The evaluation of the optimization design and application effect of same-well-injection-production technique’s injection-production circulatory system

Zheng Guoxing¹,², Jiang Minghu¹, Gong Hongliang², Zhang Nannan³, Wei Jianguang⁴

¹ School of Mechanical Science and Engineering, Northeast Petroleum University, Daqing 163318, Heilongjiang, China;
² Daqing Oilfield Production Technology Institute, Daqing 163453, Heilongjiang, China;
³ Daqing Oilfield third oil extraction plant geologic team, Daqing 163113, Heilongjiang, China;
⁴ School of Petroleum Engineering, Northeast Petroleum University, Daqing 163318, Heilongjiang, China
E-mail: zhengguoxing@petrochina.com.cn

Abstract: According to basic principles of combining series of strata and demands of same-well injection-production technique, the optimization designing method of same-well injection-production technique’s injection-production circulatory system is given. Based on oil-water two-phase model with condition of arbitrarily well network, a dynamic forecast method for the application of same-well injection-production reservoir is established with considering the demands and capacity of same-well injection-production technique, sample wells are selected to launch the forecast evaluation and analysis of same-well injection-production reservoir application’s effect. Results show: single-test-well composite water cut decreases by 4.7% and test-well-group composite water cut decreases by 1.56% under the condition of basically invariant ground water injection rate. The method provides theoretical support for the proof of same-well injection-production technique’s reservoir development improving effect and further tests.

1. Introduction
The same well’s injection-production technique began in the early 1990s¹⁻² and it’s still being in the technique exploration & field test stage. There are many literatures¹¹⁻¹³ about its process principle³⁻⁴, pipe string⁵⁻⁶ designing and bottom hole fluid treatment⁷⁻¹⁰. However the same well injection-production circulatory system’s optimization designing and reservoir application effect evaluation is still in the blank stage. The same well injection-production circulatory system’s optimization designing and application effect evaluation have the characteristics below: the flooding effect should be considered with conditions of different well networks while optimizing the pressure system; numerical simulation is needed to achieve the visualization of the test-well flooding effect; prediction and contrast evaluation of the before/after-application development index and experiment index should be settled swiftly. Therefore, it is significant to launch the optimization designing and application effect evaluation. The research of the application effect evaluation method has important
engineering guiding significance for the promotion and application of injection-production technique in the same well.

2. Injection-production circulatory system optimization design

2.1. Production interval design
The designing method is suggested to be launched as follow:
- Determine the coordinate of production well and injection well in design interval. (test well centered)
- Determine the reservoir flow coefficient and skin factor according to water flooding stage’s production drawdown pressure and design interval’s injection & production liquid yield.
- Determine BHP and flow rate of the injection well and production well in design interval. (test well excepted)
- Determine the minimum value of the test well’s production interval BHP ($p_{wf_{min}}$).
- Calculate production interval’s maximum liquid production capacity ($q_{max}$) according to arbitrary well network condition’s oil-water two-phase seepage model.
  - Contrast the test well production interval’s designed liquid production yield ($q_o$) with calculated maximum liquid production capacity ($q_{max}$). Design will be approved only if test-well production interval’s maximum liquid production capacity ($q_{max}$) is more than designed liquid production yield ($q_o$), otherwise the test well production interval should be redesigned with means increasing production interval thickness or decreasing the designed liquid production yield until meet the demands.

2.2. Injection interval design
The designing method is suggested to be launched as follow:
- Determine the coordinate of production well and injection well in design interval. (test well centered)
- Determine the reservoir flow coefficient and skin factor according to water flooding stage’s production drawdown pressure and design interval’s injection & production liquid yield.
- Determine BHP and flow rate of the injection well and production well in design interval. (test well excepted)
- Determine test well injection interval’s reasonable injection ratio and injection rate. ($q_i=R\cdot q_0$)
- Calculate test well’s injection interval minimum liquid rate for successful designed flow rate ($q_i$) injection according to arbitrary well network condition’s oil-water two-phase seepage model. ($p_{wf_{min}}$)
  - Contrast the maximum working pressure ($p_{work}$) provided by same well’s injection-production technique in injection interval with calculated test-well-injection-interval minimum injection pressure ($p_{work}$). Design will be approved only if calculated test-well-injection-interval minimum injection pressure is less than the maximum working pressure provided by same well’s injection-production technique, otherwise the test well injection interval should be redesigned with means increasing injection interval thickness or working pressure until meet the demands.

The injection interval and production interval are considered as an integral circulatory system. The production interval design and injection interval design above must satisfy the engineering demands, as shown in Figure 1.
3. Forecast and evaluation of same-well injection-production technique’s reservoir application effect

3.1. Production-interval/injection-interval BHP calculating method in each designed well. There are interferences amidst wells in the condition of well network. According to the Potential superposition principle, the potential of arbitrary point is determined as:

$$\Phi_M = \frac{1}{0.54287} \sum_{i=1}^{n} q_i \ln r_i + C$$

By taking particular points from supply boundary and borehole wall, the relation between BHP and flow rate is determined as:

$$p_e - p_{w,i} = \frac{\mu}{0.54287 h K} \sum_{i=1}^{N} q_n \ln \left( \frac{r_e}{r_{n,i}} \right)$$

$$r_{n,i} = \begin{cases} \left[ \ln \left( (x_n - x_i)^2 + (y_n - y_i)^2 \right) \right]^{1/2} & (i \neq n) \\ r_w & (i = n) \end{cases}$$

Taking the typical five-spot network as the example, relation equation set between BHP and flow rate with the condition of single-phase flow is arranged as:

$$p_e - p_{+1} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,1}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,1}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,1}} \right) + \ldots + q_{14} \ln \left( \frac{r_e}{r_{15,1}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,1}} \right) \right]$$

$$p_e - p_{+2} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,2}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,2}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,2}} \right) + \ldots + q_{13} \ln \left( \frac{r_e}{r_{15,2}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,2}} \right) \right]$$

$$p_e - p_{+3} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,3}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,3}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,3}} \right) + \ldots + q_{12} \ln \left( \frac{r_e}{r_{15,3}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,3}} \right) \right]$$

$$p_e - p_{+4} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,4}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,4}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,4}} \right) + \ldots + q_{11} \ln \left( \frac{r_e}{r_{15,4}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,4}} \right) \right]$$

$$p_e - p_{+5} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,5}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,5}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,5}} \right) + \ldots + q_{10} \ln \left( \frac{r_e}{r_{15,5}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,5}} \right) \right]$$

$$p_e - p_{+6} = \frac{\mu}{0.54287 h K} \left[ q_1 \ln \left( \frac{r_e}{r_{1,6}} \right) + q_2 \ln \left( \frac{r_e}{r_{2,6}} \right) + q_3 \ln \left( \frac{r_e}{r_{3,6}} \right) + \ldots + q_{9} \ln \left( \frac{r_e}{r_{15,6}} \right) + q_{14} \ln \left( \frac{r_e}{r_{16,6}} \right) \right]$$
Adding relative permeability to equation set, relation equation set between BHP and flow rate under the condition of oil-water two-phase flow is determined as:

\[
P_e - P_{w,t} = \frac{\mu_o}{0.54287 h K_{rw}} \left[ q_1 \ln \left( \frac{r_o}{r_{1,1}} \right) + q_2 \ln \left( \frac{r_o}{r_{1,2}} \right) + \cdots + q_n \ln \left( \frac{r_o}{r_{1,n}} \right) \right]
\]

\[
P_e - P_{w,16} = \frac{\mu_o}{0.54287 h K_{rw}} \left[ q_1 \ln \left( \frac{r_o}{r_{1,1}} \right) + q_2 \ln \left( \frac{r_o}{r_{1,2}} \right) + \cdots + q_{16} \ln \left( \frac{r_o}{r_{1,16}} \right) \right]
\]

Based on the oil-water two-phase flow model with arbitrary well network condition, the same-well injection-production technique reservoir application’s dynamic forecasting method is established with considering same-well injection-production technique’s demands and capacity, as shown in Figure 2.

**Figure 2.** Dynamic forecast method of same-well injection-production reservoir’s application affect

3.2. Calculating method of the original-development-plan reservoir development index.

3.2.1. Calculating method of original-plan well group’s total ground water injection rate.

Production interval:

\[
q_{\text{out,ground}} = \sum_{i=1}^{n} q_{\text{in},i}
\]

In the formula above, \( q_{\text{out,ground}} \) stands for the total ground water injection rate of original-plan well group’s production-interval injection well, m\(^3\)/d; \( q_{\text{in},i} \) stands for original-plan well group’s production-interval ground water injection rate of the \( i \)th injection well, m\(^3\)/d.

Injection interval:
\[ q_{\text{in,ground}} = \sum_{i=1}^{n} q_{\text{in},i} \]

In the formula above, \( q_{\text{in,ground}} \) stands for the total ground water injection rate of original-plan well group’s injection-interval injection well, \( m^3/d \); \( q_{\text{in},i} \) stands for original-plan well group’s injection-interval ground water injection rate of the \( i \)th injection well, \( m^3/d \).

3.2.2. Calculating method of original-plan well group’s total ground liquid production yield.

Production interval:

\[ q_{\text{out,ground}} = \sum_{i=1}^{n} q_i + q_{\text{out,test}} \]

In the formula above, \( q_{\text{out,ground}} \) stands for the total ground liquid production yield of original-plan well group’s production interval, \( m^3/d \); \( q_i \) stands for original-plan well group’s production-interval ground liquid production yield of the \( i \)th production well, \( m^3/d \); \( q_{\text{out,test}} \) stands for the test-well liquid production yield, \( m^3/d \).

Injection interval:

\[ q_{\text{in,ground}} = \sum_{i=1}^{n} q_i \]

In the formula above, \( q_{\text{in,ground}} \) stands for the total ground liquid production yield of original-plan well group’s injection interval, \( m^3/d \); \( q_i \) stands for original-plan well group’s production-interval ground liquid production yield of the \( i \)th production well, \( m^3/d \).

3.2.3. Calculating method of original-plan well group’s ground composite water cut.

Production interval:

\[ f_{w,\text{out}} = 1 - \left( \sum_{i=1}^{n} (1 - f_{w,i}) \cdot q_i + (1 - f_{\text{out,test}}) \cdot q_{\text{out,test}} \right) \cdot \left( \sum_{i=1}^{n} q_i + q_{\text{out,test}} \right)^{-1} \]

In the formula above, \( f_{w,\text{out}} \) stands for the ground composite water cut of original-plan well group’s production interval, dimensionless; \( f_{w,i} \) stands for the \( i \)th production well’s average water content ratio of the production interval, dimensionless; \( f_{\text{out,test}} \) stands for production interval’s test-well average water content ratio, dimensionless.

Injection interval:

\[ f_{w,\text{in}} = \left( \sum_{i=1}^{n} f_{w,i} \cdot q_i \right) \cdot \left( \sum_{i=1}^{n} q_i \right)^{-1} \]

In the formula above, \( f_{w,\text{in}} \) stands for the ground composite water cut of original-plan well group’s injection interval, dimensionless; \( f_{w,i} \) stands for the \( i \)th production well’s average water content ratio of the injection interval, dimensionless; \( f_{\text{out,test}} \) stands for production interval’s test-well average water content ratio, dimensionless; \( q_i \) stands for the \( i \)th production well’s ground liquid production yield of the injection interval, \( m^3/d \).

3.2.4. Calculating method of the original-plan well group’s total crude output.

Production interval:

\[ q_{\text{out,o}} = q_{\text{out,ground}} \cdot (1 - f_{w,\text{out}}) \]

Injection interval:

\[ q_{\text{in,o}} = q_{\text{in,ground}} \cdot (1 - f_{w,\text{in}}) \]
In the formula above, \( q_{\text{out,group}} \) stands for original-plan well group’s production-interval total ground crude output, m\(^3\)/d; \( q_{\text{in,group}} \) stands for original-plan well group’s injection-interval total ground crude output, m\(^3\)/d.

3.3. Calculating method of same-well injection-production technique’s reservoir development index.

3.3.1. Calculating method of test-well-group total ground water injection rate.
Production interval:

\[
q_{\text{out,ground}} = \sum_{i=1}^{n} q_{\text{in,i}}
\]

In the formula above, \( q_{\text{in,ground}} \) stands for test well group’s production-interval injection-well total ground water injection rate, m\(^3\)/d; \( q_{\text{in,i}} \) stands for the \( i \)th injection well’s ground water injection yield of test-well-group production interval, m\(^3\)/d.

Injection interval:

\[
q_{\text{in,group}} = \sum_{i=1}^{n} q_{\text{in,i}}
\]

In the formula above, \( q_{\text{in,ground}} \) stands for test well group’s injection-interval injection-well total ground water injection rate, m\(^3\)/d; \( q_{\text{in,i}} \) stands for the \( i \)th injection well’s ground water injection yield of test-well-group injection interval, m\(^3\)/d.

3.3.2. Calculating method of test-well-group total ground liquid production yield.
Production interval:

\[
q_{\text{out,ground}} = \sum_{i=1}^{n} q_{i} + q_{\text{out,test}} - q_{\text{in,test}}
\]

In the formula above, \( q_{\text{out,ground}} \) stands for test well group’s production-interval injection-well total ground liquid production yield, m\(^3\)/d; \( q_{i} \) stands for the \( i \)th production well’s ground liquid production yield of test-well-group production interval, m\(^3\)/d; \( q_{\text{out,test}} \) stands for the test-well liquid production yield, m\(^3\)/d; \( q_{\text{in,test}} \) stands for test-well reinjection rate, m\(^3\)/d.

Injection interval:

\[
q_{\text{in,ground}} = \sum_{i=1}^{n} q_{i} + q_{\text{in,test}}
\]

In the formula above, \( q_{\text{in,ground}} \) stands for test well group’s injection-interval total ground liquid production yield, m\(^3\)/d; \( q_{i} \) stands for the \( i \)th production well’s ground liquid production yield of test-well-group injection interval, m\(^3\)/d.

3.3.3. Calculating method of test well group’s ground composite water cut.
Production interval:

\[
f_{w,\text{out}} = 1 - \left( \sum_{i=1}^{n} (1 - f_{w,i}) \cdot q_{i} + (1 - f_{w,\text{out,test}}) \cdot q_{\text{out,test}} \right) \cdot \left( \sum_{i=1}^{n} q_{i} + q_{\text{out,test}} - q_{\text{in,test}} \right)^{-1}
\]

In the formula above, \( f_{w,\text{out}} \) stands for the ground composite water cut of test well group’s production interval, dimensionless; \( f_{w,i} \) stands for the \( i \)th production well’s average water content ratio of the production interval, dimensionless; \( f_{w,\text{test}} \) stands for production interval’s test-well average water content ratio, dimensionless.

Injection interval:

\[
f_{w,\text{in}} = \left( \sum_{i=1}^{n} f_{w,i} \cdot q_{i} \right) \cdot \left( \sum_{i=1}^{n} q_{i} \right)^{-1}
\]
In the formula above, $f_{w,in}$ stands for the ground composite water cut of test well group’s injection interval, dimensionless; $f_{w,i}$ stands for the $i$th production well’s average water content ratio of the injection interval, dimensionless; $f_{out,test}$ stands for production interval’s test-well average water content ratio, dimensionless; $q_i$ stands for the $i$th production well’s ground liquid production yield of the injection interval, m$^3$/d.

3.3.4. Calculating method of test well group’s ground crude output.

Production interval:

$$q_{out,o} = q_{out,ground} \cdot (1 - f_{w,out})$$

Injection interval:

$$q_{in,o} = \left( q_{in,ground} + q_{in,test} \right) \cdot (1 - f_{w,in})$$

In the formula above, $q_{out,o}$ stands for the total ground crude output of test well group’s production interval, m$^3$/d; $q_{in,o}$ stands for the total ground crude output of test well group’s injection interval, m$^3$/d.

4. Evaluation analysis of same-well injection-production technique’s reservoir applications effect.

A well group is selected to launch the forecast analysis of same-well injection-production reservoir application’s effect in the well site, as well as the contrast evaluation of same-well injection-production technique’s before-application & after-application development indexes.

4.1 Forecast-Accuracy verification of same-well injection-production technique’s reservoir application effect.

Contrast the water contents’ predicted values with actual values and numerical simulation result, as shown in Figure 3. The error between the predicted value and the numerical simulation is 2.6%; the error is 6.7% with the nearest actual value and the average actual error is 19.6%.

![Figure 3. The change of water content with time in different plans.](image-url)
Figure 4. The change of BOPD with time in different plans

Contrast the barrels oil per day’s (BOPD) predicted values with actual values and numerical simulation result, as shown in Figure 4. The error between the predicted value and the numerical simulation is 9.1%; the error is 11.1% with the nearest actual value and the average actual error is 10.7%.

4.2 Contrast evaluation of before-test and after-test application effect.
The before-well-group-test and after-well-group-test development indexes can be determined by using the reservoir application effect’s dynamic-forecast method above, as shown in Table 1.

| Plan Index          | Production interval | Injection interval |
|---------------------|---------------------|--------------------|
|                     | Original plan       | Same-well          | Contrast | Original plan       | Same-well          | Contrast |
|                     |                     | injection-         |          |                     | injection-          |          |
|                     |                     | production technique |          |                     | production technique |          |
| Total ground        | 392.3 m³/d          | 392.3 m³/d        | invariant| 243.4 m³/d          | 243.4 m³/d        | invariant         |
| water injection     |                     | invariant         |          |                     |                     |          |
| Total ground        | 100 m³/d            | 30 m³/d           | decreases by 70 m³/d | 80.64 m³/d         | 80.64 +70 m³/d     | increases by 70 m³/d |
| liquid production   |                     | decreases by 4.7% |          |                     |                     |          |
| Ground composite    | 98%                 | 93.33%            | decreases by 4.7% | 96.98%             | 96.98%             | invariant         |
| water cut           |                     |                  |          |                     |                     |          |
| Total ground        | 2.0 m³/d            | 2.0 m³/d          | invariant| 2.44 m³/d           | 4.41 m³/d          | increases by 1.97 m³/d |
| crude output        |                     |                   |          |                     |                     |          |

Contrast shows:
After the application of same-well injection-production technique, production-interval total ground liquid production yield decreases by 70m³/d; injection-interval ground liquid production yield increases by 70m³/d.
After the application of same-well injection-production technique, single-test-well composite water cut decreases by 4.7% under the condition of basically invariant ground water injection rate; test-well-
group composite water cut decreases by 1.56% under the condition of basically invariant ground water injection rate.

Before/after-test production-interval ground crude output doesn’t change. After the application of same-well injection-production technique, injection-interval total ground crude output increases 1.97 m³/d.

5. Conclusions
The optimization designing method of same-well injection-production technique’s injection-production circulatory system is given. The method is able to achieve the optimization design of injection-production technique’s injection-interval and production-interval injection-production circulatory system under condition of arbitrarily well network.

Based on oil-water two-phase flow model and test well group’s basic data under the condition of arbitrarily well network, a dynamic forecast method for the same-well injection-production reservoir application is established with considering same-well injection-production technique’s demands and capacity.

A well group is selected to launch the sample forecast analysis of same-well injection-production reservoir application’s effect in the well site, as well as the contrast evaluation of same-well injection-production technique’s before-application & after-application development indexes. Contrast results show: single-test-well composite water cut decreases by 4.7% and test-well-group composite water cut decreases by 1.56% under the condition of basically invariant ground water injection rate.

Reference
[1] Zhao L X and Jiang M H 1999 review of downhole oil-water separation & produced water re-injection J. FOREIGN 03 51-56
[2] Amr I and Abdel F 2016 acoustic downhole three-phase separation method in oil field applications C. SPE 183265
[3] Kaya A S, Sarica C and Brill J P 2001 mechanistic modeling of two-phase flow in deviated wells C. SPE 72998
[4] Wang S Q 2014 field test of same-well injection-production downhole oil-water separation technique J. Oil-Gas Field Surface Engineering 11 28-29
[5] SUN A J, Xu Y N, Li H L and et al. 2003 force analysis and theoretical caculation of water injection string J. Drilling & Production Technology 26(3) 55-57
[6] Yang K 2011 packer design and mechanical analysis of injection-production string in one well D. China University of Petroleum (EastChina) 2-3
[7] Stuebinger L A and Elphingstone J G 2000 multipurpose wells downhole oil/water separation in the future J. SPE 65071
[8] Yang S R and Xie W 2011 optimization design of oil—water separator for injection — production in the same well J. Special Oil & Gas Reservoirs 06 106-108
[9] Suarez L, Kenyery F and Asuaje M 2005 3D CFD simulation of rotary gas-separator performance under two-phase-flow condition C. SPE 94959
[10] Golam M, Moli'd M A and Andreas S 2016 review and applicability of downhole separation technology C. SPE 184201.
[11] CAO M J, DU Y and ZHANG F T 2005 analysis of down hole oil-water separation for injection-production technique in the same well to the adaptability of producers in polymer-flooding oilfields J. Journal of Northeast Petroleum University 29(6) 55-58
[12] CHEN S N, LI H and et al 2007 design method and parameters sensitivity analysis of down-hole oil water separation system J. ODPT 29(3) 32-35
[13] Q S Zeng, Z M Wang and X Q Wang 2016 a novel oil–water separator design and its performance prediction J. Journal of Petroleum Science and Engineering 145 83-94