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A statistical approach to investigate oil displacement efficiency in thermal recovery techniques for heavy oil based on one-dimensional core experiment

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Precise description of displacement efficiency (E_d) is extremely important for evaluating the performance, economic effectiveness and final recovery of thermal recovery techniques. Current researches mainly focused on one-dimensional core displacement experiment, and it is difficult to obtain precise E_d beyond the range of test points. In addition, there are two ways to improve the E_d for thermal flooding: Increasing injection pore volume (PV) or raising injection temperature (*T*), it's hard to make decisions. In this study, the above two problems were solved by a statistical approach research. At the beginning, one dimensional core displacement experiment was carried out for hot water and steam, respectively. Then, dozens of curves and correlations about E_d varied with injection *PV* number and injection temperature was regressed, respectively. Based on this, the formula of E_d and *PV*, E_d and *T* for injection hot water and steam was established respectively, which makes up for the shortage of the finite test data points. Next, chart of the E_d between the *PV* and *T* was obtained. In addition, sensitivity analyses of injection rate and steam quality are discussed in this paper. Finally, the precise of the regression formula was verified by three steam flooding case of different heavy oil fields. The results indicated that, in order to get higher E_d, higher injection *PV* and temperature are beneficial. With the E_d chart, technicians can determine different schemes to improve oil displacement efficiency according to specific reservoir conditions. Besides, main production indexes such as oil recovery can be predicted quickly and precisely.

Key words: Fossil energy, heavy oil, displacement efficiency, thermal recovery, steam flooding.

INTRODUCTION

Oil reserves in the world can be classified into light oil, heavy oil and bitumen according to the density and viscosity (Butler, 1981). Because heavy oil and bitumen take up about 70% of the total remaining hydrocarbon resources (Alboudwarei, 2006), heavy oil has fascinated a great deal of attention and focus in the past decades (Munawar et al., 2015). As conventional oil reserves are running out and the demand for energy has been increasing day by day, the heavy oil resources play an more and more important role in crude oil reserve replacement to meet the world's future energy needs (Xiong et al., 2017a, b). Because of the high viscosity of

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the heavy oil, heavy oil dose not easily flow naturally in the reservoir, so it cannot be produced by conventional techniques (Ankit and Ajay, 2012; Wang et al., 2016; Xu et al., 2013).

Many processes of exploiting heavy oil have been developed and improved, such as water flooding, chemical flooding, thermal recovery, and microbial recovery (Sheikholeslami et al., 2016). Among a variety of enhanced oil recovery technologies, the thermal recovery technology has been widely used for heavy oil reservoirs (Khansari et al., 2014; Hou et al., 2016a, b), such as steam assisted gravity drainage(SAGD) (Yang et al., 2016), steam flooding (SF) (Zhao et al., 2013; Mahood et al., 2016) and cyclic steam stimulation (CSS) (Hou and Chen, 1997; Escobar et al., 2000; Bao et al., 2016), cyclic multi-thermal fluids stimulation (Hou et al., 2016c; Kuigian, 2018; Liu et al., 2018; Dong et al., 2014a, b; Dong et al., 2016). Nowadays, CSS and SF are known as the most widely used and mature technologies (Dong et al., 2012).

Sweep efficiency (E_v) and displacement efficiency (E_d) are essential parameters in oilfield development; they are the final determinant of oil recovery. For conventional cold production displacement, there are two ways to improve the final oil recovery. One is to increase the swept volume of the injected fluid, such as weak gel drive, stratified water injection, etc. The other is to increase the displacement efficiency within the swept volume, such as polymer flooding, high displacement ratio (amount of water injection divide the porosity volume). When the swept volume cannot be increased (for example, in the absence of new wells, and the injected water or steam has broken through the production well), the E_d needs to be improved. For E_d, predecessors have obtained some valuable research results. Water displacement efficiency mainly depends on the geologic factors and fluid properties, such as reservoir type, reservoir heterogeneity, rock wettability and crude oil viscosity. There are many researches on the effects of single factor on oil displacement and the ultimate oil displacement efficiency. Previous studies have focused on several aspects. First, a lot of research work has been done on the influence of wettability on E_d (Donaldson and Thomas, 1971; Anderson, 1987; Morrow, 1990). Because the wettability of reservoir rock is the main factor that determines the distribution position, flow state and distribution of fluid in pore medium. One of the main conclusions is that weak hydrophilic rock samples can obtain the highest E_d. Second, the relationship between pore structure and water E_d has been a subject that geologists and oil recovery engineers have been paying close attention (Gao et al., 1986; Okasha et al., 2005; Farzaneh et al., 2011; Huang et al., 2018). The pore structure of rock refers to the geometric shape, size, distribution and interconnection of pore and throat of rock. Some scholars start from the heterogeneity of pore structure by means of core mercury pressure data, then they think that there is a good linear relationship between them (Wang and Bao, 1999; Sun and He, 1999). However, many contradictions have been found in this research. For example, there is no close relationship between oil displacement efficiency and permeability, and there is even an inverse relationship between oil displacement efficiency and permeability. Due to the limitations of the study, there is no universally recognized rule (Zhong, 2000). The third aspect is the study on the influence of oil-water viscosity ratio on oil displacement efficiency. Some scholars pointed out that oil displacement efficiency has a significant negative correlation with the logarithm of oil-water viscosity ratio (Wensheng, 2003; Zhang et al., 1995). Another important aspect is to study the effect of injection PV number on oil displacement efficiency. It believed that the core oil displacement efficiency increased with the increase of the injection PV number (Wang et al, 2002). They pointed out that after the observation that the water content was up to 99.98%, the core oil displacement efficiency could still be improved by increasing the injection PV number.

In addition, the relevant empirical formula has become one of the commonly used methods to study oil displacement efficiency. Some scholars have made statistical analysis on the test results of laboratory water flooding and obtained the mathematical model to predict the oil displacement efficiency. The relationship between the ultimate oil displacement efficiency with oil water viscosity ratio and air permeability was obtained based on the core water displacement test in the oil fields of China, the United States and the Soviet Union (Fen, 2009). According to development data of Shuanghe oil field, the multivariate regression relational expression between oil displacement efficiency and permeability, oil water viscosity ratio and injection ratio was built (Huang et al., 1997).

Oil displacement efficiency is a significant index in water drive oilfield, and is usually obtained by water drive cores experiments. In recent years, pioneer works were conducted on oil displacement efficiency. According to the characteristics of water drive reservoir, the method of applying geological parameters and production history data to forecast the oil displacement efficiency based on water flooding curve was deliberately deduced (Xianke, 2005). The oil displacement efficiency calculated by oil-water relative permeability test is only the final oil displacement efficiency of oil field. For this reason, the statistical rule of oil displacement efficiency and effective rock permeability in Bohai oilfield by taking the oil and water relative permeability curves measured by 283 natural cores of Bohai oilfield as a sample were obtained (Gong et al., 2015). At the same time, the calculation formula of water displacement oil efficiency is deduced theoretically by using relative permeability curve, fractional flow equation and Welge equation. Above all, the research results are at the same temperature. In this case, increasing PV is an important way to improve the oil displacement efficiency.

For hot water or steam displacement, there are two ways to improve oil displacement efficiency. One is to reduce viscosity of crude oil and the residual oil saturation by increasing the temperature of the injected fluid. The other is to increase the total amount of injected fluid to improve oil washing efficiency. There is one question now, that is, for a particular reservoir, how do technical people make decisions? At the same time, many analytical models of performance prediction of SF are used in steam flooding project evaluation. The value of oil saturation change of heating area before and after steam injection is an important parameter for the analytical models. Whether this value is correct or not directly determines the accuracy of the prediction. Regrettably, this parameter is difficult to obtain, and an empirical value is usually taken in previous studies, which reduces the accuracy of project prediction. So, another question is, how to predict the value of oil saturation before and after steam injection precisely?

Therefore, the present study is concerned with solving the above two problems about thermal flooding oil displacement efficiency. At the beginning, one dimensional core displacement experiment was carried for hot water and steam, respectively. Then, dozens of curves and correlations about E_d varied with injection *PV* number and injection temperatures were regressed, respectively. Based on this, the formula of E_d and *PV*, E_d and *T* for injection hot water and steam was established respectively, which makes up for the shortage of the finite test data points. Next, chart of the E_d between the *PV* and *T* was obtained. Besides, sensitivity analyses of injection rate and steam quality are discussed in this paper. Finally, the precise of the regression formula was verified by three steam flooding case of different heavy oil fields. The results indicated that, in order to get higher E_d, higher injection *PV* and temperature are beneficial. With the E_d chart, technicians can determine different schemes to improve oil displacement efficiency according to specific reservoir conditions. Besides, main production indexes such as oil recovery can be predicted quickly and precisely.

ONE-DIMENSIONAL CORE DISPLACEMENT EXPERIMENT

In this section, one dimensional core displacement experiment data of a typical well B14M in heavy oil field are applied to explain the statistical approach to investigate oil displacement efficiency. The core samples of the test were frozen core samples from well B16, and the samples were drilled, sealed, pumped, washed and dried in the laboratory according to the requirements of the experience research. The determinations of high temperature relative permeability and oil displacement efficiency are based on the oil industry standard SY/T.

6315-2006 (SY/T, 2006).

Test method

Mainly including the following procedures:

(1) Fill the natural cores of N oil field after wash oil to single tube model (porosity and permeability are close to actual reservoir.
(2) Determine saturated water pore volume, and saturation oil to establish irreducible water, simulated the original reservoir conditions.
(3) Then, according to the requirements of high temperature relative permeability and oil displacement efficiency measurement standards, the unsteady method with constant speed was used to inject steam and hot water until the oil was not released at the outlet.
(4) Record the water and oil production at the outlet of the model, calculate the oil displacement efficiency under different displacement conditions according to the calculation method of oil displacement efficiency, and draw the oil displacement efficiency curve.

Test equipment

The oil displacement efficiency equipment is mainly composed of thermostat box, single pipe core holder, injection system, temperature pressure measurement and control system and output liquid measurement system. The main equipment includes thermostat box, high-pressure advection pump, steam generator, single pipe model, temperature display and control instrument, pressure regulator and air water separator.

Test scheme design

A total of 7 displacement comparative tests were conducted. During the test, 7 parallel sample simulation core models were established, and part of the physical parameters of the simulated core were shown in Table 1.

Test result data

Under the condition of displacement speed 20 ml/h, four oil displacement efficiency tests of were conducted at injection temperature of 56, 100, 150 and 200°C, respectively. Through displacement tests, oil-water separation and data processing, oil displacement efficiency curves at different water injection temperatures were obtained, as shown in Table 2 and Figure 1a.

Figure 1 shows that, water injection temperature has a significant influence on the oil displacement efficiency. It also shows that there are two ways to improve the oil displacement efficiency for hot water displacement: one is to keep the total amount of hot water (the same PV number), and to improve the oil displacement efficiency by raising the temperature. The other is to keep the injected fluid at the same temperature (sometimes restricted by the heat injection equipment) and increase the efficiency by increasing the volume of the injected fluid. The changes of the two methods are different at different stages, so quantitative analysis is needed.

Correlations studies based on statistical analysis

Relationship between oil displacement efficiency and PV at the same temperature

Figure 2 shows that, under the same water injection temperature, the oil E_d increases with the increment of injection PV number. Especially in the early stage of water flooding, with the increase of water injection, the oil E_d increases rapidly. When the injection PV number is between 0.5 and 0.7, it reaches the inflection point of the curve. Statistical studies show that the displacement efficiency has a good linear correlation with the natural logarithm of injection PV number. Therefore, the statistical relations at different temperatures can be obtained as formula 1 to formula 4.

Table 1. Physical parameters of physical model of hot water and steam flooding test.

Parameter	Value for water flooding	Value for steam flooding
Model permeability, mD	6201~6541	6386~6467
Model porosity, %	39.8~40.7	40.2~40.8
Oil saturation, %	80.9~82.1	80.0~82.6
Saturated oil temperature, °C	56	56
Model length, cm	15	15
Model diameter, cm	2.54	2.54
Displacement speed, mL/h	20	30
Displacement medium,	Hot Water	Superheated steam

Annotation: The saturated oil temperature 56°C is the original reservoir temperature of N oil field.

Table 2. Data table of hot water and steam drive effect at different temperatures.

Hot water								Steam					
56°C		100°C		150°C		200°C		200°C		240°C		280°C	
PV	E_d %	PV	E_d %	PV	E_d %	PV	E_d %	PV	E_d %	PV	E_d %	PV	E_d %
0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00	0.000	0.00
0.059	7.92	0.116	14.11	0.117	15.83	0.042	5.14	0.049	6.10	0.115	13.89	0.097	12.10
0.209	18.48	0.381	29.03	0.278	25.83	0.141	16.60	0.163	20.33	0.213	25.79	0.213	26.60
0.373	25.52	0.977	40.32	0.537	34.17	0.271	29.25	0.327	30.08	0.607	45.63	0.535	49.60
0.634	29.92	1.639	45.97	0.974	43.75	0.598	46.64	0.817	45.53	1.262	58.73	1.019	62.10
1.059	33.44	2.599	50.00	1.460	48.75	1.219	54.15	1.471	51.63	1.918	63.49	1.665	66.50
1.876	36.96	3.262	52.42	2.430	53.75	1.742	57.71	2.778	57.30	2.902	66.67	2.632	69.80
3.183	40.56	4.255	55.24	3.239	56.67	2.526	61.26	4.412	62.20	4.869	68.65	4.568	71.80
5.797	43.56	5.911	58.06	4.534	59.58	4.160	64.82	6.373	65.40	6.836	70.63	6.503	73.80
-	-	7.566	59.68	5.828	61.25	5.794	65.90	8.987	67.80	8.803	72.62	8.439	75.40
-	-	-	-	8.094	62.92	8.245	66.30	-	-	-	-	-	-

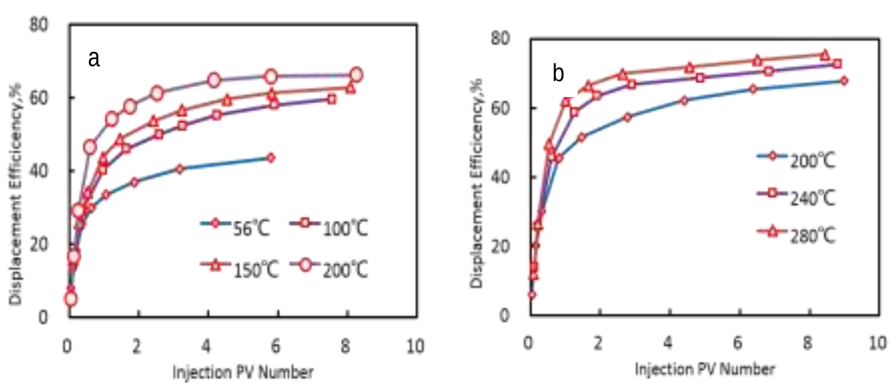

Figure 1. Comparison curve of oil displacement efficiency at different temperatures for (a) injection hot water, (b) injection steam.

$$E_{d-water56^\circ C} = 7.8639\ln(PV) + 31.7428 \quad (R^2 = 0.9854) \tag{1}$$

$$E_{d-water100^\circ C} = 10.9414\ln(PV) + 39.2214 \quad (R^2 = 0.9947) \tag{2}$$

$$E_{d-water150^\circ C} = 11.5682\ln(PV) + 41.9314 \quad (R^2 = 0.9875) \tag{3}$$

$$E_{d-water\,200^\circ C} = 12.5987\ln(PV) + 46.7483 \quad (R^2 = 0.9590) \tag{4}$$

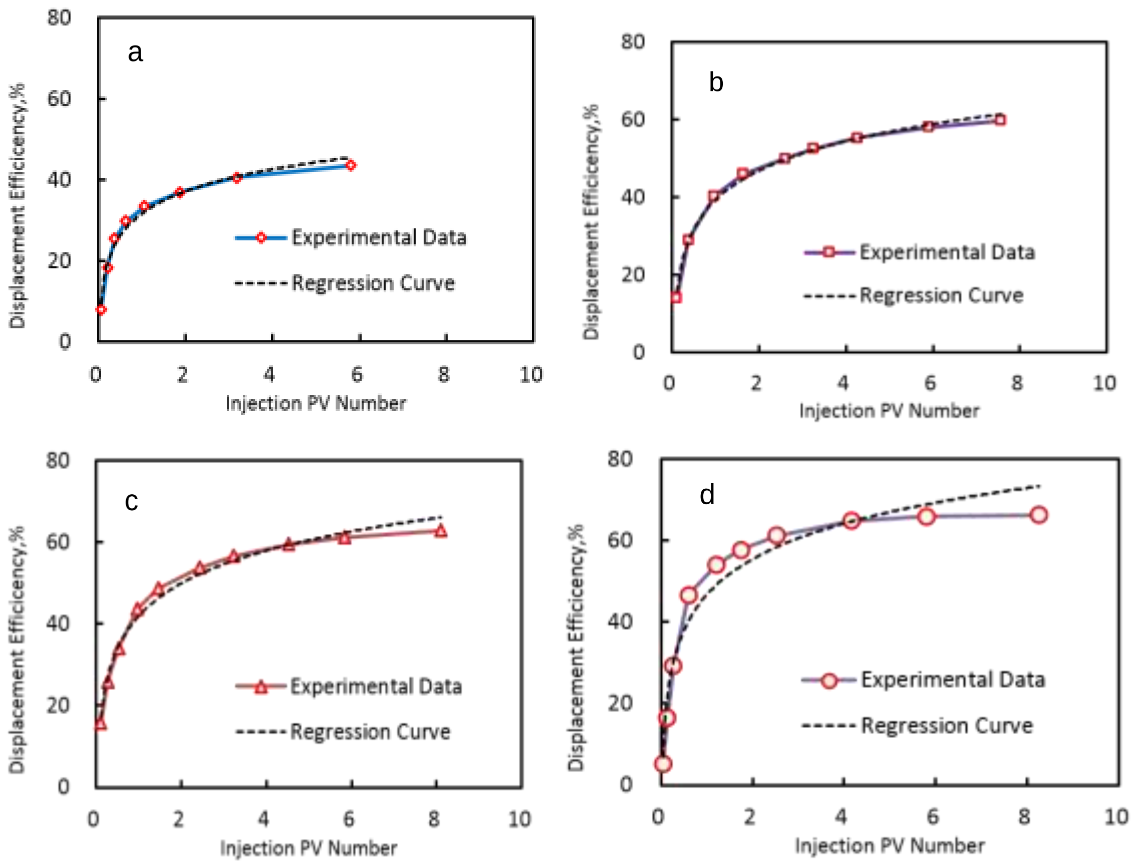

Figure 2. Comparison of oil displacement efficiency of experimental data and regression curve varied with temperature for (a) 56°C, (b)100°C, (c) 150°C, (d) 200°C.

The correlation coefficient R^2 is high, ranging from 0.9590 to 0.9947. By analyzing the above four equations, a rule can be obtained: at any temperature, a similar relation can be obtained, which can be expressed as Equation 5.

$$E_{d-water} = \mathrm{a}\ln(PV) + \mathrm{b} \quad (5)$$

Since the number of tests is limited, displacement efficiency beyond the test temperature range cannot be obtained, and the relationship between oil displacement efficiency and PV number at any temperature can be calculated by equation 5. Where, *a* and *b* are slope and intercept of linear relation respectively. In order to get corresponding relation between temperature and the oil displacement efficiency, the corresponding relations between coefficient a, b and injection temperature were established respectively, which were shown in Figure 3, formula 6, formula 7.

$$a = 3.6009\ln T - 6.3069 \quad (R^2 = 0.9514) \quad (6)$$

$$b = 11.2658\ln T - 13.4311 \quad (R^2 = 0.9827) \quad (7)$$

Substitute formula 6 and formula 7 into formula 5, oil displacement efficiency is obtained and the relation between the water injection PV and injection temperature can be expressed by formula 8.

$$E_{d-water} = 3.6009\ln T\ln(PV) - 6.3069\ln(PV) + 11.2658\ln T - 13.4311 \quad (8)$$

Relationship between oil displacement efficiency and temperature at the same PV

The oil displacement efficiency of different injection temperatures at the same PV number can be plotted in Figure 4. Figure 4 shows that the oil displacement efficiency is increased with water injection temperature increment at different injection PV number. Statistical studies show that the displacement efficiency has a good linear correlation with the injection temperature at different PV number. Therefore, the statistical relations of E_d and T at different PV number can be obtained as Equations 9 to14.

$$E_{d-water\ 0.5\,PV} = 0.0773T + 22.6826 \quad (R^2 = 0.9698) \quad (9)$$

$$E_{d-water\ 1.0\,PV} = 0.0984T + 27.4629 \quad (R^2 = 0.9540) \quad (10)$$

$$E_{d-water\ 1.5\,PV} = 0.1107T + 30.2592 \quad (R^2 = 0.9462) \quad (11)$$

$$E_{d-water\ 2.0\,PV} = 0.1195T + 32.2433 \quad (R^2 = 0.9414) \quad (12)$$

$$E_{d-water\ 2.5\,PV} = 0.1263T + 33.7822 \quad (R^2 = 0.9379) \quad (13)$$

$$E_{d-water\ 3.0\,PV} = 0.1318T + 35.0396 \quad (R^2 = 0.9353) \quad (14)$$

The correlation coefficient R^2 is high, ranging from 0.9353 to 0.9698. By analyzing the above six formulas, a rule can be obtained:

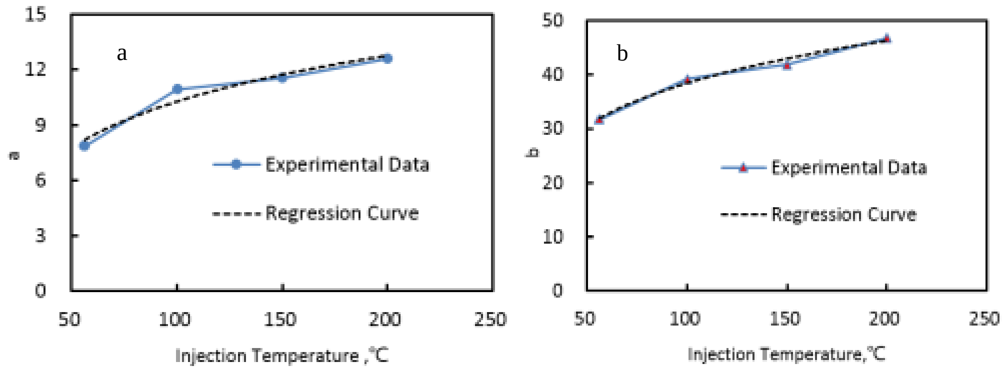

Figure 3. Diagram of the relationship between the injected fluid temperature and the coefficient (a) slope a, (b) intercept b.

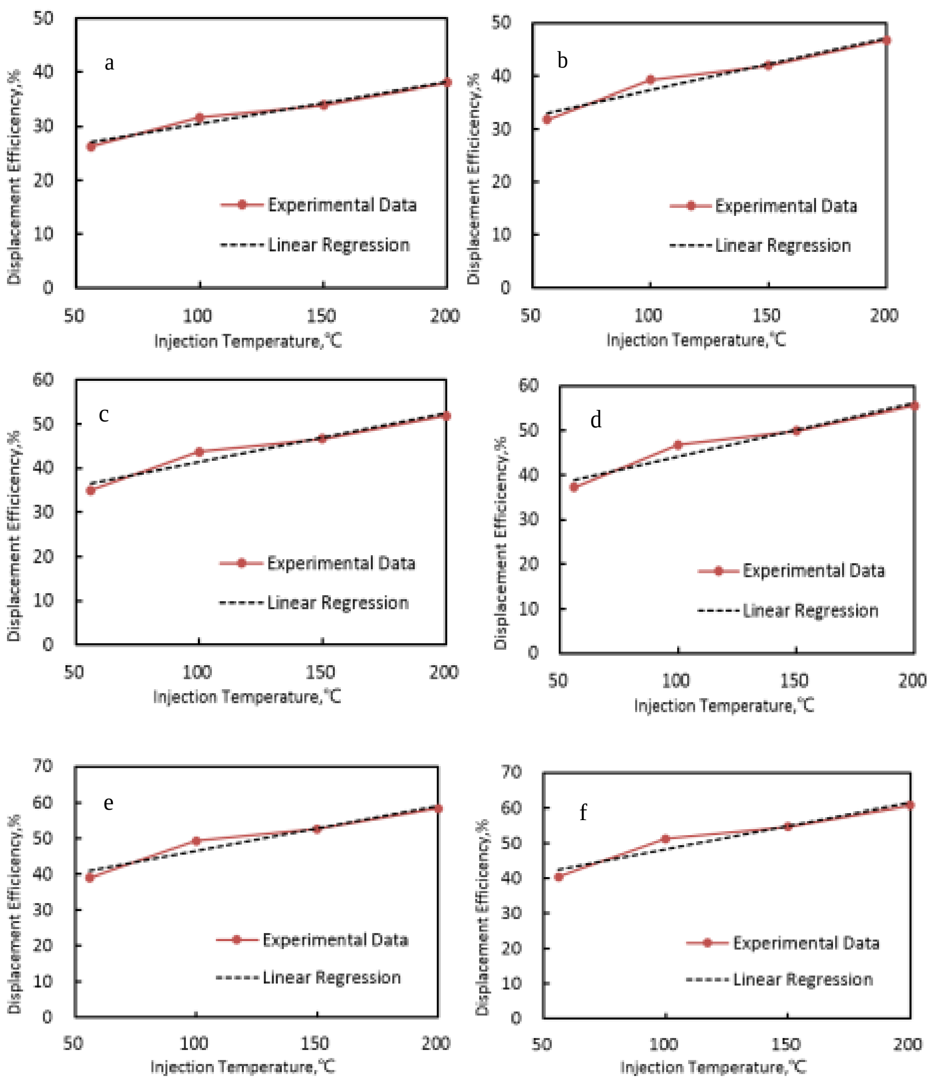

Figure 4. Comparison of oil displacement efficiency of hot water experimental data and regression curve varied with injection PV number for (a) 0.5 (b)1.0 (c)1.5 (d)2.0 (e) 2.5 (f)3.0.

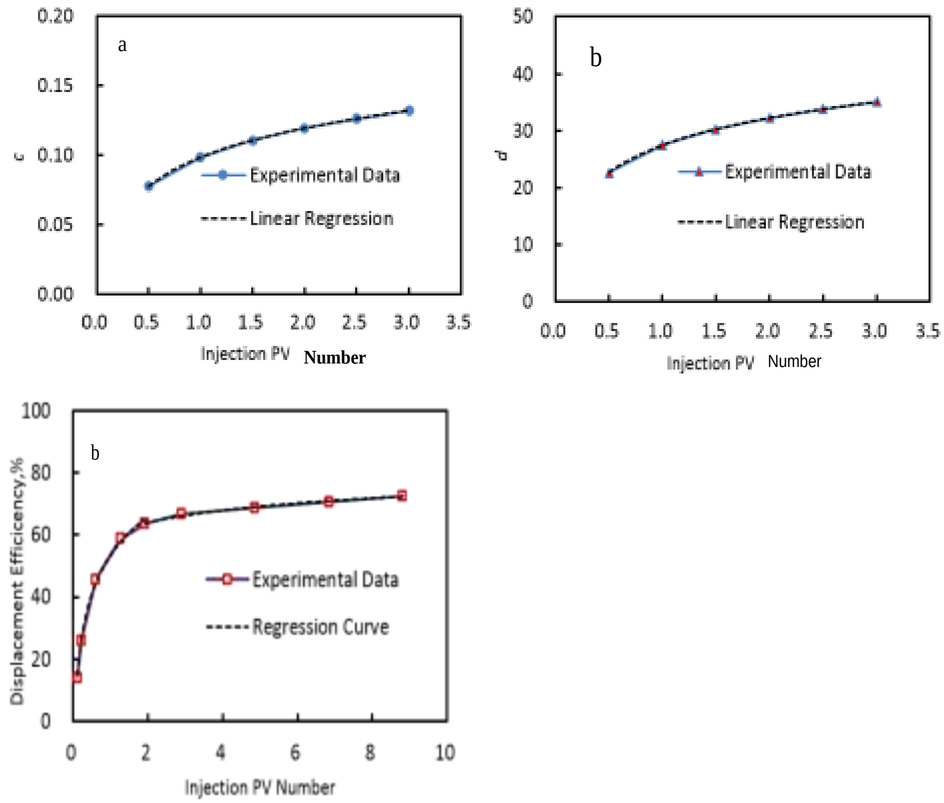

Figure 5. Diagram of the relationship between the injected PV number and the coefficient (a) slope c, (b) intercept d.

at any temperature, a similar relation can be obtained, which can be expressed as Equation 15.

$$E_{d-water} = cT + d \quad (15)$$

In order to get corresponding relation between injection PV number and the oil displacement efficiency, the corresponding relation between coefficient of c, d and injection PV number were established respectively, which are shown in Figure 5, formula 16, formula 17.

$$c = 0.0304\ln(PV) + 0.0984 \quad (R^2 = 1.0) \quad (16)$$

$$d = 6.8966\ln(PV) + 27.4629 (R^2 = 1.0) \quad (17)$$

Substitute formula 16 and formula 17 into formula 15, oil displacement efficiency is obtained. Moreover, formula 18 can express the relation between the water injection PV and injection temperature.

$$E_{d-water} = 0.0304T\ln(PV) + 0.0984T + 6.8966\ln(PV) + 27.4629 \quad (18)$$

Changing injection medium from hot water to steam

Water can exist in different states at different temperatures and pressures. Compared with hot water, steam has the characteristics of higher heat carrying capacity and greater specific capacity, etc., which is very beneficial to improve the thermal recovery effect. Therefore, steam is a common medium for thermal oil production (Hou and Sun, 2013). Under the injection speed of 30 ml/h (water equivalent) conditions, steam flooding experiments at different steam injection temperature for 200, 240 and 280°C were carried out, result were shown in Table 2 and Figure 1(b). With the increase of steam injection temperature, oil displacement efficiency also increases, but the amplitude of increase is small. Only 9.1% oil displacement efficiency was increased by raising the temperature from 200 to 280°C.

The experimental data showed different change ranges under different PV numbers, so it was necessary to carry out regression by subdivided into two segments of 0<PV<2 and PV>2. Therefore, the statistical relations at different temperatures can be obtained as Equations 19 to 21 which are shown in Figure 6.

$$\begin{cases} E_{d-steam\,200^\circ C} = 13.7822\ln(PV) + 46.6218 & (R^2 = 0.9949) \quad (0 < PV < 2) \\ E_{d-steam\,200^\circ C} = 9.12711\ln(PV) + 48.1979 & (R^2 = 0.9968) \quad (2 < PV < 10) \end{cases} \quad (19)$$

$$\begin{cases} E_{d-steam\,240^\circ C} = 17.9543\ln(PV) + 53.4439 & (R^2 = 0.9968) \quad (0 < PV < 2) \\ E_{d-steam\,240^\circ C} = 5.64061\ln(PV) + 60.0674 & (R^2 = 0.9861) \quad (2 < PV < 10) \end{cases} \quad (20)$$

$$\begin{cases} E_{d-steam\,280^\circ C} = 20.1312\ln(PV) + 59.3897 & (R^2 = 0.9881) \quad (0 < PV < 2) \\ E_{d-steam\,280^\circ C} = 5.22701\ln(PV) + 64.1403 & (R^2 = 0.9884) \quad (2 < PV < 10) \end{cases} \quad (21)$$

The correlation coefficient R^2 is high, ranging from 0.9881 to 0.9968.By analyzing the above formulas, a rule can be obtained which can be expressed as Formula 22.

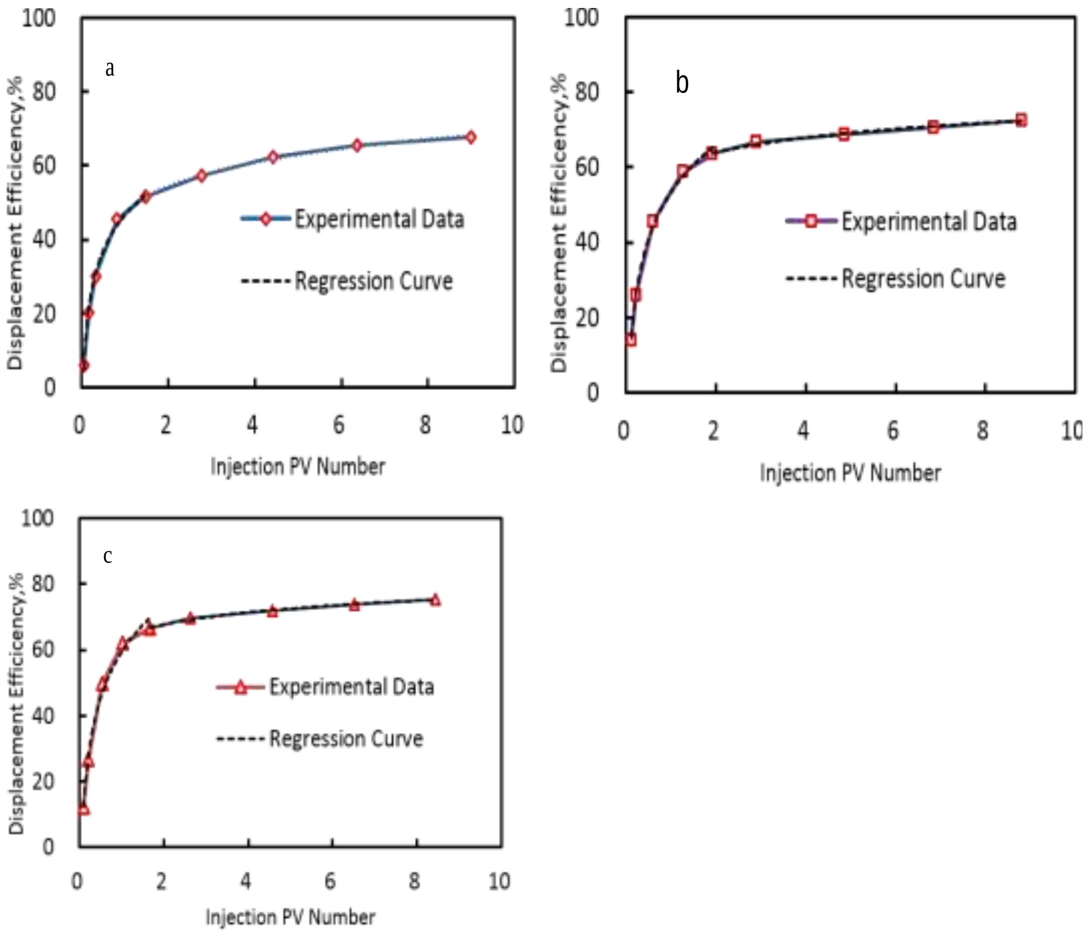

Figure 6. Comparison of oil displacement efficiency of steam flooding experimental data and regression curve varied with temperature for (a) 200°C, (b) 240°C (c) 280°C.

$$\begin{cases} E_{d-steam} = e\ln(PV) + f & (0 < PV < 2) \\ E_{d-steam} = g\ln(PV) + h & (2 < PV < 10) \end{cases} \quad (13)$$

The corresponding relations between coefficient e, f, g , h and injection temperature are established respectively, which were shown in Figure 7, formula 23, formula 24, formula 25, formula 26.

$$e = 18.9904\ln T - 86.6121 \quad (R^2 = 0.9829) \quad (23)$$

$$f = 37.9304\ln T - 154.3750 \quad (R^2 = 0.9999) \quad (24)$$

$$g = 34.3725e^{-0.0070T} \quad (R^2 = 0.8503) \quad (25)$$

$$h = 47.9157\ln T - 204.6904 \quad (R^2 = 0.9494) \quad (26)$$

Substitute formula 23 to formula 26 into formula 22, oil displacement efficiency is obtained and the relation between the water injection PV and injection temperature can be expressed by formula 27.

$$\begin{cases} E_{d-steam} = 18.9904\ln T\ln(PV) - 86.6121\ln(PV) + 37.9304\ln T - 154.3750 & (0 < PV \\ E_{d-steam} = 34.3725e^{-0.0070T}\ln(PV) + 47.9157\ln T - 204.6904 & (2 < PV < \end{cases} \quad (27)$$

Average oil saturation prediction model

When the oil saturation of the pore volume affected by water drops to the remaining oil saturation, the displacement efficiency is expressed as follows (Jiang et al., 2006):

$$E_d = 1 - \frac{S_{or}}{S_{oi}} \cdot \frac{B_{oi}}{B_o} \quad (28)$$

If the oil volume is constant, the above equation can be rewritten as:

$$E_d = 1 - \frac{S_{or}}{S_{oi}} \quad (29)$$

The oil displacement efficiency calculated by formula 29 is the extreme oil displacement efficiency. The displacement at a certain time of water injection can be calculated by the following formula:

$$E_d = \frac{\bar{S}_{oi} - \bar{S}_o}{\bar{S}_{oi}} \quad (28)$$

Substitute formula 30 into formula 18, it can be got that:

$$\frac{\bar{S}_{oi} - \bar{S}_o}{\bar{S}_{oi}} = 0.0304T\ln(PV) + 0.0984T + 6.8966\ln(PV) + 27.4629 \quad (29)$$

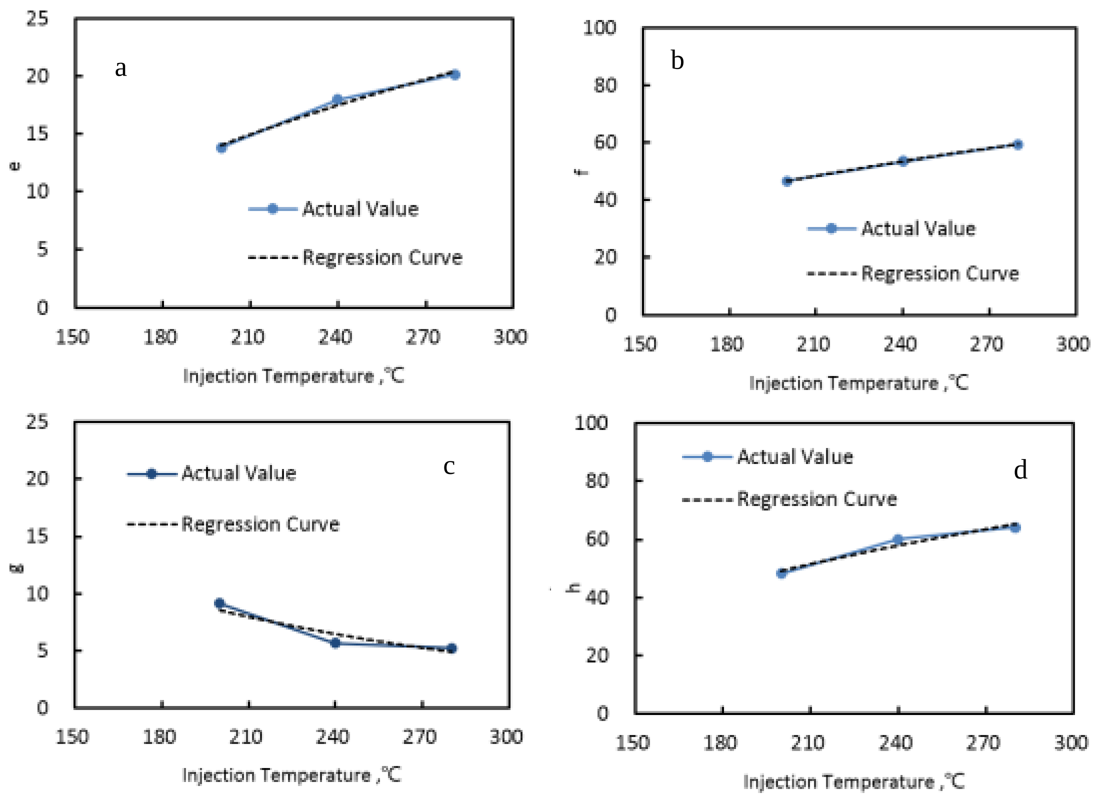

Figure 7. Diagram of the relationship between the injected temperature and the coefficient (a) slope e, (b) intercept f, (c) slope g, (d) intercept h.

Substitute formula 30 into formula 27, it can be got that:

$$\begin{cases} \frac{\bar{S}_{oi}-\bar{S}_o}{\bar{S}_{oi}} = 18.9904\ln T\ln(PV) - 86.6121\ln(PV) + 37.9304\ln T - 154.3750 & (0 < PV < 2 \\ \frac{\bar{S}_{oi}-\bar{S}_o}{\bar{S}_{oi}} = 34.3725e^{-0.0070T}1\mathrm{n}(PV) + 47.9157\ln T - 204.6904 & (2 < PV < 10 \end{cases} \quad (30)$$

For injection hot water and steam, Formula (31) and (32) can estimate the current oil saturation at different PV numbers and temperatures, respectively.

RESULTS AND DISCUSSION

Oil displacement efficiency chart and its application

According to formula 18 and formula 27, the correlation between injection temperature and PV number can be obtained under different oil displacement efficiency conditions, which has been shown in Figure 8.

The four curves of Figure 8 (a), each curve indicates different oil displacement efficiency. Moreover, four curves are 30, 40, 50 and 60% from left to right, respectively. The abscissa represents in injection pore volume ratio, ordinate represents the corresponding injection temperature. For any one of these curves, the injection PV number is negatively correlated with the injection temperature. In other words, the same oil displacement efficiency, the higher the temperature, the lower the PV injected. The lower the temperature, the greater the PV injected. For steam injection, it has the same characteristics, as shown in Figure 8 (b).

Sensitivity analysis of injection rate and steam quality

The first parameter is the injection rate of water. At water injection temperature of 100°C, four speeds of 57, 100, 200, 100 m^3 /d were investigated. The corresponding water injection speed is reduced to 20, 35, 70, 105 mL/h respectively for single tube model. Figure 9 shows the effect of different injection rates on slope *a* and intercept *b*. The quantitative expressions are shown in formula 33 and formula 34.

$$a = 11.8789e^{-0.0019V} \quad (R^2 = 0.9783) \quad (33)$$

$$b = 5.4188\ln V + 17.2302 \quad (R^2 = 0.9186) \quad (34)$$

The second parameter is the steam injection speed.

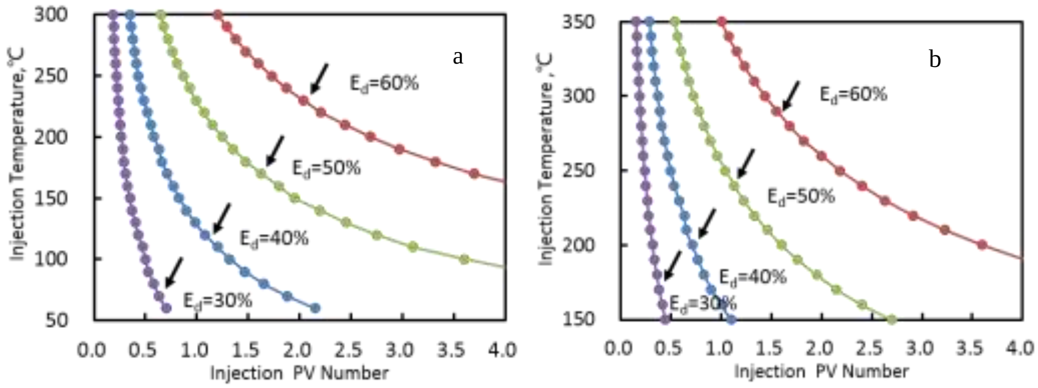

Figure 8. Diagram of the relationship between the injected temperature and the injection PV number of (a) hot water, (b) steam.

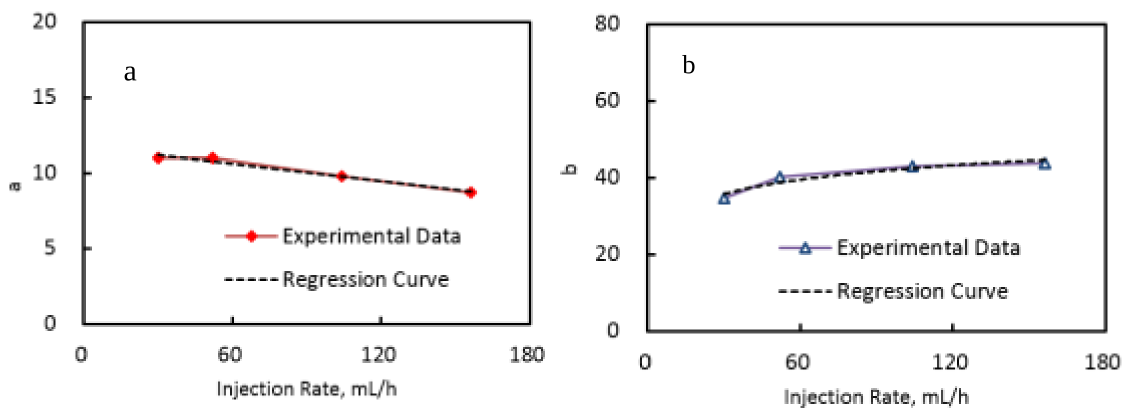

Figure 9. Diagram of the relationship between the injected rate and the coefficient (a) slope a, (b) intercept b.

Under the injection temperature of 240°C condition, four speeds of 45, 80, 160, and 80 m^3/d were carried out. And in laboratory, the corresponding injection rates of one dimension core are 30, 52, 104, 156 mL/h respectively. Figure 10 shows the effect of different injection rates on slope e and g and intercept f and h. The quantitative expressions are shown in formula 35 to formula 38.

$$e = -0.0444V + 18.7167\ (R^2 = 0.9593) \quad (35)$$

$$f = 62.7803e^{-0.0024V}\ \ (R^2 = 0.9640) \quad (36)$$

$$g = 1.9120\ln V - 0.3769\ (R^2 = 0.8741) \quad (37)$$

$$h = 55.4786e^{-0.0023V}\ \ (R^2 = 0.9504) \quad (38)$$

The third parameter is the steam quality, that is, the mass percentage of dry saturated steam containing in per kilogram of wet steam. Under the condition of steam injection temperature 240°C and steam injection rate of 52 ml/h, four different steam quality tests of 20, 40, 50, 70% were carried out, respectively. Figure 11 shows the effect of different injection rates on slope e and g and intercept f and h. It can be concluded that the steam quality has little effect on the slope e and g, intercept f and h. Therefore, in steam flooding progress, the steam quality mainly increases the swept volume, not the oil displacement efficiency.

Calculate the change value of oil saturation in heated zone

In many analytical models of dynamic prediction of thermal recovery, there is a parameter ΔS_o, that is, the oil saturation change value of reservoir before and after steam displacing (Myhill and Stegemeier, 1978; Butler and Stephens, 1981; Chandra and Mamora, 2005; Huang et al., 2016). It is a core and indispensable parameter of the analytical model, such as steam drive and steam

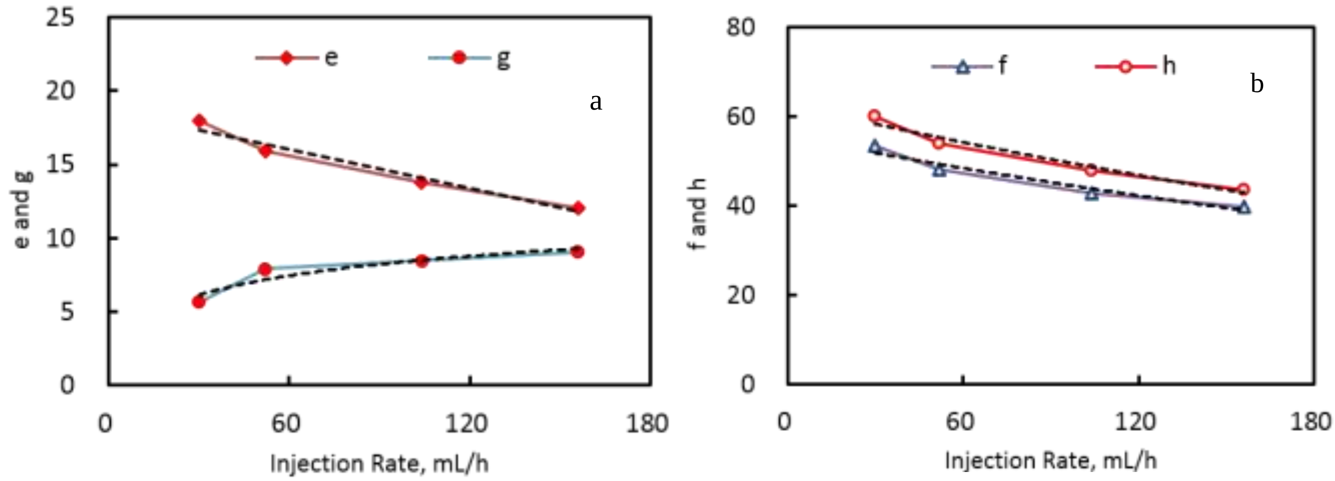

Figure 10. Diagram of the relationship between the injected rate and the coefficient (a) slope e and g, (b) intercept f and h. Real line: experimental data. Dotted line: regression curve.

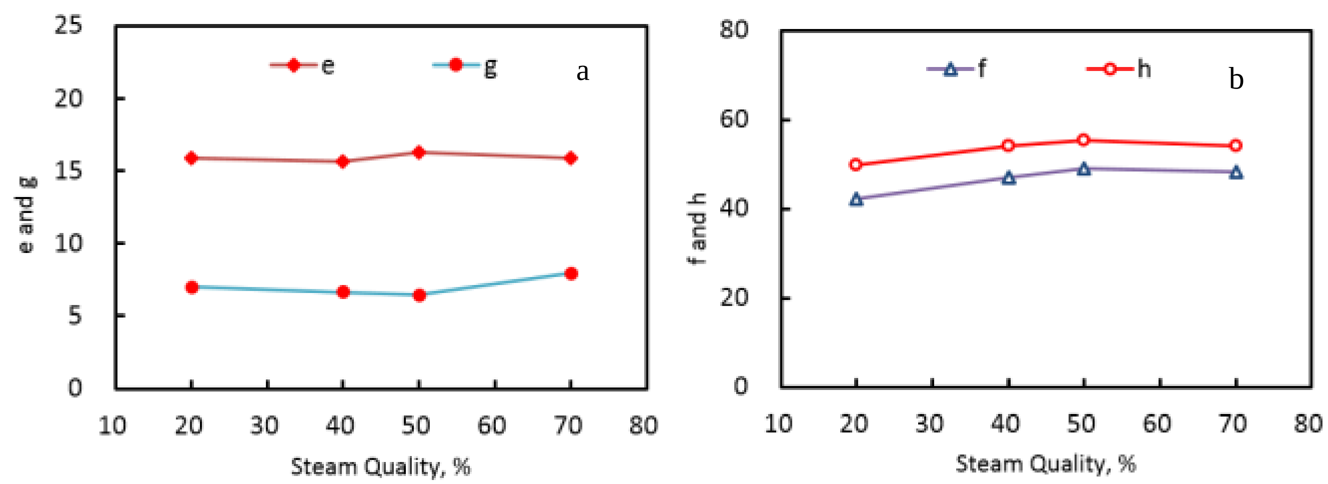

Figure 11. Diagram of the relationship between the injected rate and the coefficient (a) slope e and g, (b) intercept f and h.

Assisted gravity oil discharge. So accurate predicting the value of $\Delta \boldsymbol{S_o}$ is of great importance for predicting thermal dynamic. According to formula 30 and formula 31, the oil saturation in different injection temperatures and PV numbers can be obtained for a steam-flooding oilfield.

To verify the accuracy of the calculation model, using the product of the sweep efficiency (E_v) and displacement efficiency (E_d) as the ultimate recovery method, three steam flooding project of different heavy oil fields of literature 6 were taken as a calculation case. The three oil fields contain Schoonebeek-in the eastern part of Netherlands, San Ardo in Monterey County, California, USA and Hamaca in Venezuela's Orinoco heavy oil belt. Basic parameters of the three fields were shown in Table 3, and the ultimate recovery calculation results were shown in Table 4. By contrasting the results of the three analytical model presented in the literature (Ankit and Ajay, 2012) and the actual result, it can be seen that , this paper calculation forecasts maximum recovery is very close to the oil field actual situation. Therefore, the model in this paper provides guidance for steam flooding evaluation in the early stages of the project.

The advantages and limitations of the model

The regression relational expressions are more convenient to calculate the oil displacement efficiency under the different injection temperatures and injection PV numbers. Moreover, this can be helpful for steam

Table 3. Reservoir characteristic and operating conditions of Schoonebeek, San Ardo and Hamaca fields (Refer to reference [6] for details) [6].

Parameter	Schoonebeek	San Ardo	Hamaca fields
Permeability, mD	1000-10000	6922	12000
Porosity, %	30	34.5	30
Initial oil saturation, %	47	73	83.2
Residual oil saturation, %	25	15	15
Reservoir temperature, °C	37.8	52.8	51.7
Initial oil viscosity under reservoir temperature, cp	180	3000	25000
Net thickness, m	25.3	35.1	30.5
Injection rate, cold water equivalent ,m^3/day	198.7	254.4	254.4
Steam quality, fraction	0.7	0.8	0.8
Total day of calculations, days	2190	6900	6900
Injection PV number	0.60	1.71	1.70
Injection temperature **(°C)**	176.7	305.7	305.7
Average oil saturation after steam flooding predicted by Formula (31), fraction	0.289	0.247	0.282
Displacement efficiency predicted by Formula (30), fraction	0.386	0.661	0.661
Average swept volume efficiency by reference 6 (%)	70.5	34.0	36.6
Maximum recovery forecasts by this article	27.20	22.50	24.20

Table 4. Comparison of maximum recovery as predicted by different models.

Oil recovery (fraction)	Schoonebeek field (%)	San Ardo field (%)	Hamaca field (%)
Jeff Jones model	18.00	22.89	16.00
Suandy Chandra model	46.00	43.00	40.00
Actual field value	33.00	27.00	30.00
Forecasts by this article	27.20	22.50	24.20

flooding performance prediction, and provides a precise oil saturation change value for analytical model, which can improve the accuracy of forecasting model.

Therefore, the main meaning and purpose of this research is to provide guidance for the evaluation steam-flooding project of heavy oil.

Although a lot of important relations and results have been achieved, there are still some shortcomings that need to be further improved later. The oil displacement efficiency obtained from core test mainly depends on geological factors and fluid properties, such as reservoir type, pore- structure, reservoir heterogeneity, rock wettability and crude oil viscosity. The oil displacement efficiency is a macroscopic oil displacement efficiency of oil field level and scale. The final recovery is the product of displacement efficiency and sweep volume coefficient. A major problem, therefore, is the microscopic oil displacement efficiency obtained by core test, represents the coring with special pore structure of itself. Therefore, it can achieve more satisfactory results only to those with the similar permeability, porosity, etc. Therefore, in order to improve the study, the number of statistical samples can be increased and make the coefficient value of more general significance.

Conclusion

Precise description the displacement efficiency is extremely important for evaluating the performance, economic effectiveness and final recovery. Current researches mainly focused on one-dimensional core displacement experiment. Regretfully, each experiment has a finite number of data points, and it is difficult to obtain data and laws beyond range of test points. In this study, the effect of injection PV number and injection temperature on oil displacement efficiency was analyzed and evaluated quantitatively. Several valuable conclusions can be drawn from the previously mentioned research.

For hot water or steam displacement, the oil displacement efficiency is not only affected by injection PV number but also the injection temperature. Based on one-dimensional core displacement experiment, dozens of curves and correlations about displacement efficiency varied with injection PV number, injection temperature were regressed, respectively.

Based on dozens of curves, the formula of displacement efficiency of injection hot water and injection steam was established respectively. It makes up for the shortage of the finite test data points.

Chart of the displacement efficiency between the injection PV number and injection temperature was obtained. It is helpful for steam flooding performance prediction.

The precise of the regression formula was verified by three steam flooding case of different heavy oil fields. Main production indexes of heavy oil field such as oil recovery can be predicted quickly and precisely.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of interest.

Nomenclature

$E_{d-water\,56℃}$, % Oil displacement efficiency for Injection 56℃ water; $E_{d-water\,100℃}$, % Oil displacement efficiency for Injection 100℃ water; $E_{d-water\,150℃}$, % Oil displacement efficiency for Injection 150℃ water; $E_{d-water\,200℃}$, % Oil displacement efficiency for Injection 200℃ water; $E_{d-water}$, % Oil displacement efficiency for Injection water; PV, Decima Pore volume multiple; a Slope of linear relation; b Intercept of linear relation; T, ℃ Temperature; e Slope of linear relation; f Intercept of linear relation; g Slope of linear relation; h Intercept of linear relation; $E_{d-steam\,200℃}$,% Oil displacement efficiency for Injection 200℃ steam; B_{oi} Volume coefficient of crude oil before water injection; B_o Volume coefficient of crude oil after water injection; $\overline{S}_{oi}$, Decima Average oil saturation in water injection; $\overline{S}_o$, Decima Average oil saturation after water injection; S_{or}, Decima Residual oil saturation after water injection; V, ml/h Injection rate of hot water or steam.

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