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ORIGINAL PAPER

A new method for evaluating the injection effect of chemical flooding

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Abstract Hall plot analysis, as a widespread injection evaluation method, however, often fails to achieve the desired result because of the inconspicuous change of the curve shape. Based on the cumulative injection volume, injection rate, and the injection pressure, this paper establishes a new method using the ratio of the pressure to the injection rate (RPI) and the rate of change of the RPI to evaluate the injection efficiency of chemical flooding. The relationship between the RPI and the apparent resistance factor (apparent residual resistance factor) is obtained, similarly to the relationship between the rate of change of the RPI and the resistance factor. In order to estimate a thief zone in a reservoir, the influence of chemical crossflow on the rate of change of the RPI is analyzed. The new method has been applied successfully in the western part of the Gudong 7th reservoir. Compared with the Hall plot analysis, it is more accurate in real-time injection data interpretation and crossflow estimation. Specially, the rate of change of the RPI could be particularly suitably applied for new wells or converted wells lacking early water flooding history.

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1 Introduction

Chemical flooding, a rapidly developed tertiary oil recovery technique, is applied successfully and widely both in the Daqing Oilfield and the Shengli Oilfield (Zhang et al. 2010; Hou et al. 2011, 2013; Shaker Shiran and Skauge 2013; Dag and Ingun 2014). Polymer flooding and surfactant-polymer flooding (SP flooding) are considered two of the most mature chemical methods (Chang et al. 2006; Vargo et al. 2000; Li et al. 2012; Delamaide et al. 2014; Sheng et al. 2015). Polymer flooding uses high-molecular weight polymers to increase the viscosity of the injection fluid, and to decrease the oil–water mobility ratio, while the SP flooding further improves the oil recovery by adding a surfactant to the injection fluid to reduce the interfacial tension and then increase the oil displacement efficiency (Shen et al. 2009; Urbissinova et al. 2010). However, due to the high prices of chemicals, in most cases, the implementation of chemical flooding is usually costly. Thus, a timely and accurate evaluation of the displacement efficiency of chemical floods, which can verify the validity of the chemical injection in advance, is urgently needed (Kaminsky et al. 2007; Dong et al. 2009; Seright et al. 2009; AlSofi and Blunt 2014; Ma et al. 2007).

Usually, the injection evaluation of chemical flooding is conducted by the variation of dynamic injection data such as the rise of the injection pressure and the drop of the injection rate. The increase in the flow resistance to the injection fluid indicates the increment of the chemical efficiency. After the chemical solution is injected into a reservoir, due to the high-molecular weight polymer dissolved in the injection fluid, the flow resistance increases, causing an increase in the injection pressure and a decline in the injection rate (Cheng et al. 2002; Li 2004). As a result, the variation of the injection pressure and the injection rate can be used to evaluate whether the chemical injection is effective.

The Hall plot describes the relationship between the time integral of the injection pressure difference and the cumulative injection volume. The Hall plot analysis was firstly used to evaluate the performance of waterflood wells (Hall 1963) and gradually was used as a simple, effective method for diagnosing the injection efficiency (DeMarco 1969). Since then, researchers have improved the Hall plot analysis. Based on the Hall plot analysis, the slope analysis method which produces an estimation of the pressure at the average water-bank radius in Hall's formula was put forward by Silin et al. (2005). The slope analysis is proved to be more accurate for all data needed is available from oilfields. After that, Izgec and Kabir (2009) presented a complete reformulation of the Hall plot analysis by updating the pressure at the average influence radius after each computing time step and studied the difference between the Hall plot and the derivative of the Hall slope, under the condition of both transient and pseudo-steady states. Compared with the Hall plot, the derivative of the Hall slope could overcome the smooth effect which is caused by integral involved in the Hall plot analysis.

With the development of chemical flooding, Hall plot analysis was used to evaluate the flow behavior of non-Newtonian fluids in the field of polymer flooding (Moffitt and Menzie 1978). Later, the analytical expressions of the Hall slope analysis for polymer floods, resistance factor, and the residual resistance factor were derived by Buell et al. (1990). Considering that the reservoir permeability is an important factor affecting the resistance factor, Kim and Lee (2014) used the effective permeability changing with the water saturation instead of regarding permeability as a constant, improving the accuracy of the Hall plot analysis. Li et al. (2011) investigated the application of the Hall plot analysis in gel flooding. Gradually, the resistance factor and the residual resistance factor have become quantitative indexes to evaluate the injection effect of chemical flooding (Honarpour and Tomutsa 1990; Sugai and Nishikiori 2006; Ghosh et al. 2012). The resistance factor is defined as the ratio of the Hall plot slope for the chemical flood to that for the water flood. As the change of the slope in the Hall plot is usually not significant in the early period of chemical flooding, it is hard to use the Hall plot analysis to obtain the resistance factor. In fact, the Hall plot analysis only represents the average injection effect over a period, rather than to reflect the real-time characteristics.

In view of this, a new method, derived from injection performance data, is proposed for the real-time characterization of the chemical flood. The assumption of the new method is the same as the Hall slope analysis [a two-phase, radial flow of Newtonian liquids (Buell et al. 1990)]. Compared to the Hall plot analysis, it is simple and accurate in parameter calculation and high permeability zone estimation. The first pilot test of SP flooding in China was implemented in the western part of the Gudong 7th reservoir and has achieved great success. In this paper, the dynamic data of this pilot test are used to verify the new method.

2 New approach for injection effect evaluation

2.1 Ratio of pressure to injection rate (RPI)

2.1.1 Theoretical basis

During the period of water flooding, the water injectivity index represents the real-time characteristics of injection wells. The water injectivity index is defined as the ratio of the injection rate to the injection pressure difference. In field applications, it is difficult to measure the injection pressure difference, so the wellhead pressure is often used to replace the injection pressure difference to determine the injectivity index. Similarly for chemical floods, after the chemical solutions are injected into the well, both the injection pressure and the injection rate will change due to an increase in flow resistance in reservoirs, and thus, the dynamic injection data in the chemical flooding can be characterized by the variation of the wellhead pressure and the injection rate. The higher the injection pressure is, the greater the flow resistance will be, and the better the displacement efficiency the chemical flood will achieve. Based on this, the RPI refers to the ratio of the wellhead pressure to the injection rate, describing as follows:

$$\beta = \frac{P_{\mathrm{wh}}}{q}, \tag{1}$$

where β is the ratio of the wellhead pressure to the injection rate (RPI) in MPa d/m^3; P_{wh} is the wellhead pressure in MPa; and q is the injection rate in m^3/d.

Figure 1 shows the relationship between the RPI and the cumulative volume of fluids injected into two injection wells (well I34-3166 and well I30-146) in the western part of the Gudong 7th reservoir. As is shown, injection well I34-3166 has experienced three stages of displacement, including water flooding, chemical flooding, and subsequent water flooding; while injection well I30-146 is a converted well (an injection well converted from a production well) and only experienced chemical flooding stage

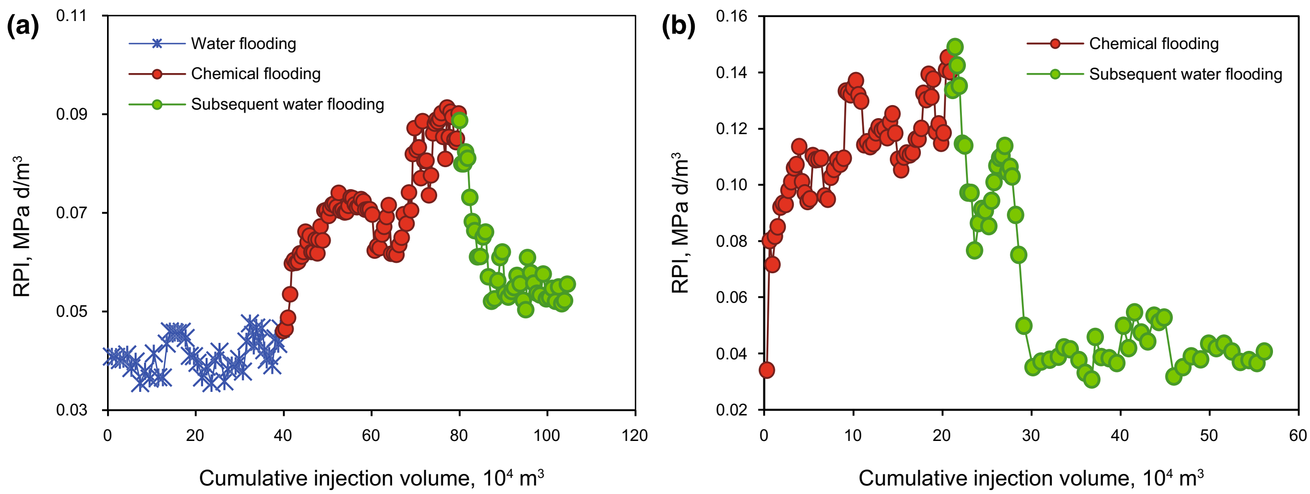

Fig. 1 Examples of the RPI under two different conditions. **a** Injection well I34-3166 with water flooding history. **b** Converted well I30-146 without water flooding history

and subsequent water flooding stage. It can be observed that at the stage of water flooding, the RPI fluctuates around a constant value; then, the curve rises rapidly and tends to vary gently with the increasing injection volume of the chemical solution; at the last stage of subsequent water flooding, the curve begins to fall fast, and eventually fluctuates steadily around a certain constant.

The variation of the RPI can be interpreted by the variation of resistance to flow in the reservoir. Due to the high viscosity of the polymer solution, the flow resistance will increase after the injection of the chemical solution. While at the stage of the subsequent water flooding, the flow resistance will decline gradually due to a decrease in the viscosity of the injection fluid. As a result, the RPI may be a reflection of the flow resistance in the reservoir at different displacement processes.

2.1.2 Relationship with apparent (residual) resistance factor

The RPI is defined as the ratio of the wellhead pressure to the injection rate in chemical flooding as well as in water flooding. It aims to calculate the apparent resistance factor and apparent residual resistance factor by the variation of the RPI, which is called the RPI method. The apparent resistance factor and the apparent residual resistance factor are used to characterize the difference of injectivity between water flooding and chemical flooding.

When the injection rate equals or nearly equals the production rate and the static reservoir pressure is constant or changes only slightly during the evaluation time, the bottom pressure can be approximated to the difference of the static water pressure and the friction pressure loss. The RPI can be presented as follows:

$$\beta \approx \frac{(P_{\mathrm{wh}} + \rho g H - \Delta P_{\mathrm{f}}) - P_{\mathrm{e}}}{q} = \frac{P_{\mathrm{wf}} - P_{\mathrm{e}}}{q}, \quad (2)$$

where ρ is the average fluid density in kg/m^3; g is the gravity acceleration in m/s^2, $g = 9.81$ m/s^2; H is the height of the wellhole liquid column in meters; ΔP_{f} is the friction pressure loss in MPa; P_{wf} is the bottom-hole pressure in MPa; and P_{e} is the static reservoir pressure in MPa.

Darcy's law for single-phase, steady-state, Newtonian flow was used to analyze the performance of the water injection wells by the Hall method. So, the RPI can be represented as follows:

$$\beta_{\mathrm{w}} \approx \frac{P_{\mathrm{wf}} - P_{\mathrm{e}}}{q} = \frac{1.867 B_{\mathrm{w}} \mu_{\mathrm{w}}}{K_{\mathrm{e}} h} \left(\ln \frac{R_{\mathrm{e}}}{R_{\mathrm{w}}} + S \right), \quad (3)$$

where β_{W} is the RPI of water flooding in MPa d/m^3; K_{e} is the effective permeability in 10^{-3} μm^2; R_{e} is the distance between the injector and the producer in meters; R_{w} is the wellhole radius in meters; S is the skin factor; B_{w} is the volume factor of water; μ_{w} is the water viscosity in mPa s; and h is the effective thickness in meters.

After a chemical flood is injected into a well, there will be several fluid banks between the injector and the producer. A simplified method to solve such a case is applying Darcy's law in a serial form and the resistance factor is defined to quantitatively characterize the variations of displacing fluid viscosity and reservoir permeability (Buell et al. 1990). Because of extensive water flooding in this reservoir, an oil bank does not form, and two banks, a water bank and polymer bank, can be taken into consideration. Thus, the RPI after the injection of the chemical fluid can be represented as

$$\beta_{\mathrm{p}} \approx \frac{1.867 B_{\mathrm{w}} \mu_{\mathrm{w}}}{K_{\mathrm{e}} h} \left\{ R_{\mathrm{f}} \left(\ln \frac{R_{\mathrm{b1}}}{R_{\mathrm{w}}} + S \right) + \ln \frac{R_{\mathrm{e}}}{R_{\mathrm{b1}}} \right\}, \quad (4)$$

where β_p is the RPI of chemical flooding in MPa d/m^3; R_f is the resistance factor; and R_{b1} is the radius of the chemical displacement front in meters.

Based on Eqs. (3) and (4), the ratio of the RPI of the chemical flooding to the RPI of the water flooding is described by Eq. (5):

$$\frac{\beta_p}{\beta_w} = \frac{R_f\left(\ln\frac{R_{b1}}{R_w} + S\right) + \ln\frac{R_e}{R_{b1}}}{\ln\frac{R_e}{R_w} + S}. \quad (5)$$

As shown in Eq. (5), under the condition that the radius of the chemical slug R_{b1} is equal to the distance between the injector and the producer R_e, the resistance factor equals the ratio of the RPI at the stage of the chemical flooding to the RPI at the stage of the water flooding. However, the size of the chemical slug is often less than the injector–producer distance, so the resistance factor does not equal the ratio of the RPI between the chemical flooding stage and the water flooding stage. Therefore, the apparent resistance factor is defined as

$$R_f' = \frac{\beta_p}{\beta_w}, \quad (6)$$

where R_f' is the apparent resistance factor. When the size of the chemical slug equals the injector–producer distance, the apparent resistance factor does equal the resistance factor.

The flow resistance in the subsequent water flooding process can also be calculated in series form. The enhanced oil recovery at this stage is due to the reservoir permeability reduction induced by the residual polymer, and therefore, the residual resistance factor is proposed to quantitatively characterize this mechanism. The residual resistance factor refers to the ratio of the reservoir permeability before chemical flooding to the permeability after the chemical injection. Thus, the RPI at the stage of subsequent water flooding can be represented as

$$\beta_{ww} \approx \frac{1.867 B_w \mu_w}{K_e h}\left\{R_{rf}\left(\ln\frac{R_{b2}}{R_w} + S\right) + R_f \ln\frac{R_{b1}}{R_{b2}} + \ln\frac{R_e}{R_{b1}}\right\}, \quad (7)$$

where β_{ww} is the RPI of subsequent water flooding in MPa d/m^3; R_{rf} is the residual resistance factor which is defined as the ratio of the absolute permeability before SP flooding to the absolute permeability after SP flooding (Buell et al. 1990); and R_{b2} is the radius of the displacement front of subsequent water flooding in meters.

The ratio of the RPI at the stage of subsequent water flooding to that at the stage of initial water flooding can be defined as

$$\frac{\beta_{ww}}{\beta_w} = \frac{R_{rf}\left(\ln\frac{R_{b2}}{R_w} + S\right) + R_f \ln\frac{R_{b1}}{R_{b2}} + \ln\frac{R_e}{R_{b1}}}{\ln\frac{R_e}{R_w} + S}. \quad (8)$$

As shown in Eq. (8), if the displacement radius R_{b2} of subsequent water flooding is equal to the injector–producer distance R_e, the residual resistance factor equals the ratio of the RPI at the stage of subsequent water flooding to that in the process of initial water flooding. The apparent residual resistance factor can be defined as

$$R_{rf}' = \frac{\beta_{ww}}{\beta_w}, \quad (9)$$

where R_{rf}' is the apparent residual resistance factor.

2.1.3 *Advantages and disadvantages*

The Hall plot analysis can only describe the average injection effect over a period of time, while the RPI is a reflection of the instantaneous value at every displacement moment. Thus, the RPI is more sensitive to the chemical injection and has more advantages over the Hall plot analysis, especially when the variation of Hall plot slope is not obvious, such as at the early stage of chemical flooding.

The disadvantage of the RPI is that it does not have a smoothing effect on the data when the injection pressure and rate have big and frequent fluctuations. An effective way to solve this problem is to apply some mathematical curve smoothing methods such as the data average method and the linear iterative method.

2.2 The rate of change of RPI

2.2.1 *Theoretical basis*

The RPI describes the variation range of the ratio of the injection pressure to the injection rate. However, the injection efficiency is related not only to the variation range of injection pressure and injection rate but also to the variation rate of injection pressure and injection rate. Under the condition of the same chemical injection rate, the faster the pressure increases, the more effective the chemical injection will be.

The rate of change of RPI refers to the variation of the RPI per unit injection volume. It can also be rearranged to the derivative value of the RPI to the cumulative injection volume:

$$\gamma = \frac{d\beta}{dW}, \quad (10)$$

where γ is the rate of change of the RPI in MPa d/m^6; and W is the cumulative injection volume in m^3.

If the injection rate between 2 months keeps constant or changes only slightly, the rate of change of the RPI can be obtained as follows:

$$\gamma = \frac{\beta_2 - \beta_1}{W_2 - W_1} = \frac{p_{\mathrm{wh2}} - p_{\mathrm{wh1}}}{q^2(t_2 - t_1)}, \quad (11)$$

where t_1 and t_1 are the injection time in days.

Based on Eq. (11), the rate of change of the RPI refers to the ratio of the wellhead pressure increment per unit time to the square of the injection rate.

The relationship between the RPI and the cumulative injection volume is illustrated in Fig. 2. It is observed that at the polymer pre-protection slug injection stage, the RPI increases along with an increase in the cumulative injection, while the rate of change of RPI behaves in a reverse manner. After curve fitting, there is a logarithmic relationship between the RPI and the cumulative injection volume, while the rate of change of the RPI has a linear relation with the reciprocal of the cumulative injection volume.

2.2.2 Relationship with resistance factor

Based on the definition Eq. (10) of the rate of change of the RPI and the expression Eq. (4) of the RPI during chemical flooding, the derivative of the RPI can be expressed as

$$\gamma = \frac{\mathrm{d}\beta}{\mathrm{d}W} = \frac{\mathrm{d}\left(\frac{1.867\mu_{\mathrm{w}}B_{\mathrm{w}}}{K_{\mathrm{e}}h}\left(R_{\mathrm{f}}\left(\ln(r/R_{\mathrm{w}}) + S\right) + \ln(R_{\mathrm{e}}/r)\right)\right)}{\mathrm{d}W}, \quad (12)$$

where r is the radius of the chemical displacement front in meters.

A small circular unit in a circular formation is selected as shown in Fig. 3. The circular unit formation can be regarded as a homogeneous formation with a constant thickness and constant effective permeability. The differential formula of the cumulative injection volume can be expressed as

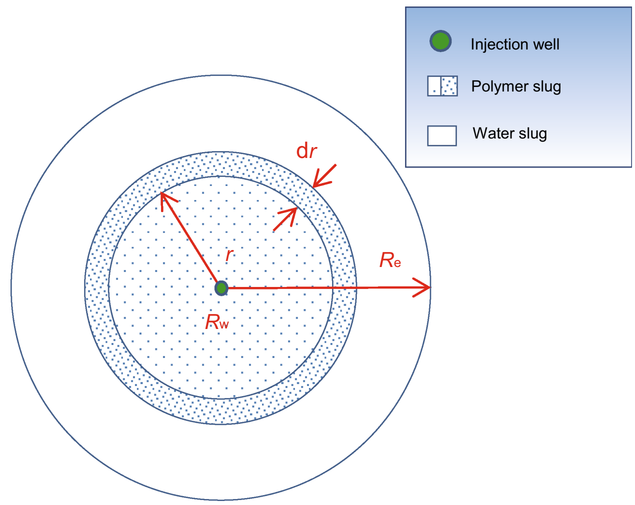

Fig. 3 Schematic diagram of the polymer injection model

$$\mathrm{d}W = 2\pi r\mathrm{d}r \cdot h \cdot \phi \cdot \phi_{\mathrm{D}}, \quad (13)$$

where ϕ is the formation porosity; and ϕ_{D} is the fraction of the accessible pore volume of the polymer solution.

Substituting Eq. (13) into Eq. (12) gives the simplified derivation:

$$\gamma = \frac{0.9335\mu_{\mathrm{w}}B_{\mathrm{w}}}{\pi K_{\mathrm{e}}h^2\phi \cdot \phi_{\mathrm{D}}} \cdot \frac{(R_{\mathrm{f}} - 1)}{r^2}. \quad (14)$$

The accumulative volume of the chemical solution injected into the reservoir is

$$W = \pi \cdot r^2 \cdot h \cdot \phi \cdot \phi_{\mathrm{D}}. \quad (15)$$

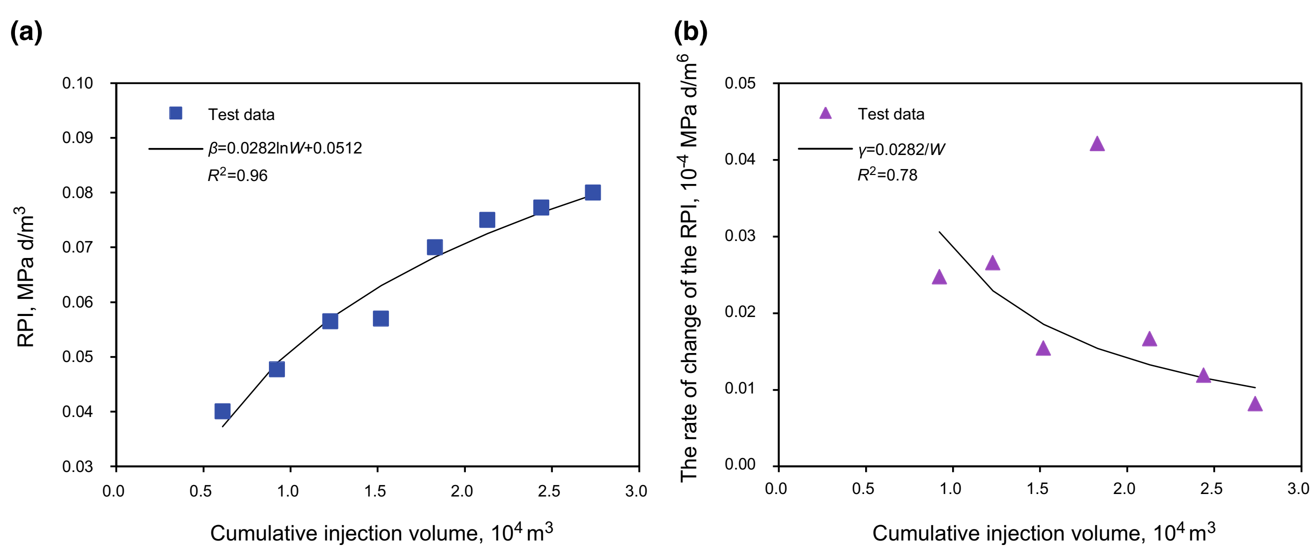

Fig. 2 Statistical relationship of new evaluation indexes and the cumulative injection volume. **a** RPI. **b** The rate of change of the RPI

The relationship between the rate of change of the RPI and the cumulative injection volume can be obtained by substituting Eq. (15) into Eq. (14):

$$\gamma = \frac{0.9335\mu_w B_w (R_f - 1)}{K_e h} \cdot \frac{1}{W}. \quad (16)$$

Equation (16) indicates that the rate of change of the RPI varies inversely with the cumulative injection volume, which also proves the validity of the regression expression in Fig. 2a. The expression of the resistance factor can be derived from Eq. (16):

$$R_f = 1 + \frac{K_e h}{0.9335\mu_w B_w} \cdot W \cdot \gamma. \quad (17)$$

Under the condition of the same cumulative injection volume, the greater the rate of change of the RPI is, the better the efficiency of the chemical injection.

2.2.3 Advantages

Dynamic data such as the injection pressure and the injection rate are indispensable to evaluate the resistance factor by both the Hall plot method and the RPI method during water flooding. However, for new wells or converted wells without water-flooding history, the rate of change of the RPI is the only effective way for injection effect evaluation.

3 Field applications

3.1 Field trial of SP flooding

The first pilot application of SP flooding in China is located in the western part of Gudong 7th reservoir, covering an area of 0.94 km^2, with nearly 277 × 10^4 tons oil in place. The target zone consists of three layers (Ng5^4, Ng5^5, and Ng6^1), with a depth of 1261–1294 m. The average porosity is 34 %, the permeability is 1320 × 10^{-3} μm^2, and the permeability variation coefficient is 0.58. Prior to production, the viscosity of the crude oil is 45 mPa s, and the initial oil saturation is 0.72. The initial reservoir pressure is 12.4 MPa, and the reservoir temperature is 68 °C, and the salinity of the formation water is 3152 mg/L.

A pilot water flood was initiated in this target zone in July 1986. Until August 2003, there were 21 production wells (20 of them were open) and 9 injection wells (8 of them were open), with an average daily fluid production rate of 123.2 t/d and an average daily injection rate of 205 m^3/d. The average daily oil production rate was 2.95 t/d and the average water cut was 97.6 %, while the average daily injection pressure was 11.6 MPa and the injection to production ratio was 0.88 with a cumulative injection to production ratio of 1.04. The oil recovery of reservoir was up to 34.5 %.

A pilot SP flood was started in September 2003 and ended in January 2010, including 27 wells, 17 production wells and 10 injection wells. As is shown in Fig. 4, a line drive pattern was adopted during oil production, while the row space is 300 m and the well space is 150 m.

The injection of the SP flood included four slugs: polymer slug (pre-slug), main SP slug I, main SP slug II, and polymer slug (post-slug). The pre-slug started in September 2003, while the main SP slug I started in June 2004, main SP slug II in June 2007, and post-slug in April 2009. After the SP flooding, the subsequent water flooding stage went into operation in January 2010. The total cumulative injection of chemicals was up to 0.635 PV, including polymer 5496 t, surfactant 8727 t, and auxiliary 3024 t. The detailed information is shown in Table 1.

3.2 Calculation of the apparent resistance factor by the RPI

The apparent resistance factor can be defined as the ratio of the RPI at the chemical flooding stage to that at the water flooding stage. Therefore, it is necessary to calculate the RPI at the water flooding stage. Since the RPI at the water flooding stage will not keep constant, as shown in Fig. 1, the average value over a period of time (in general, 1 month is enough) is used in calculation. Using the above method, the apparent resistance factor and the apparent residual resistance factor of injection well I34-3166 are shown in Fig. 5 and Table 2.

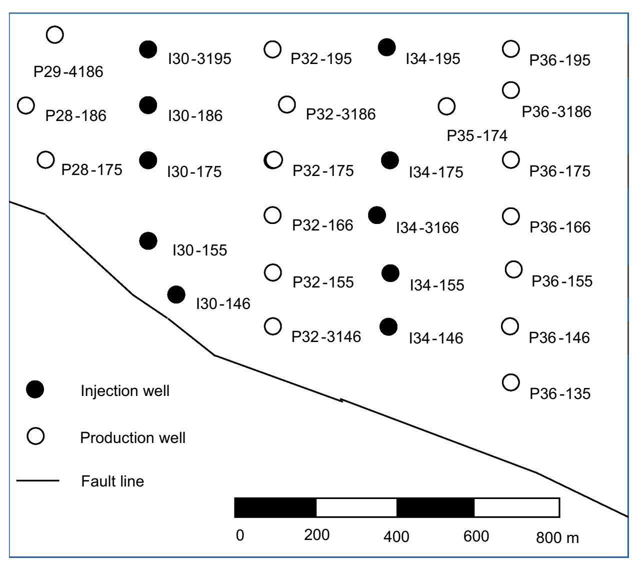

Fig. 4 Location of studied wells

Table 1 Injection data of SP flooding

Injection slug	Starting time	End time	Injection concentration			Slug size, PV
			Polymer, mg/L	Surfactant, mg/L	Auxiliary, mg/L	
Polymer slug (pre-slug)	Sep. 2003	May 2004	1934	0	0	0.078
Main SP slug I	Jun. 2004	May 2007	1856	4618	1610	0.302
Main SP slug II	Jun. 2007	Apr. 2009	1713	3056	1043	0.188
Polymer slug (post-slug)	Apr. 2009	Jan. 2010	1500	0	0	0.067

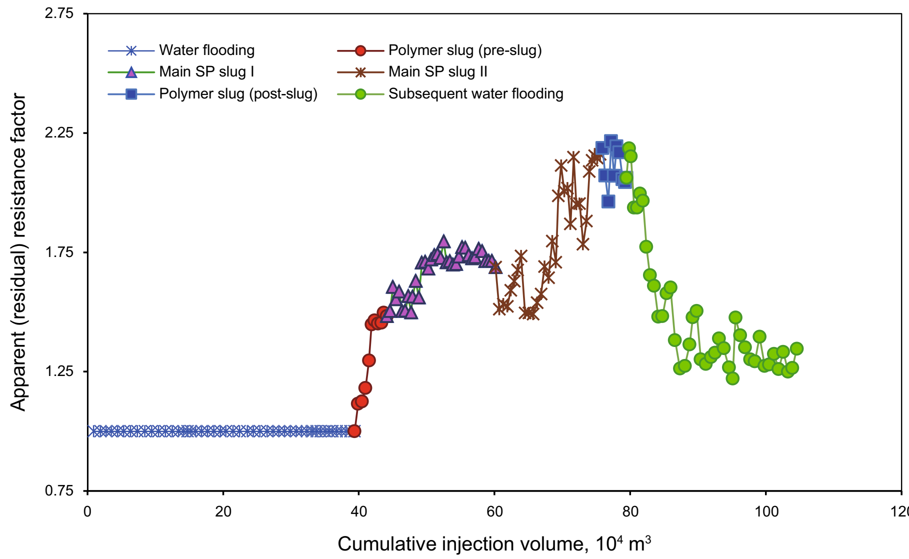

Fig. 5 Apparent (residual) resistance factor of injection well I34-3166 derived by the RPI method

Table 2 Apparent (residual) resistance factor of injection well I34-3166

Injection stage	Apparent (residual) resistance factor			
	RPI method			Hall plot analysis method
	Minimum	Maximum	Mean	
SP flooding				
Polymer slug (pre-slug)	1.1	1.5	1.35	1.65
Main SP slug I	1.5	1.8	1.67	
Main SP slug II	1.5	2.2	1.82	
Polymer slug (post-slug)	2.0	2.2	2.09	
Subsequent water flooding	1.2	2.2	1.48	1.40

Figure 5 indicates that the apparent resistance factor increases from 1.0 to 1.5 rapidly during the injection of the polymer slug (pre-slug), with an average value of 1.35. During the injection of the main SP slug I, the apparent resistance factor rises gradually from 1.5 to 1.8, and the average value is 1.67. However, when the main SP slug II is injected into the reservoir, the apparent resistance factor decreases a little with the cumulative injection volume first and then increases gradually to the maximum value of 2.2, with an average value of 1.82. During the injection of the polymer slug (post-slug), the apparent resistance factor changes relatively little, changing from 2.0 to 2.2, with an average value of 2.09. At last, during the subsequent water flooding, the residual apparent resistance factor decreases slowly until reaching a steady level near 1.3.

Meanwhile, the apparent resistance factors for the chemical flooding and the subsequent water flooding were also calculated from the Hall plot analysis, as shown in Fig. 6 and Table 2. There is a small difference in the apparent resistance factors calculated from these two

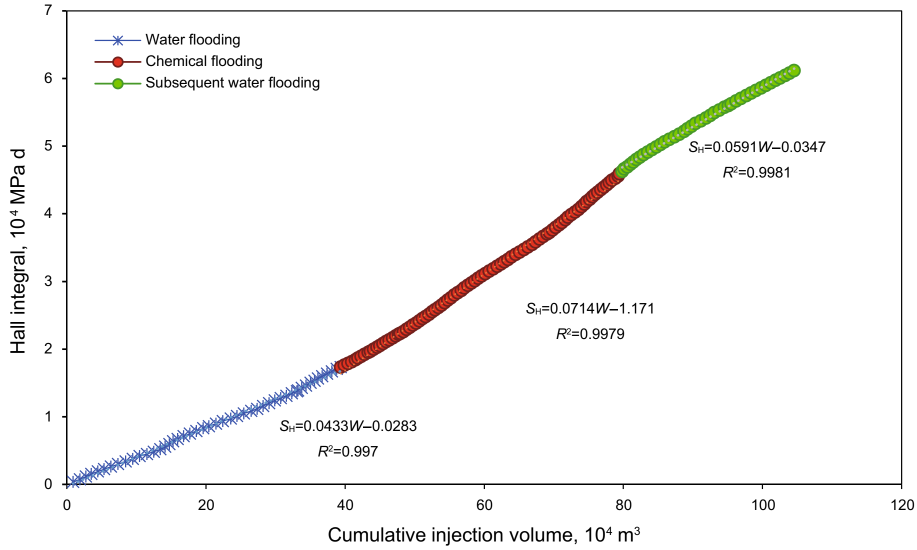

Fig. 6 Hall plot of injection well I34-3166

methods. In fact, both methods are based on the assumption of steady flow, but the RPI can reflect the instantaneous value at every displacement moment and be more sensitive than the Hall plot method. Thus, this method is more helpful for dynamic analysis, especially when the slope difference of the Hall plot is not obvious, i.e., at the early stage of chemical flooding.

3.3 Prediction of crossflow of the chemical floods by the RPI

If the concentration of chemicals fluctuates slightly in the process of the chemical injection, the RPI would increase gradually or remain unchanged with an increase in the injection volume. However, a sharp drop in the RPI indicates a decrease in the resistance to flow in the reservoir, and the possibility of chemical crossflow.

SP flooding pilot tests were conducted in the Shengli Oilfield, and Fig. 7 shows the RPI of injection well I34-175 and the concentration of polymer in the produced fluids from the surrounding production wells. When the cumulative volume of the SP solution injected into the reservoir reached 8×10^4 m^3, there was a sharp drop in the RPI, and 2 months after the drop, polymer was detected in the produced fluids from production well P32-3186 with a polymer concentration of 181 mg/L. A second drop in the RPI occurred when the cumulative injection volume came to 16×10^4 m^3, and 2 months later, polymer of high concentration was produced from wells P32-175 and P32-166. In addition, when the cumulative injection volume amounted to 30×10^4 m^3, a third drop in the RPI appeared and a significantly increase appeared in the concentration of polymers in the produced fluids from wells P32-175, P32-166, P35-174, P36-175, and P36-166.

Based on the analysis above, it is observed that after the RPI drops for some time, polymer will appear in production fluids. For a production well, both the early production of chemical fluids and the rapid growth of the polymer concentration might be caused by polymer crossflow. The existence of thief zones is the most common case causing chemical crossflow. To verify the prediction method by the RPI theoretically, a heterogeneous reservoir model with a production well and an injection well is shown in Fig. 8. The model is composed of two stratified homogeneous layers. The first layer has a low permeability k_1 and a thickness of h_1, while the second layer has a high permeability k_2 and a thickness of h_2. Figure 8 describes the flow without or with crossflow.

According to Darcy's law, the flow resistance can be defined as the ratio of the injection pressure difference to the injection rate. To compare the flow resistance in two cases, the reservoir is divided into four parts, and the length of each part is L_1, L_2, L_3, and L_4. Under the condition that no chemical crossflow exists, the flow resistance of these four part are R_1, R_2, R_3, and R_4, while with chemical crossflow, the flow resistance of these four part are R_1', R_2', R_3', and R_4'. Since under both conditions, a chemical solution is only in the first part with a length of L_1, R_1 is equal to R_1'. Similarly, for the fourth part with a length of L_4 in which only water flows, so R_4 is also equal to R_4'. When the cumulative injection volume of polymer is equal in two cases, the relationship between parameters can be described by Eq. (18):

$$L_2(h_1 + h_2)B\phi = (L_2 + L_3)h_2B\phi, \tag{18}$$

where B is the formation width in meters.

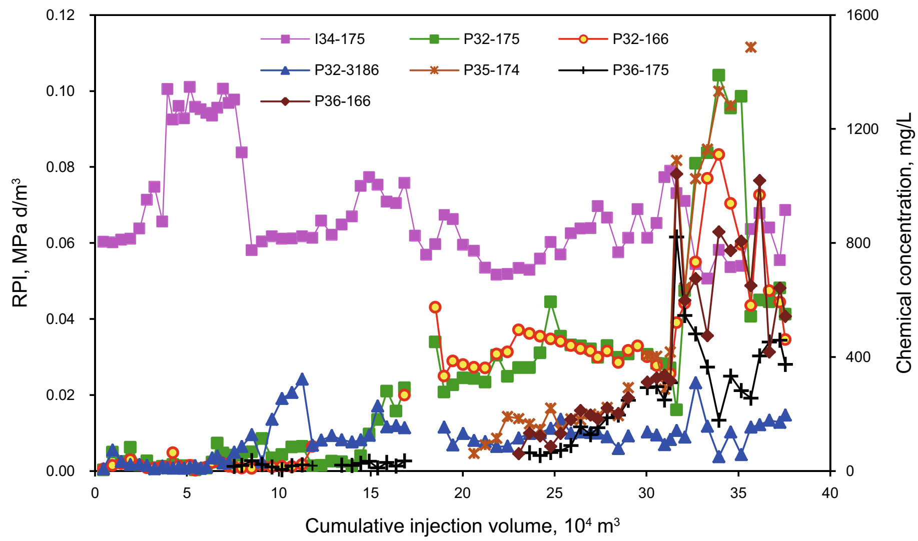

Fig. 7 RPI of injector I34-175 and chemical concentrations of surrounding producers

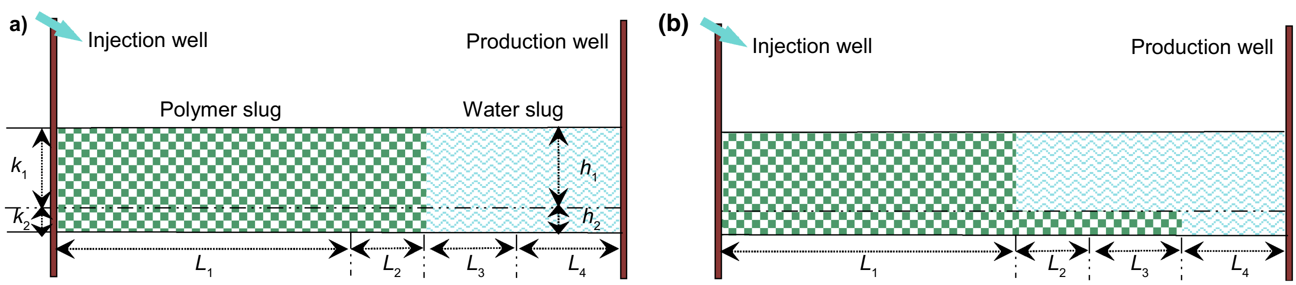

Fig. 8 Schematic diagram of the chemical flood in a reservoir. **a** No chemical crossflow. **b** Chemical crossflow

The difference of the flow resistance in two cases is expressed as

$$
\begin{aligned}
& R - R' \\
& = (R_1 + R_2 + R_3 + R_4) - \left(R_1' + R_2' + R_3' + R_4'\right) \\
& = R_2 + R_3 - R_2' - R_3' \\
& = \frac{1}{\frac{k_1 B_w h_1}{\mu_p L_2} + \frac{k_2 B_w h_2}{\mu_p L_2}} + \frac{1}{\frac{k_1 B_w h_1}{\mu_w L_3} + \frac{k_2 B_w h_2}{\mu_w L_3}} \\
& \quad - \frac{1}{\frac{k_1 B_w h_1}{\mu_w L_2} + \frac{k_2 B_w h_2}{\mu_p L_2}} - \frac{1}{\frac{k_1 B_w h_1}{\mu_w L_3} + \frac{k_2 B_w h_2}{\mu_p L_3}} \\
& = \frac{L_2 h_1 \left(\mu_p - \mu_w\right)\left(k_1 \mu_p - k_2 \mu_w\right)}{B_w (k_1 h_1 + k_2 h_2)\left(k_1 h_1 \mu_p + k_2 h_2 \mu_w\right)}
\end{aligned}
\quad , \qquad (19)
$$

where R is the flow resistance without chemical crossflow; R' is the flow resistances with chemical crossflow; and μ_p is the viscosity of the chemical fluid in mPa s.

In actual cases, because the viscosity ratio of the chemical fluid to water is larger than the permeability ratio of the two layers, R is greater than the R'. It can also be set out that when the chemical crossflow exists, the RPI decreases as a result of the drop in the flow resistance. Based on this theory, the chemical crossflow can be estimated by the variation of the RPI.

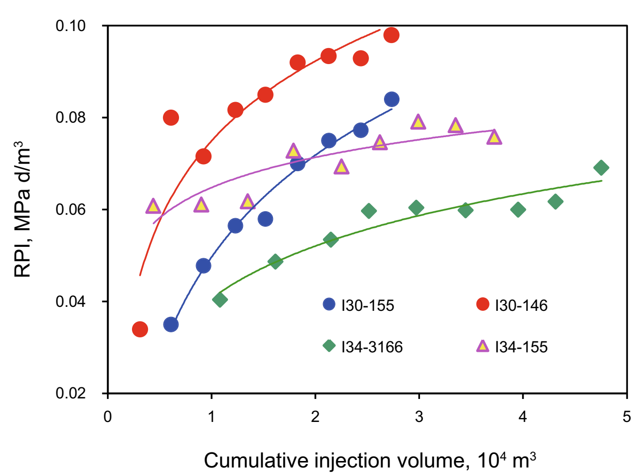

Fig. 9 The relationship between the RPI and the cumulative injection volume

Table 3 Input parameters and the (apparent) resistance factor

Injection well	Input parameters				(Apparent) resistance factor	
	Thickness, m	Water viscosity, mPa s	Permeability, μm^2	Regression coefficient	RPI change rate method	RPI method
I30-146	11.2	0.45	0.99	0.025	1.68	Conversion well (no water flooding history)
I30-155	11.4	0.45	1.40	0.033	2.23	
I34-155	18.0	0.45	0.78	0.009	1.30	1.41
I34-3166	17.5	0.45	0.51	0.016	1.34	1.35

3.4 Calculation of the resistance factor by the rate of change of RPI

The relationship between the resistance factor and the rate of change of the RPI is given by Eq. (17). By calculating the resistance factor of the polymer slug (pre-slug), the curve in Fig. 9 shows the RPI versus the cumulative injection volume of wells I30-155, I30-146, I34-3166, and I34-155. It is observed that the RPI of the four injection wells have a good logarithmic relationship with the cumulative injection volume, which further verifies Eq. (16).

The calculation of the apparent (residual) resistance factor is as follows:

Firstly, the regression expression of the RPI versus the cumulative injection volume is calculated:

Injection well I30-155

$$\beta = 0.033 \ln W + 0.050, \quad R^2 = 0.94 \tag{20}$$

Injection well I30-146

$$\beta = 0.025 \ln W + 0.075, \quad R^2 = 0.84 \tag{21}$$

Injection well I34-155

$$\beta = 0.009 \ln W + 0.064, \quad R^2 = 0.81 \tag{22}$$

Injection well I34-3166

$$\beta = 0.016 \ln W + 0.040, \quad R^2 = 0.91, \tag{23}$$

where R^2 is the coefficient of determination.

Secondly, the rate of change of the RPI versus the cumulative injection volume is calculated. For injection well I30-155, the equation is

$$\gamma = \frac{\mathrm{d}\beta}{\mathrm{d}W} = \frac{A}{W} = \frac{0.033}{W} \tag{24}$$

where A is the slope of the regression curve.

Lastly, the resistance factor is obtained based on the relational expression of the rate of change of the RPI and the cumulative injection volume (Table 3). For injection well I30-155, the expression of the resistance factor is

$$R_\mathrm{f} = 1 + \frac{K_\mathrm{e}h}{0.9335\mu_\mathrm{w}B_\mathrm{w}} \cdot A = 1 + 0.033\frac{K_\mathrm{e}h}{0.9335\mu_\mathrm{w}B_\mathrm{w}} = 2.23. \tag{25}$$

Similarly, the resistance factor of the remaining three injection wells is shown in Table 3. Meanwhile, the RPI is also used to calculate the apparent resistance factor. Since both injection wells I30-146 and I30-155 in Table 3 are converted wells, the traditional Hall plot analysis is not applicable for the resistance factor calculation. The resistance factor of the remaining two wells shows no obvious difference between the RPI method and RPI change rate method. However, for new wells without water flooding history or converted wells, the RPI change rate method is an effective way for injectivity evaluation.

4 Conclusion

(1) A new method (RPI and RPI change rate) is developed for evaluating the efficiency of chemical flooding. It is proved to be a more sensitive and rapid method for calculating parameters than the Hall plot method. Also, it is proved to be an effective way in estimating the existence of chemical crossflow.

(2) The RPI characterizes the real-time injection performance of chemical flooding in a simple form. It is verified that the apparent resistance factor and the apparent residual resistance factor can be obtained by the RPI at different displacement stages, and this method is most attractive at the early stage of chemical injection or when no obvious effect is observed.

(3) The RPI will fall sharply when the resistance to flow declines (caused by chemical crossflow). According to this theory, the RPI can be used to indicate the existence of chemical crossflow.

(4) The rate of change of the RPI can quantitatively describe the response rate of chemical flooding. The greater the rate of change of the RPI is, the faster the

chemical flooding takes effect. Since only injection data of the chemical flooding stage is needed for evaluation, the rate of change of the RPI is most suitable for wells without water flooding history.

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