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Investigating the Possibility of Optimizing the Water Injection Rate During Waterflooding in Iranian Oil Reservoirs

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ABSTRACT

Water flooding, the oldest and the most common EOR method, increases the displacement efficiency in a reservoir and also maintains the reservoir pressure for a long period of time. In Iran, water injection is widely used as a method to enhance recovery from oil reservoirs. Defining the optimized injection rates and injection patterns which is dependent on geological structure of the reservoir is essential in operational and economical decisions for reservoir management. In this paper, we use Capacitance-Resistive Model to find interwell connectivity, and optimized injection rates in a synthetic field. The results showed that the change in oil and water prices can significantly influence the optimized water injection rates.

KEYWORDS: Waterflooding, Water injection, Optimization, Capacitance Resistive Model.

1. INTRODUCTION

Oil recovery operations traditionally have been subdivided into three stages: primary, secondary, and tertiary. Historically, these stages described the production from a reservoir in a chronological sense. Primary production, the initial production stage, resulted from the displacement energy naturally existing in a reservoir. Secondary recovery, the second stage of operations, usually was implemented after primary production declined. Traditional secondary recovery processes are waterflooding, pressure maintenance, and gas injection, although the term secondary recovery is now almost synonymous with waterflooding. Tertiary recovery, the third stage of production, was that obtained after waterflooding (or whatever secondary process was used). Tertiary processes used miscible gases, chemicals, and/or thermal energy to displace additional oil after the secondary recovery process became uneconomical [1, 2].

2. MATERIALS AND METHODS

The idea of this model is similar to the electrical current in the electrical circuits including a network of capacitors and resistors. Hence, by considering flow stream, storage capacity in porous media, pressure difference and permeability similar to electrical current, capacitance, potential difference and resistance, respectively, the mathematical relations in electrical circuits can be used in the reservoir. In this model, a reservoir is supposed to receive a signal (injection) and deliver a reaction signal (production) to what it receives. Historical injection and production rates are the main input data for this model. Analyzing these data could facilitate us with a lot of useful information about the reservoir and reduce the uncertainties in reservoir modeling. Final purpose is the economical and operational optimization in water flooding projects to maximize the oil recovery [3, 4].

Albertoni et al. (2003) used a simple model to find the interwell connectivity. He showed that even the injection rates of injectors which are far away from producers can affect their production rates. He estimated the interwell connectivity by a linear model and estimated coefficients by using Multiple Linear Regression [5]. Yousef et al. (2005) added a new parameter and developed the model to consider both capacitance and resistance effects by using compressibility and transmissibility concepts, respectively [6, 7]. Sayarpour et al. (2007) defined three different simplified models and presented analytical solutions for each of them and validated these solutions by applying them for some real fields [8, 9]. Weber et al. (2009) reviewed the problems of using this model in large scale fields with a large number of wells and suggested some solutions for minimizing the error caused by these problems [10]. Delshad et al. (2009) used this model to detect the presence of fractures in a reservoir and calculate the fracture permeability [11].

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The material balance for a simple reservoir including one injector/producer pair as shown in fig. 1. Is as follows:

$$c_t V_P \frac{d\bar{P}}{dt} = i(t) - q(t) \tag{1}$$

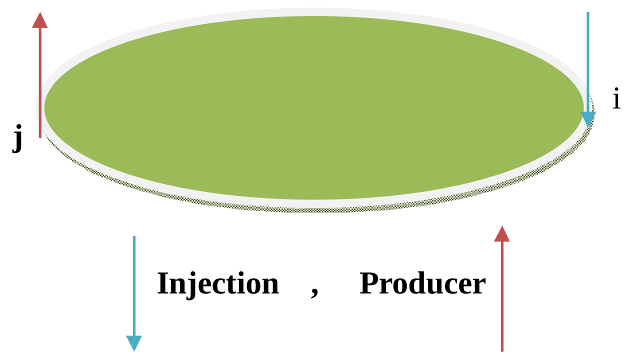

Fig.1. A control volume including one injector/producer pair.

To find an equation based on only injection and production rates, linear productivity index can be used.

$$q = J\left(\bar{P} - P_{wf}\right) \tag{2}$$

By replacing average pressure from equation (2) in equation (1),

$$\tau \frac{dP}{dt} + q(t) = i(t) - \tau J \frac{dP_{wf}}{dt} \tag{3}$$

Where $\boldsymbol{\tau}$ is time constant. The solution of this first order differential equation is as follows:

$$q(t) = q(t_0)e^{\frac{-(t-t_0)}{\tau}} + \frac{e^{\frac{-t}{\tau}}}{\tau}\int_{\xi=t_0}^{\xi=t} e^{\frac{\xi}{\tau}} i(\xi)d\xi \; + $$

$$J\left[P_{wf}(t_0)e^{\frac{-(t-t_0)}{\tau}} - P_{wf}(t) + \frac{e^{\frac{-t}{\tau}}}{\tau}\int_{\xi=t_0}^{\xi=t} e^{\frac{\xi}{\tau}} P_{wf}(\xi)d\xi\right] \tag{4}$$

This is the basic formulation of this model.

To estimate the oil fractional flow in the production stream, we should use an oil fractional flow model in association with Capacitance Resistive Model. One of the suggested models is a power law relation between instantaneous water/oil ratios, F_{wo}, and cumulative water injection rate, W_i [12]. Hence, the estimated water/oil ratio can be calculated from equation (5).

$$F_{wo} = \alpha W_i^{\beta} \tag{5}$$

For a balanced system, total injection and total production are equal; hence,W_i is equal to the total liquid production. This equation can be used for each well separately. By using equation (5); as the oil fractional flow model, we have:

$$f_{oj}(t) = \frac{q_{oj}}{q_{oj}+q_{wj}} = \frac{1}{1+\frac{q_{oj}}{q_{wj}}} = \frac{1}{1+F_{wo,j}} = \frac{1}{1+\alpha_j W_{i,j}^{\beta,j}} \tag{6}$$

In this equation, cumulative water injection is as follows:

$$W_{i,j} = \int_{t_0}^{t} \left[\sum_{k=1}^{N_{inj}} \lambda_{kj} i_k(S)\right].dS = \sum_{k=1}^{N_{inj}} \lambda_{kj} \int_{t_0}^{t} i_k(S)dS \quad (7)$$

Where $\lambda$is the connectivity between an injector/producer well pair or weight coefficient. On the other hand, oil production rate from producer j, is equal to the oil fraction, f_{oj}, multiply by total production, $q_j(t)$ as follow:

$$q_{oj}(t) = f_{oj}(t) \times q_j(t) \quad (8)$$

The combination of equation (6), equation (7) & equation (8) leads to the oil production rate from each producer:

$$q_{oj}(t) = \frac{q_j(t)}{1+\alpha_j\left(\sum_{k=1}^{N_{inj}} \lambda_{kj} \int_{t_0}^{t} i_k(s)ds\right)^{\beta_j}} (j = 1,2, \ldots, N_{Pro}) \quad (9)$$

Hence, after estimating the CRM parameters (time constants & weight coefficients), the oil fractional flow parameters (α_j, β_j) should be estimated by minimizing the difference between real and estimated values during history matching. Since, the direct application of equation (5) in this form for finding model parameters is very difficult, a logarithmic form of this equation is suggested here.

$$\log(F_{wo,j}) = \log(\alpha_j) + \beta_j \times \log(W_{i,j}) \quad (10)$$

By using a linear regression and minimizing the difference between real and estimated values, $\log(\alpha_j)$ and $\beta_j$can be calculated. This linear form of power law relation shows the limitations of using this model in predicting oil production rate. In the other words, this model can be applied, if logarithmic plot of water/oil ratio versus cumulative water injection is linear.

2.1 OPTIMIZATION ALGORITHM

The most important part of an optimization problem is determining the objective function. Depending on the purpose of the optimization, different objective functions can be defined. Some of these objective functions are as follows:

1. Maximizing cumulative oil production during a definite time interval
2. Minimizing cumulative water production during a definite time interval
3. Maximizing net present value of the project by considering injection costs
4. Maintaining the oil production rate from a specific field

Hence, the purpose of optimization can be maximizing ultimate oil production rate or maximizing the profit of the waterflooding in a reservoir. To maximize the profit of a follows:

$$R = P_o.\sum_{j=1}^{N_{pro}} \int_{t_0}^{t} q_{oj}(s).ds - P_w.\sum_{k=1}^{N_{inj}} \int_{t_0}^{t} i_k(s).ds \quad (11)$$

Where, $P_o$and P_w and are oil and water price per barrel, respectively. Furthermore, decision variables are production and injection rates. An upper and a lower boundary for injection through injectors can be defined according to the conditions of the reservoir. The overall procedure of this optimization by using capacitance resistive model and oil fractional flow model is illustrated in fig. 2.

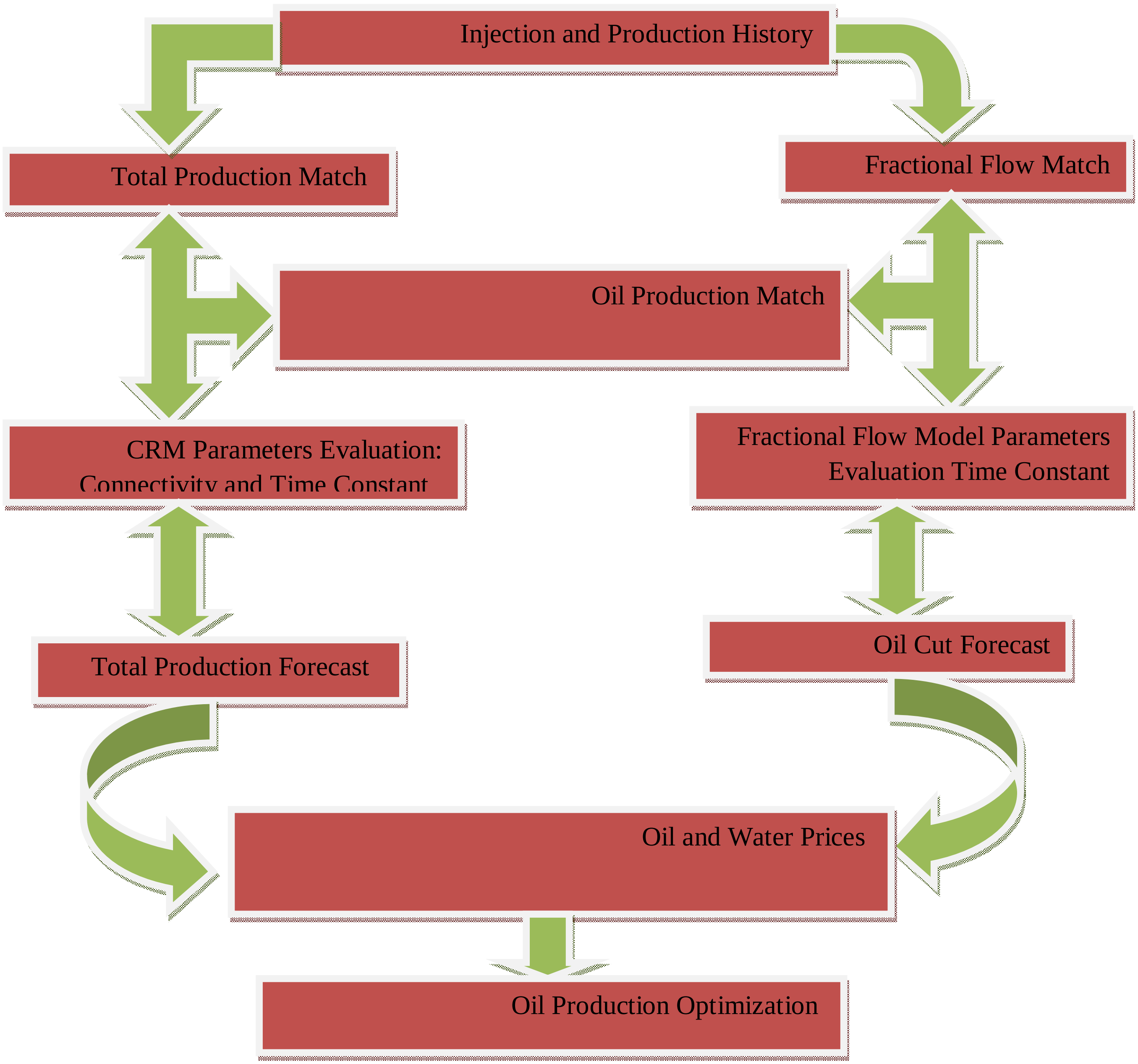

Fig.2. Workflow for the CRM application in history-matching and optimization [13]

2.2 CASE STUDY

In this section, Capacitance-Resistive Model for a synthetic field with 1 injector-1 producer is applied. These historical injection and production rates are for a real field and this well pair is supposed to be separated from the other part of the field. In fig. 3, the injection rate versus time is illustrated. By applying CRM, the interwell parameters are calculated as it is shown in table 1. In fig. 4, the real production rate is compared to the estimated production rate which is calculated by CRM. Hence, CRM is able to estimate liquid (water + oil) production rate accurately. In addition, we are able to predict production rate for any change in the injection rate by using CRM parameters. In fig.5, the calculation procedure to find fractional flow model parameters (power low model) is illustrated.

Using power low model in parameters, table 2 and selecting the objective function which is discussed in the previous section, injection rate optimization is possible. The objective function in this study, is maximizing the profit by considering the water injection cost equal to 1-3 \$/bbl and different oil prices. In addition, the minimum and maximum limits of injection rate are supposed to be 0, 10000 bbl/day, respectively.

According to this results (Table 3, 4,& 5), if water injection costs 1\$/bbl, for oil prices less than 18 \$/bbl, water injection is not feasible. Also, if each oil barrel worth 19 \$, optimized water injection rate is equal to 5100 bbl/day. Finally, if each oil barrel worth 20 \$, optimized water injection rate is equal to 10000 bbl/day. These calculations for different water injection costs and oil prices are presented in the below tables.

Table 1.Capacitance resistive model parameters.

	τ	λ	q_0, RB/T	q_t , Error, RB/T	q_t Correlation ratio
P1	0.59	1	15657	267	0.97

Table 2.Power low parameters.

α	β	q_o Correlation ratio
6.412E-13	1.857	0.91

Table 3. Optimized injection rate dependent on oil price, and water injection cost equal to 1 \$/bbl.

Oil Price (\$)	Water Price (\$)	Optimize Injection Rate (RB/D)
18	1	0
19	1	5100
20	1	10000

Table 4. Optimized injection rate dependent on oil price, and water injection cost equal to 2 \$/bbl.

Oil Price (\$)	Water Price (\$)	Optimize Injection Rate (RB/D)
36	2	0
37	2	774
38	2	5100
39	2	9329
40	2	10000

Table 5. Optimized injection rate dependent on oil price, and water injection cost equal to 3 \$/bbl.

Oil Price (\$)	Water Price (\$)	Optimize Injection Rate (RB/D)
55	3	0
56	3	2227
57	3	5100
58	3	7930
59	3	10000

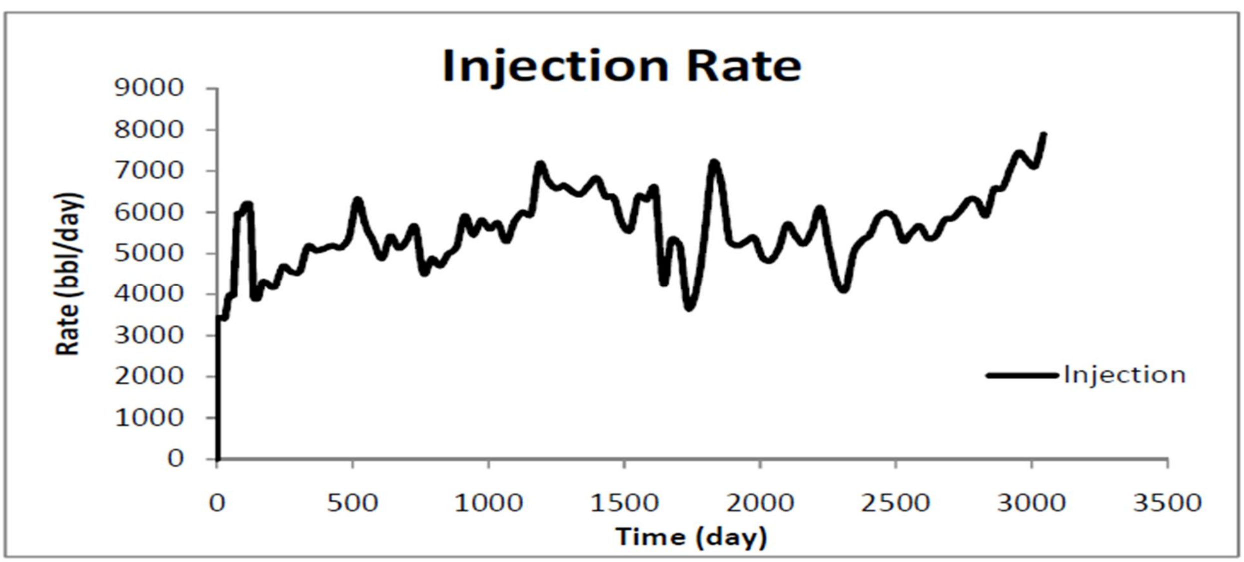

Fig.3.The injection rate versus time

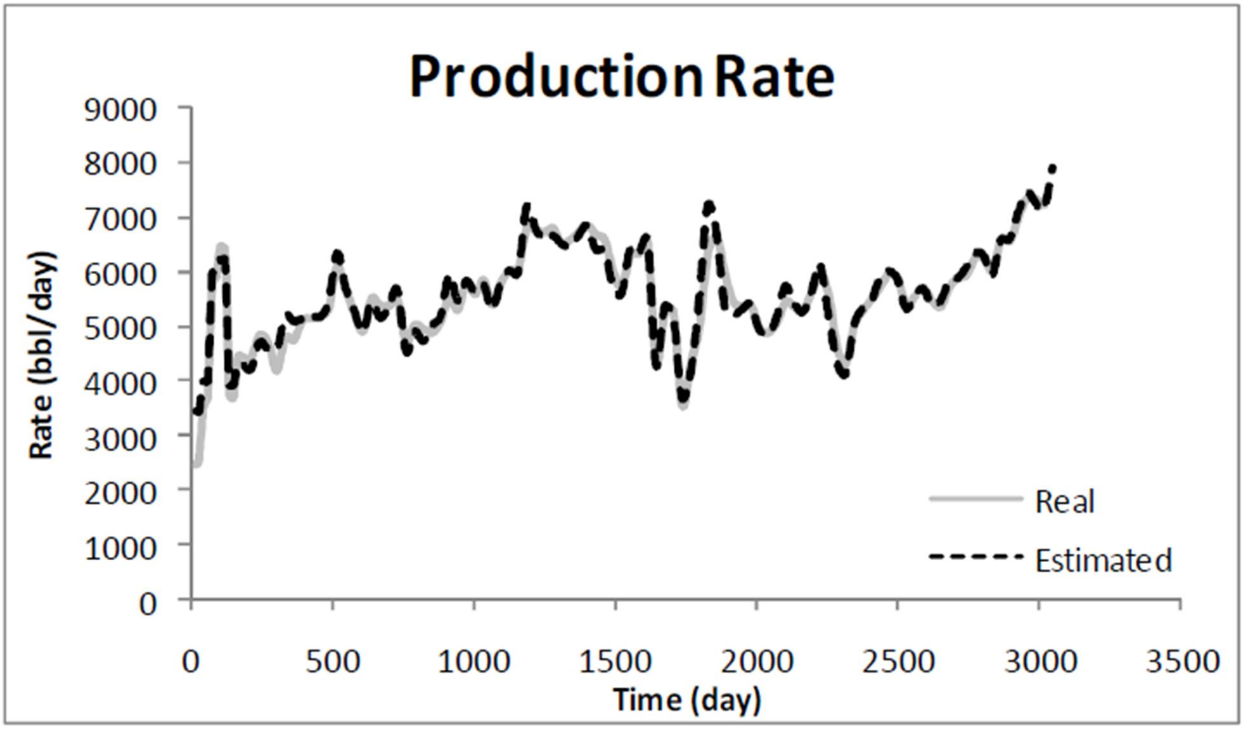

Fig. 4. The real production rate in comparison with estimated production rate.

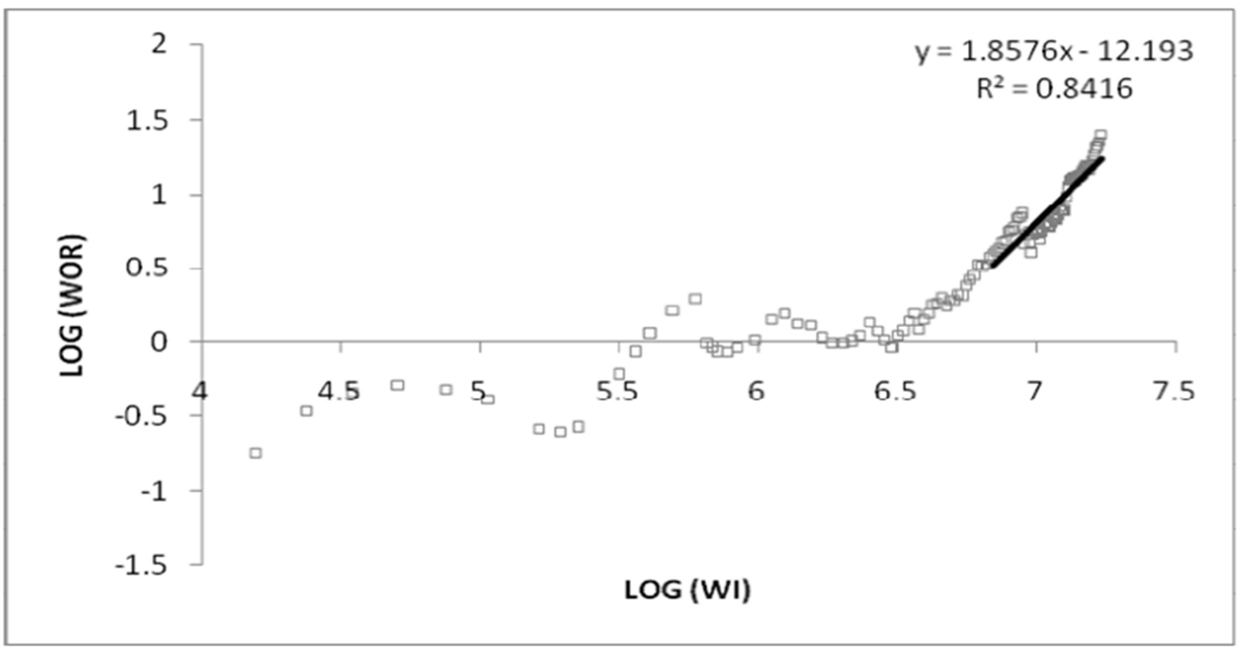

Fig. 5.The graph of fractional flow model calculation.

3. CONCLUSION

Nowadays, waterflooding is known as one of the most common EOR methods and also as a method to maintain the reservoir pressure in order to increase the ultimate oil recovery, in the oil industry. Therefore, optimized water injection rate as an operational factor and also as an economical factor is very important. It has a considerable effect on the ultimate performance of the enhanced oil recovery project. In this paper, a new method for a rapid and continuous operational and economical calculation in an injection project is presented. In addition, it has been shown that it is possible to calculate optimized injection rate by using this model for different reservoir and well geometries.

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Notation

$\boldsymbol{\alpha}$Model coefficient

$\boldsymbol{\beta}$Model coefficient

$\boldsymbol{\lambda}$Weight coefficient

$\boldsymbol{\xi}$Integrating variable

$\boldsymbol{\tau}$Time constant

$\boldsymbol{c_t}\ {L^2}/_{F}$Total compressibility

$\boldsymbol{F_{wo}}$Water/oil ratio

$\boldsymbol{i(t)}\ {L^3}/_{day}$Total injection rate

$\boldsymbol{J}\ {L^5}/_{F-t}$Productivity index

$\boldsymbol{\overline{P}}\ {F}/_{L^2}$Average pressure in the pore volume

$\boldsymbol{P_{wf}}\ {F}/_{L^2}$Bottomhole pressure

$\boldsymbol{q(t)}\ {L^3}/_{day}$Total production rate

$\boldsymbol{V_p} L^3$Pore volume

$\boldsymbol{W_i} L^3$Cumulative water injection

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