A NEW METHOD FOR INFERRING RESERVOIR INTERWEILL CONNECTIVITY AND ITS APPLICATION IN BZ OILFIELD OF BOHAI BAY

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ABSTRACT

Knowledge of interwell dynamic connectivity and finding out injection water flow direction is an important content of reservoir evaluation. The injection wells, production wells and reservoir porous media consists of a complete system. Injection rate of injection wells is the excition of the system while produced rate of production wells is the response of the system. Injected signal exhibits attenuation during its propagation process in reservoir porous media. Based on an evaluation index which characterizing the injection's attenuation, a mathematic model for interwell dynamic connectivity invertion was established by method of signal processing. By this method, injected signals will firstly be preprocessed by use of a convolver and then be used to infer interwell connectivity. The solution method of the model was proposed based on least square method. The model was applied to numerically simulated data on a homogenous synthetic field consisting of five injector and four producer. The connectivity coefficient was calculated by this method and the interwell dynamic connectivity graph was drawn using the connectivity coefficient got from invertion. The results shows that the interwell dynamic connectivity coefficients are consistent with the real reservoir condition. The model was also applied to inhomogeneous field(BZ reservoir of Bohai Bay) and the result consistent with the result of tracer test.

Keywords: Interwell connectivity; injection's attenuation; connectivity coefficients.

INTRODUCTION

Interwell connectivity is an important content of reservoir evaluation. Knowledge of interwell dynamic connectivity and finding out injection water flow direction, can guide the optional enforcement of injection profile modification operations. Besides it is also helpful to quantitatively describe remaining oil in high water cut stage.

The commonly used methods of evaluating reservoir interwell dynamic connectivity are pressure test, tracer test, numerical simulation and well testing, etc. But these methods needs spending huge property and affect normal production. Many researchers put forward the method of inferring interwall connectivity combined with the injection-production data and geological statistic. The injection-production data is easy to obtain, so, inferring the interwell dynamic connectivity based on injection-production data becomes a commonly used method. Heffer firstly put forward the ideal that well-rate fluctuations can reflects the reservoir connectivity. A multivariate linear regression model was put forward by Albertoni and Lake to estimate interwell connectivity by the injection-production rate. The model coefficients were calculated which quantitatively indicates the communication between a producer and the injectors in a waterflooding reservoir. A multivariate linear regression model was built by Anh Dinh only based on bottom hole flowing pressure and a more accurate result was obtained using the model. However, in practical production, Bottom-hole pressure (BHP) fluctuations are very small and are difficult to acquire. So, other methods were proposed to determine interwell connectivity, such as, downhole temperature data were used to reservoir connectivity information (Hutchinson).

When signals propagating in reservoir porous media, it present time lag and attenuation. Based on this, time lag of interwell signal was studied and signal processing technology are becoming more and more widely applied. Nonlinear diffusivity filters was used by Albertoni and Lake to account for the time lag and attenuation of the data. A capacitance model based on injection-production rates and pressure data was built by Yousef et al, according to material balance principle. Besides, an Extended Kalman Filter was used by Feilong Liu and Jerry Mendel to forecast the injector-producer relationships based on measured production and injection rates. This researchers eliminate the effect of time lag and attenuation of injection signals, however, time lag and attenuation was not quantitatively introduced.

2. METHODOLOGY

2.1 The mathematic model for interwell dynamic connectivity invertion

The first-order system are commonly used in engineering practice and some high-order system's characteristics can be characterized by first-order system. The response of the injection-production system increases under the excitation of injected signals and when excitation is revoked, the response signal of the system begins to attenuate and finally tends to its initial value. Considering this, the injection-production system of water flooding reservoir is a first-order linear system. The transfer function is given as equation (1), when the initial condition of the first-order system equals to zero.

$$\Phi(s) = \frac{q(s)}{i(s)} = \frac{1}{\alpha s + 1} \tag{1}$$

where α is the time constant of the first-order linear system; s is the Laplace transform variable.

The value of time constant calculated by regression relation fit well with the numerical simulation results, meeting the need of practical engineering：

$$\alpha = \frac{0.066 r^{1.73}}{æ^{0.915}} \tag{2}$$

where r is well spacing, m; æ is pressure conductivity, cm^2/s.

The unit step-response of first-order linear system is given as equation (3), according to the transfer function of injection-production system:

$$q(t) = \Phi(t) = 1 - e^{-t/\alpha} \qquad (t > 0) \tag{3}$$

where q(t) is the calculated value of production rate, m^3/d; t is time, month.

The injection rate of every injection well generally keeps constant in water-flooding reservoir, and the injected signals can be regarded as rectangle pulsation signals. The first month is the initial time, considering the effect of initial production rates and regarding the first month as the initial time, the response of production rate signal under the condition of the effect of rectangle pulsation is given as follows:

$$q(t) = \begin{cases} q(1)e^{-t/\alpha} + i(t)\left(1 - e^{-t/\alpha}\right) & (1 \le t \le 2) \\ q(1)e^{-t/\alpha} + i(t)\left(1 - e^{-t/\alpha}\right)e^{-(t-1)/\alpha} & (t \ge 2) \end{cases} \tag{4}$$

where q(1) is production rate of first step, m^3/d.

The real reaction of the injection rate signal on production well can be obtained (Equation 5) by superimposing the injection rates' response at each time step in the condition when the injection rate changes continuously. In the condition that a reservoir with one injection well and one production well, and the sampling period is one month, the production rate can be estimation by Equation 5.

$$q(n) = q(n_0)e^{\frac{-(n-n_0)}{\tau}} + \sum_{h=1}^{h=n} e^{\frac{(h-n)}{\alpha}}(1 - e^{-\frac{1}{\alpha}})G(h) \qquad (5)$$

where n is the sampling time step, month; n_0 is the first time step, month; $q(n_0)$ is the production rate of the first step, m^3/d; h is the m^{th} month; G(h) is the injection rate of m^{th} month,m^3/d.

The production changes of each producer associate with the all the producers, in practical oil field production. In an injection-production system which contains M_i injection wells and M_p production wells, the production rate of producer j can be estimated by the injection rate of adjacent injectors:

$$\hat{q}_j(n) = \varepsilon_0 + \sum_{i=1}^{N_i} \varepsilon_{ip} q_{ij}(n_0) e^{\frac{-(n-n_0)}{\alpha_{ij}}} + \sum_{i=1}^{N_i} \varepsilon_{ij} \sum_{h=1}^{h=n} e^{\frac{(h-n)}{\alpha_{ij}}} (1 - e^{-\frac{1}{\alpha_{ij}}}) G_i(h) \qquad (6)$$

where $q_{ij}(n_0)$ is the initial production rate at producer j that corresponds only to injector i, m^3/d; $\hat{q}_j$ is the estimated production rate of a producer j; G_i is the injection rare of injector i, m^3/d; α_{ij} is the time constant for each (ij) injector-producer pair; ε_{ip} is the weight for the initial production rate between injector i and producer j; ε_{ij} is the multivariate linear regression weight between injector i and producer j that dedicates the dynamic connectivity between the ($\boldsymbol{ij}$) well pair; n is the sampling time step of injection-production dynamic data; ε_0 is the constant term that accounts for the unbalance of injection and production, m^3/d. Equation.6 concludes three parts. The first part is on the right of Equation.6, is the constant term that indicates the unbalance of injection and production. The second part is the response of the production rate of the first step. The last part is the correct value of injected signal after preprocessing. Because the effect of production rate of the first step is little, so the second part can be simplified as equation (7).

$$\hat{q}_j(n) = \varepsilon_0 + \varepsilon_p q_j(n_0) e^{\frac{-(n-n_0)}{\alpha_p}} + \sum_{i=1}^{M_i} \varepsilon_{ij} \sum_{h=1}^{h=n} e^{\frac{(h-n)}{\alpha_{ij}}} (1 - e^{-\frac{1}{\alpha_{ij}}}) G_i(m) \qquad (7)$$

where α_p is coefficient which indicates the influence of production rate of the first step. When the reservoir has a balanced injection-production system and the production rate of the first step is zero, the model only has the third component.

2.2 Solution

New dynamic data of injection and production rate can be obtained after determining time constant. The estimated value of weight coefficient can be solved based on least square method. The solutions satisfy equation (8).

$$\frac{\partial}{\partial \varepsilon_{ij}} \left[\sum_{n=1}^{M_n} (q_j(n) - \hat{q}_j(n))^2 \right] = 0 \qquad (8)$$

where n is the sampling time step of injection-production dynamic data; q_j is the real production rate of producer j, m^3/(dMPa). This formula can be expressed by normal equation of $N_i + 1$ order:

$$\begin{bmatrix} D_{ss} & D_{s1} & D_{s2} & \cdots & D_{sM_i} \\ D_{1s} & D_{11} & D_{12} & \cdots & D_{1M_i} \\ D_{2s} & D_{21} & D_{22} & \cdots & D_{2M_i} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_{M_is} & D_{M_i1} & D_{M_i2} & \cdots & D_{M_iM_i} \end{bmatrix} \begin{bmatrix} \varepsilon_{sj} \\ \varepsilon_{1j} \\ \varepsilon_{2j} \\ \vdots \\ \varepsilon_{M_ij} \end{bmatrix} = \begin{bmatrix} D_{sj} \\ D_{1j} \\ D_{2j} \\ \vdots \\ D_{M_ij} \end{bmatrix} \qquad (9)$$

where $D_{ss}$is the production rate covariance of the first step; $D_{si}$is the covariance between production rate of the first step and injection rate; D_{ii} is the injection rate covariance; $D_{ij}$is covariance between production rate and injection rate. The equation concludes three parts. The first part is the covariance matrix of production rate of the first step and column vector of injection data; the second part is the estimated value of weight coefficient; the last part is the covariance column vector of production rate of the first step and injection rate.

When the weight coefficient have been calculated the constant term $\varepsilon_0$accounting for the unbalance can be obtained by:

$$\varepsilon_0 = \overline{q_j} - \varepsilon_s\overline{p_0} - \sum_{i=1}^{M_I} \varepsilon_{ij}\overline{G_i^d} \qquad (10)$$

where $\overline{G_i^d}$is the modified injection rate for injector i, $\overline{p_0}$ is the average of initial production rate.

3. RESULTS AND DISCUSSION

3.1 homogenous field

A homogenous synthetic field consisting of five injectors and four producers（Figure 1）was built and the model was applied to the field . The parameters of the synthetic field are as show in Table 1.

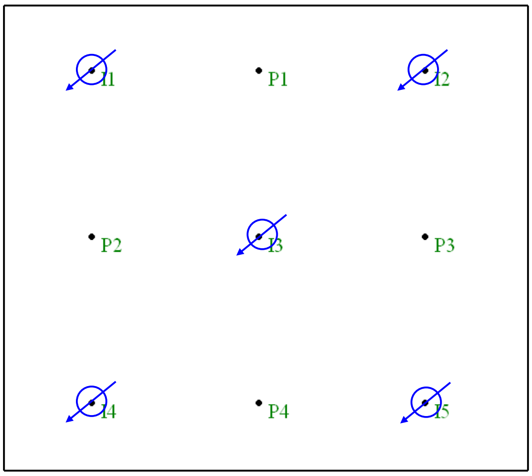

Figure 1. Well Locations Map of 5×4 Homogeneous Synfield

Table 1. The parameters of Homogeneous Synfield

irreducible water saturation, f	0.20
residual oil saturation, f	0.25
Water index	2.00
oil index	2.00
porosity	0.25
permeability, $10^{-3}\mu m^2$	1000
rock compressibility, MPa^{-1}	7.5×10^{-5}
formation oil viscosity, mPa•s	10
well distance, m	360
grid size, m	30×30×1

Based on this method, the dynamic connectivity coefficient was calculated(Table.2)

Table2 Intewell Dynamic Connectivity weight of Homogeneous Synfield

	P1	P2	P3	P4	∑
I1	0.38	0.39	0.19	0.19	1.15
I2	0.40	0.20	0.41	0.20	1.20
I3	0.28	0.29	0.29	0.30	1.16
I4	0.18	0.39	0.19	0.39	1.15
I5	0.21	0.21	0.44	0.45	1.31
∑	1.45	1.48	1.52	1.53	

The interwell dynamic connectivity graph was drawn using the connectivity coefficient got from invertion(Figure.2). In this graph, the interwell dynamic connectivity coefficient β_{ij} are represented by arrows that start from injector i and point to producer j. The length of the arrow is proportion to the value of the weigh. The longer the arrow is, the better the interwell connectivity is. As can be seen from Figure.2, the interwell dynamic connectivity coefficients are consistent with the real reservoir condition.

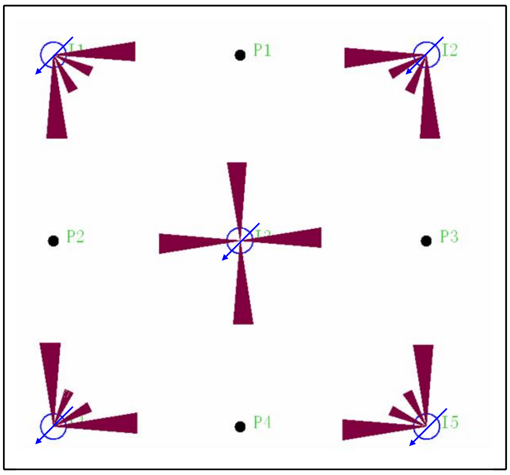

Figure 2. Connectivity Map of Synfield

3.2 Inhomogeneous model

This method has been applied to many water flooding reservoirs of Bohai Bay and the evaluation results are consistent with field performance. This paper gives an examples of 117 reservoir of BZ oilfield to illustrate the application of this method.

117reservoir of BZ oilfield belong to Minghuazhen formation and shallow water delta deposits. The porosity of the reservoir is 0.30, permeability is $1682\times10^{-3}\mu m^2$, formation oil viscosity is 12mPa.s,formation water viscosity is 0.5mPa.s, irreducible water saturation is 0.29, residual oil saturation is 0.22,water index is 1.67, oil index is 1.95, oil relative permeability at irreducible water saturation is 1.00, water relative permeability at residual oil saturation is 0.31(Table 3).

Table3 The parameters of Homogeneous Synfield

irreducible water saturation, f	0.29
residual oil saturation, f	0.22
water index	1.67
oil index	1.95
porosity	0.30
permeability, $10^{-3}\mu m^2$	1682
rock compressibility, MPa^{-1}	7.5×10^{-5}
formation oil viscosity, mPa•s	12
formation water viscosity, mPa•s	0.5
well distance, m	360
water relative permeability at residual oil saturation	0.31
oil relative permeability at irreducible water saturation	1.00

Based on the method proposed this paper, the interwell dynamic connectivity was inferred and the dynamic connectivity coefficient was calculated. Based the dynamic connectivity coefficient, the interwell connectivity graph was drawn. Because the severe heterogeneity of the reservoir, the dynamic connectivity between different wells are very different. The dynamic connectivity between well A27H and A4H is best of all, with the value of dynamic connectivity coefficient is 0.51; The dynamic connectivity between well A27H and A25H is in the second place, with the value of dynamic connectivity coefficient is 0.27. The dynamic connectivity between well A27H and A25H is worst of all with the value of dynamic connectivity coefficient is 0.22(figure 3).

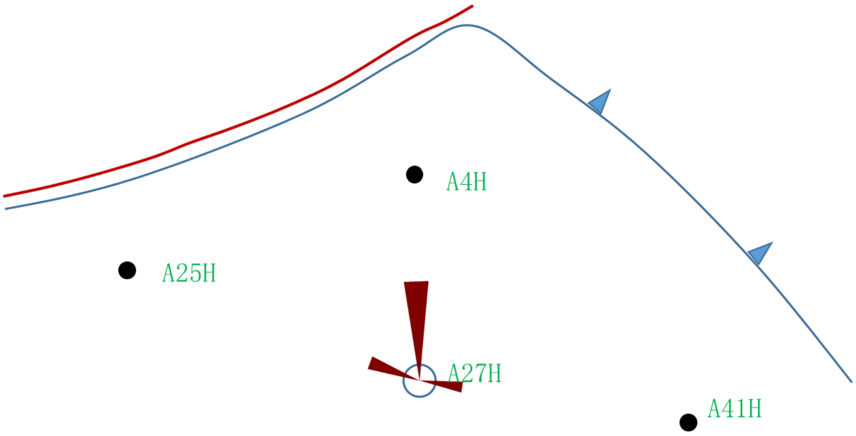

Figure 3. The dynamic connectivity of well group A27H

Tracer test was conducted on the well group of A27H in May 2012, and the result shows that there exits thief layer between well A25H and well A27H (Figure 4). The result consistent with the evaluation result of the method proposed by this paper which indicates the correctness of this method.

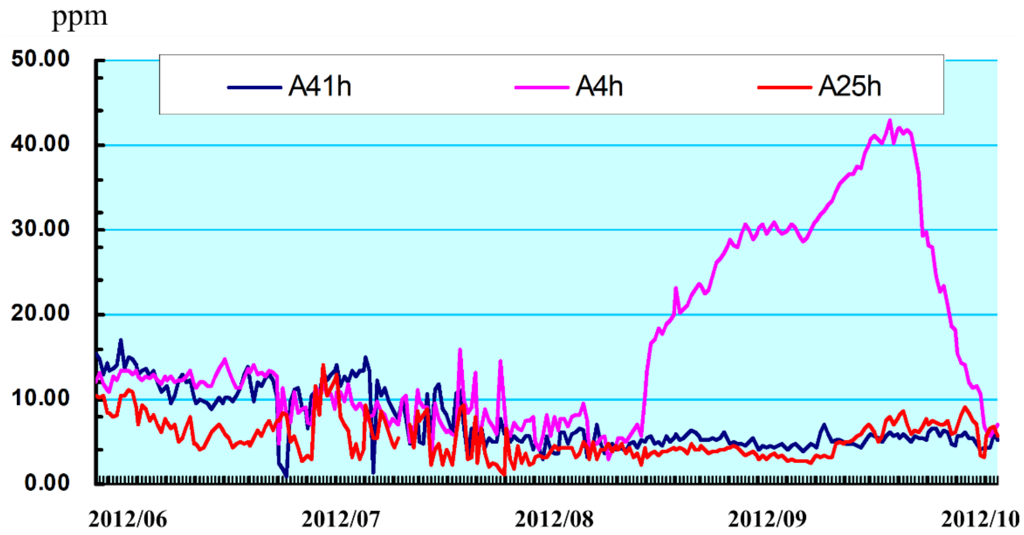

Figure 4. the production concentration of tracer on the well group of A27H

4. CONCLUSIONS

(1) Considering the injected signal's time lag and attenuation, a new mathematic model for inferring interwell dynamic connectivity was established by method of signal processing and the solution method of the model was proposed.
(2) The characterization parameters have clear physical meaning and can accurately describe the dynamic propagation features of injection signals in reservoir porous media. The application of homogenous field and inhomogenous field shows that this method can correctly inferring interwell dynamic connectivity and can quantitatively characterize the real reservoir condition.

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