area, it is necessary to expand the swept volume technology research. Through the research and application of a series of swept volume expansion technologies, such as high concentration and low speed stage parameters of different types of well groups, application of concentration reduction and speed increase, injection modification and deep profile control, the oil recovery is enhanced. At the stage of high concentration and low speed injection, the suitable injection concentrations of ABCD-IV wells are 1800mg/L-2100mg/L, 1500mg/L-1800mg/L, 1200mg/L-1500mg/L and 1200mg/L and below respectively. Based on the inflection point pressure of the indicator curve during water injection, after the pressure limit of concentration reduction and speed increase is determined to be 8.0MPa, the ratio of liquid absorption thickness before and after the measures and the relative liquid absorption of thin and poor layers show a trend of rising first and then falling; According to the pressure rising space, the injection pressure of all kinds of wells has decreased and the water absorption profile has been improved, and the effect of C and D wells is better than that of A and B; Seen from the drop of apparent water absorption index, the increase of liquid absorption thickness, the maximum water cut drop of connected production wells and the cumulative oil increase of single well, the effect of deep adjustment is the best in blank water drive period, followed by water cut drop period and poor in water cut recovery period.

Keywords: Polymer flooding; Polymer injection; Concentration; Change the note; Profile control.

1. Introduction
In view of polymer injection in the first well pattern, three polymer field tests and five industrial blocks have been carried out in T Oilfield since 1999. By reducing well spacing and subdividing strata, the EOR effect in the test area has gradually improved. From 5.1% in the old test area to 9.6% in the small well spacing area and then to 10% in the salt-resistant test area, the ratio of enhanced oil recovery gradually increased. The research shows that [1-3], expanding swept volume is helpful to further
enhance polymer flooding recovery. The swept volume is closely related to polymer injection parameters, liquid absorption in thin and poor layers, injection modification opportunity, and deep profile control effect [2-8]. In order to realize the development effect of the newly added K1 polymer flooding block in T oilfield, meet the recovery ratio not lower than that of the old test area and the small well spacing area, and reach or exceed the established development goal of the salt-resistant test area, it is necessary to expand the swept volume technology research in order to obtain better development benefits at the end of polymer flooding.

2. Overview of K1 polymer flooding industrial zone

2.1. Geologic feature
K1 polymer area is located in the pure oil area of T development area, covering 6.79km². The reservoir is located in Yaojia-Qingshankou Formation of Lower Cretaceous in Mesozoic, including SⅡ and PⅠ Formation. Among them, PⅠ3 layer contains abundant distributary plain channel sand, which is the main target layer of polymer flooding. The basic parameters of PⅠ3 layer are: On average, the sandstone developed in a single well is 13.82m, the perforated and effective thickness are 10.57m and 8.27m respectively, the geological reserve of the target layer is 634.38×10⁴t, and the underground pore volume is 1263.11×10⁴m³.

2.2. Production status of oil layer
The total water washing ratio of PⅠ3 layer is 73.5%, including strong water washing 46.5% and oil displacement efficiency 69.7%; Medium water washing 27.0%, oil displacement efficiency 42.5%; 26.5% unwashed. Affected by the heterogeneity in the layer and the interlayer of physical properties in the thick oil layer, there are still thick layers with low water washing and perfect injection-production relationship.

2.3. Development status
Up to now, K1 polymer flooding industrial zone has injected a total of 13507t tons of dry powder, 919.78×10⁴m³ of polymer, 0.73PV of injection pore volume, 1,292 mg/L of cumulative injection concentration and 944.1mg/L.PV of polymer. The cumulative recovery rate of polymer flooding wells reached 51.66%, and the oil increase was 50.50×10⁴t.

3. Analysis of measures to expand swept volume

3.1. Parameters of injection well at high concentration and low speed stage
According to the effective thickness, permeability and the proportion of thin and poor layers, the wells are divided into four categories, namely excellent, good, medium and poor. (Table 1).

| Well category | Effective thickness of whole well(m) | Thickness ratio of different permeability (%) | Effective thickness ratio less than 1m(%) | Score |
|---------------|-------------------------------------|---------------------------------------------|-----------------------------------------|-------|
| Excellent     | ≥8                                  | >0.3µm² ≥50                                 | ≤20                                     | 10    |
| Good          | ≥6                                  | >0.2µm² ≥50                                 | ≤30                                     | 8     |
| Middle        | ≥4                                  | >0.1µm² ≥50                                 | -                                       | 6     |
| Poor          | -                                   | -                                           | -                                       | 4     |

According to table 1, well groups are distinguished. There are 33, 29, 23 and 18 well groups in ABCD, with effective thickness of 12.1m, 8.2m, 5.7m and 4.1m and permeability of 0.302µm², 0.267µm², 0.208µm² and 0.169µm² respectively.
In K1 polymer flooding industrial zone, according to the idea of "adjusting first and then flooding", high concentration and low speed slugging is adopted at the initial stage of polymer injection, and the formation pressure is suppressed to the starting pressure of the poor layer, so that the concentration is reduced and the speed is increased to ensure the effective use of the poor layer. According to the pressure rising space and concentration at different well spacing, it is determined that the average injection at the initial stage of polymer injection is about 1750mg/L. In the implementation, the injection concentration of 1200-2500mg/L is designed according to the permeability and injection pressure of single well (Table 2).

Table 2. Classification statistics according to aggregation time

| Concentration grading (mg/L) | Number of wells | Mean concentration (mg/L) |
|-------------------------------|-----------------|--------------------------|
| 1200                          | 24              | 1186                     |
| 1500                          | 33              | 1476                     |
| 1800                          | 18              | 1782                     |
| 2100                          | 23              | 2115                     |
| 2500                          | 5               | 2492                     |
| Total                         | 103             | 1736                     |

(1) 1800mg/L-2100mg/L should be adopted at the initial stage of polymer injection in class A wells After one year, the pressure increase and apparent liquid absorption index decrease by 2.4MPa and 22.7%, which are lower than the average of 3.2MPa and 32% in the whole region. At this time, the pressure suppression effect is poor. At the same time, when the injection concentration is 2500 mg/L, the pressure rise and apparent liquid absorption index decrease are obviously higher than the regional average, and the profile inversion is earlier at this time, which is not conducive to the overall adjustment of the block [3-4]. However, when the concentration of 1800mg/L and 2100mg/L is adopted, the pressure rise and the apparent liquid absorption index decrease reasonably, the ratio of liquid absorption thickness increases continuously, and the profile improvement effect becomes better. Therefore, it is considered that the injection concentration of 1800mg/L-2100mg/L is suitable for the initial stage of polymer injection in class a wells. (Figure 1).

(2) 1500mg/L-1800mg/L should be adopted in the initial stage of polymer injection in class B wells Similar to Class A wells, the increase of average injection pressure and the decrease of apparent liquid absorption index are relatively low after injection with the concentration of 1200mg/L for one year, and the effect is poor. With the concentration of 2100mg/L, the injection pressure and liquid absorption index increased and decreased obviously, and the profile reversed too early. However, when 1500mg/L and 1800mg/L are used, the increase of injection pressure and the decrease of apparent liquid absorption index are reasonable, and the profile is better improved. It is considered that the injection concentration of 1500mg/L-1800mg/L is suitable for Class B wells at the initial stage of polymer injection. (Figure 2)

(3) 1200mg/L-1500mg/L should be adopted in the initial stage of polymer injection in class C wells When 1800mg/L and 2100mg/L are used, the injection pressure and apparent liquid absorption index change too fast, and the profile inversion is too fast. However, when the injection concentration is 1200mg/L and 1500mg/L, the increase of injection pressure and the decrease of apparent liquid absorption index are reasonable, the profile is improved well, and the matching with the reservoir is good. It is considered that the injection concentration of 1200mg/L-1500mg/L is suitable for Class C wells. (Figure 3)

(4) At the initial stage of polymer injection in class D wells, 1200mg/L and below should be adopted When the initial injection concentration of polymer injection is 1200mg/L in Class D wells, the increase of injection pressure is slightly faster than the average of the whole region, and the drop of apparent absorption index is slightly higher than that of the whole region, so the profile is improved to a certain extent, and the effect is better at this time. When the injection concentration is more than 1200
mg/L, the profile inversion is too fast. At the initial stage of polymer injection in class d wells, the concentration is 1200mg/L and below. (Figure 4)

3.2. Practice of reducing concentration and speeding up
Based on the inflection point pressure of the indicator curve during water injection, the pressure limit of concentration reduction and speed increase in the whole area is determined to be 8.0MPa; According to the thickness ratio of high permeability layer, the polymer injection amount is determined to be 120mg/L.PV. (Figure 5 and Figure 6)

Actually, when the injection pressure is 8.4MPa and the polymer injection amount is 137mg/L.PV, the block starts to implement concentration reduction and speed increase. According to the situation, 76 wells are divided into three batches for concentration reduction and speed increase. After the measures, the injection concentration decreased by 367mg/L and the daily injection volume increased by 775m³. On the whole, good results have been achieved in reducing concentration and increasing speed (Table 3)

Table 3. Statistical tables for decreasing concentration and increasing speed wells in batches

| Divide into batches | Number of wells | Injection pressure (MPa) | Daily injection volume (m³) | Injection concentration (mg/L) | Injection pressure (MPa) | Daily injection volume (m³) | Injection concentration (mg/L) |
|--------------------|-----------------|--------------------------|-----------------------------|-------------------------------|--------------------------|-----------------------------|-------------------------------|
| Before adjustment  |                 |                          |                             |                               |                          |                             |                               |
| 1                  | 28              | 8.1                      | 1253                        | 1792                          | 8.5                      | 1559                        | 1398                          |
| 2                  | 20              | 9.7                      | 760                         | 1825                          | 10.3                     | 1001                        | 1482                          |
| 3                  | 28              | 11.8                     | 1650                        | 1919                          | 12.2                     | 1829                        | 1510                          |
| Total              | 76              | 9.9                      | 3663                        | 1836                          | 10.4                     | 4438                        | 1469                          |
| After adjustment   |                 |                          |                             |                               |                          |                             |                               |
| 1                  | 28              | 8.0                      | 1559                        | 1398                          | 0.4                      | 306                         | -394                          |
| 2                  | 20              | 9.7                      | 1001                        | 1482                          | 0.6                      | 241                         | -353                          |
| 3                  | 28              | 11.6                     | 1829                        | 1510                          | 0.4                      | 179                         | -409                          |
| Total              | 76              | 9.9                      | 4438                        | 1469                          | 0.5                      | 775                         | -367                          |

As shown in Figure 7, from the perspective of batch wells, the ratio of liquid absorption thickness and the relative liquid absorption of thin and poor layers of the three batches of wells before and after the measures are increased by 6.4%, 12.2%, 3.6% and 3.6%, 11.6%, 6.9% respectively, both of which show a trend of rising first and then falling.

3.3. Improve the practice of changing notes
When 0.52PV and 800.4mg/L.PV were injected into K1 polymer flooding industrial zone, 7 million salt-resistant polymers were injected instead, and the polymer injection concentration was optimized according to the single well pressure rising space [5-7]:

①Reduce the concentration and viscosity of wells with pressure rise space less than 0.5MPa;
②0.5M Pa-1.0MPa to maintain the viscosity before injection modification;
③1.0M Pa-2.0MPa to keep the concentration before injection;
④Greater than or equal to 2.0M Pa.

Compared before and after the injection change, the injection concentration decreased by 85mg/L, the injection viscosity increased by 4.1mPa.s, and the daily injection increased by 3m³/well. The overall effect of the injection change was good. (Table 4)

Table 4. Design parameters of injection parameters for single injection wells in K1 polymer flooding industrial area

| Pressure rising space (MPa) | Type                        | Number of wells | Before changing the note | After changing the note, |
|-----------------------------|-----------------------------|-----------------|--------------------------|----------------------------|
|                             |                             |                 | Concentration (mg/L)     | Injection quantity (m³)   |
|                             |                             |                 | Viscosity (mPa.s)        |                            |
|                             |                             |                 | Injection quantity (m³)  |                            |
|                             |                             |                 |                          |                            |
| <0.5                        | Thickening and viscosity reduction | 16              | 1009                     | 30.3                     |
|                             |                             |                 |                          | 37                        |
|                             |                             |                 |                          | 841                      |
|                             |                             |                 |                          | 25.6                     |
|                             |                             |                 |                          | 36                       |
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|     | Maintain viscosity |          |          |          |          |
|-----|--------------------|----------|----------|----------|----------|
| 0.5-1 |                     | 22       | 1089     | 35.2     | 47       | 893      | 34.2     | 48       |
| 1-2  | Maintain concentration |        | 44       | 1146     | 38.9     | 40       | 1123     | 44.3     | 41       |
| ≥2   | Thickening and speeding up |     | 21       | 1243     | 44.1     | 49       | 1358     | 60.3     | 58       |
| Total|                     | 103      | 1125     | 37.6     | 44       | 1040     | 41.7     | 47       |

After the measures, the injection pressure decreased by 0.4MPa, the apparent liquid absorption index increased by 0.03m³/d.m.MPa, the layer utilization ratio increased by 5.7%, and the effective thickness utilization ratio increased by 6.3%. As shown in Figure 8, from the classified wells, the injection pressure of all kinds of wells has decreased and the water absorption profile has been improved. From the aspect of effective thickness liquid absorption ratio and relative liquid absorption of thin and poor layer, CD class is better than AB class.

3.4. Improve the depth profile control method

3.4.1. Develop technical specifications. In the process of polymer injection, for some Class A and Class B wells, it is still impossible to effectively block the high permeability layer by injecting polymer with high concentration and high concentration. However, deep profile control can block high permeability layers in time and improve the production status of oil layers [8-13]. In the process of profile control, through analysis and summary, the technical specifications for deep profile control are gradually formed (Table 5):

1. Blocking ultra-high permeability zone in blank water flooding stage;
2. At the stage of water cut decline, take measures to adjust the profile and balance the pressure;
3. Breakthrough measures to control polymer concentration are taken in low water cut stage

| Stage                  | Blank water drive | Water cut descending order | Low water cut                  |
|------------------------|-------------------|-----------------------------|--------------------------------|
| Demand                 | Blocking ultra-high permeability strips | Adjust the profile equalization pressure | Control the breakthrough of polymer concentration |
| Target well            | 1. starting pressure ≤ 5.0mpa.  
2. Injection pressure ≤85% in the whole area 
3. permeability ratio ≥3 
4. Water absorption strength ≥ 40% of the whole area | 1. injection pressure rising speed and injection pressure level ≤ 75% of the whole area 
2. The injection profile has not been improved, and there are high permeability horizons 
3. Apparent water absorption index ≥1.1 times of the whole area 
4. It is ineffective to see the gathering of connected production wells, and the liquid production index is ≥1.1 times that of the whole region | 1. the injection pressure drops 
2. The injection profile is reversed, and there is a single-layer dash phenomenon 
3. Water cut rises, and polymer concentration ≥1.3 times the block average 
4. The decline of liquid production index is ≤90% in the whole region |
| Target layer           | 1. Relative liquid absorption ≥60% for the whole well 
2. Control degree ≥50% 
3. The corresponding production well is the main producing layer 
4. High permeability layer | 1. the relative liquid absorption is ≥ 50% of the whole well 
2. Control degree ≥50% 
3. The corresponding production well is the main producing layer 
4. High permeability layer |
3.4.2. **Optimize slug design.** Optimize the design of profile control slug according to injection pressure level, injection concentration and production status of connected production wells in different polymer injection stages (Table 6).

| Polymer injection stage       | Preposition slug (mg/L) | Main slug (mg/L) | Sealing slug (mg/L) |
|-------------------------------|-------------------------|------------------|---------------------|
| Blank water flooding period   | 2000                    | 1800             | 2000                |
| Water cut decline period      | 2000                    | 1500             | 2000                |
| Water cut recovery period     | 1800                    | 1500             | 1800                |

There are 27 deep profile control wells in K1 Industrial Zone, including 8 wells in blank water drive stage, 12 wells in water cut down stage and 7 wells in water cut up stage. According to Table 7, from the drop of water absorption index, the increase of liquid absorption thickness, the maximum water cut drop of connected production wells and the cumulative oil increase effect of single well in profile control horizon, the effect of deep adjustment is the best in blank water drive period, followed by water cut drop period and poor in water cut recovery period.

| Stage                  | Profile control well effect | Effect of connecting production wells |
|------------------------|----------------------------|--------------------------------------|
|                        | Pressure rise range(%)    | Decrease of apparent liquid absorption index in profile control horizon(%) | Increase ratio of liquid absorption thickness(%) | Maximum decrease of water cut(%) | Low value period time (month) | Accumulated oil increase of single well (t) |
| Blank water flooding period | 45.2                      | 62.3                                 | 12.1                          | 7.95                          | 16                            | 5369                     |
| Water cut decline period   | 28.3                      | 56.7                                 | 8.9                           | 7.41                          | 14                            | 4472                     |
| Water cut recovery period       | 12.7                      | 36.4                                 | 7.5                           | 6.53                          | 11                            | 3257                     |

4. **Implementation effect**

From the current development effect, compared with other blocks, K1 polymer flooding effect is better than the small well spacing test area and the old test area and equivalent to the salt resistance test area, as shown in Figure 9.

![Fig. 1 Matching curve of block flooding block in whole area](image-url)
The effect of K1 polymer flooding is compared with other blocks in the northern oilfield: as shown in Table 9, four polymer injection blocks with similar reservoir conditions to K1 polymer flooding industrial zone are selected for effect comparison. Compared with the northern block, the enhanced oil recovery has the same amplitude and recovery degree.

Table 8. Comparison with North polymer flooding block

| Block                     | The end of polymer flooding is to enhance oil recovery (%) | Recovery degree at the end of polymer flooding (%) |
|---------------------------|----------------------------------------------------------|-------------------------------------------------|
| Type II of fault east block | 10.14                                                   | 49.40                                           |
| Zone 2 of Northwest block | 8.81                                                    | 49.72                                           |
| South Central East District 1 | 11.53                                                  | 53.41                                           |
| Central part of district 4-5 | 9.93                                                    | 53.09                                           |
| K1 polymer flooding Industrial Zone | 9.78                                                   | 51.98                                           |

5. Conclusions
1. At the stage of high concentration and low speed injection, the suitable injection concentrations of ABCD-IV wells are 1800mg/L-2100mg/L, 1500mg/L-1800mg/L, 1200mg/L-1500mg/L and 1200mg/L and below, respectively. At this time, the increase of injection pressure and the decrease of apparent absorption index are reasonable, and the profile improvement effect is the best.
2. Based on the inflection point pressure of the indicator curve during water injection, the pressure limit of concentration reduction and speed increase is determined to be above 8.0MPa, and the ratio of liquid absorption thickness before and after the measures and the relative liquid absorption of thin and poor layers first increase and then decrease;
3. According to the pressure rising space, the injection pressure of all kinds of wells decreased, and the improvement of C and D wells was better than that of A and B wells;
4. During deep profile control, measures should be taken to block ultra-high permeability strips in blank water drive stage, to adjust profile to equalize pressure in water cut down stage, to control breakthrough of polymer concentration in low water cut stage, and to increase oil production in production wells, at the same time, apparent water absorption index of injection horizon decreases, liquid absorption thickness increases and maximum water cut of production wells decreases.
5. Compared with the northern polymer flooding block, the recovery ratio and recovery percent have increased by a similar margin, and the development of the whole region has achieved good results.

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