

Investigation on Flow Rule and Productivity in Poorly Consolidated Reservoirs

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Abstract: Based on the production data and statistical information of a practical oilfield, it is proved that the flow rule in wormhole or extra wormhole can be regarded as a high speed Non-Darcy flow, and used the Forchheimer equation to represent. The Forchheimer model is superior to the exponent model and Mazaheri model. Then, the productivity equation of poorly consolidated reservoir with wormhole is derived based on the Forchheimer equation. Finally, the productivity equation is used to investigate the effect of viscosity ratio of crude oil to displacing fluid, the permeability ratio of wormhole to non-wormhole and injection-production pressure gradient on the yield percentage of the wormhole. The viscosity has the strongest effect on the yield distribution, and the injection-production pressure gradient has the weakest effect. Also, several improvement measures for enhancing oil recovery in poorly consolidated reservoirs with wormhole or extra wormhole are presented, such as polymer flooding, cross-linked polymer flooding, body gel blocking, pre-gelled particles flooding and foam flooding.

Keywords: poorly consolidated reservoir, wormhole, high speed Non-Darcy flow, productivity equation, enhanced oil recovery.

1. INTRODUCTION

Water flooding is a widely used method for field exploitation and secondary oil recovery all over the world. The success of any water flooding depends largely upon the ability of bank oil for efficient sweep to occur, regardless of the mobility ratio. However, after a long period of water flooding, the pore structure has been changed greatly, and the channeling is serious in the high and extra high permeability strip (namely wormhole and extra wormhole), which are formed in reservoirs. These strips make lots of injected water cyclically produced inefficiently along the wormhole, so that the utilization efficiency of the injected water is lower, and the swept volume reduced, and the oil recovery and development benefit is seriously affected [1-3]. At present, lots of matured oil fields are in the stage of high water-cut, utilization efficiency of injected water and development benefit is becoming lower. All these effects may have some relationship with the wormhole in the poorly consolidated reservoirs [4-6].

It is very necessary to strengthen the study on the wormhole to guide the development of poorly consolidated reservoirs at the high water-cut period for enhancing oil recovery. Many works have been done in the identification of wormhole such as forming influence factors, forming process and identification method [7-9]. The theory that fluids flow in wormhole is only restricted to the traditional percolation theory, or it is approximately regarded as pipe

flow. However, it is significant to understand the flow rule in the wormhole, because different flow rules will result in different development performances. Also, the flow rule is important for the reservoir numerical simulation. Therefore, in this paper the flow rule in the wormhole is studied based on the data from practical oilfield firstly. Then, the productivity equation of poorly consolidated reservoir with wormhole is obtained. Finally, sensitive analysis and improvement measure for development of poorly consolidated reservoirs are studied. This study is extremely significant to the development of poorly consolidated reservoir in the high water-cut period.

2. FLOW RULE AND ITS CHARACTERIZATION IN THE WORMHOLE

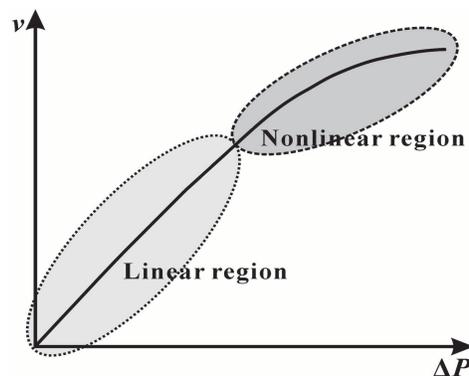


Fig. (1). Curve of velocity and pressure differential.

In general, the flow rule in the porous media obeys Darcy's law. However, as the speed increases, the relationship of pressure and speed deviates from the linearity

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and a curve appears in some cases, as shown in Fig. (1). The reason is that, when the speed is lower, the viscous resistance is the dominant force, and inertia force is so small that it can be ignored. At this moment, the pressure difference and speed represent a linear relation, which can be described by Darcy's law. When the speed is higher, the inertia force is so large that it can not be neglected. At this moment, the flow resistance is the sum of viscous resistance and inertia force, and the pressure difference and speed deviate from the linear relation.

When the wormhole or extra wormhole is existent in the poorly consolidated reservoir, the flow speed is high, and the Reynolds number is large, so a high speed Non-Darcy flow may appear, and modeled by a high speed Non-Darcy equation. The wormhole or extra wormhole is formed in the later period of oilfield development. After washing with water for a long period of time, the crude oil is almost completely driven out, which results in a single-phase flow in the wormhole or extra wormhole. The development effect is limited in the low permeability layers, and a two-phase flow exists. But the flow rate is low, and the Darcy's law is still obeyed in this region. Therefore, a single phase model is used to represent the flow rule in wormhole or extra wormhole which is full of water. The Forchheimer equation is usually used to represent the high speed Non-Darcy flow [10-14],

$$-\frac{dP}{dL} = \frac{\mu}{k}v + \beta_f \rho v^2 \quad (1)$$

Where, p is injection-production pressure, 10^{-1} MPa; L is well spacing, m; μ is fluid viscosity, mPa·s; v is flow velocity, cm/s; k is permeability, μm^2 ; ρ is fluid density, g/cm^3 ; ϕ is porosity, dimensionless; β_f is Non-Darcy coefficient, and modelled as [15-17],

$$\beta_f = 0.005/(\phi^{5.5} \cdot k^{0.5}) \quad (2)$$

Forchheimer equation has a good theoretical basis. Because the similar form of Forchheimer equation can be derived from the Navier-Stokes equation [18-20]. The pressure drop in the equation is the sum of viscous resistance and inertia force. When the speed is low, the quadratic term is so small that it can be neglected, and the Forchheimer

equation will be consistent with Darcy's law; when the speed is high, the pressure loss will be dominated by the quadratic term. All these features represent that using Forchheimer equation to describe high speed Non-Darcy flow is reasonable.

Belhaj *et al.* [21] presented the dimensionless parameter Be to predict the high speed Non-Darcy flow. It is the ratio of quadratic term to linear term,

$$Be = \frac{\beta_f \rho v^2}{\mu v/k} = \frac{\beta_f \rho k v}{\mu} \quad (3)$$

Theoretically, when the flow rate is very small, it will be in Darcy regime; then, as the flow rate increases, the pressure gradient gradually deviates from linear Darcy equation and the nonlinear effect increases. So there is no critical value for a Darcy and non-Darcy flow. However, in order to differentiate the flow rules in the porous media, the $Be_c=0.0526$ is mostly used as the critical value in field application [21], and this conclusion has been validated by the statistical results of field tests.

Zeng *et al.* [22] found that there are 53% wells in the presence of wormhole in the Ng⁶³⁺⁴ of Gudong Oilfield Block 7. And the permeability is as high as 8-80 μm^2 , with the average value of 10 μm^2 , which is 6.5 times higher than the initial value of 1.5 μm^2 . The pore radius of wormhole is between 12 and 60 μm , with the average value of 20 μm , which is 3 times larger than the initial value of 6 μm .

In this paper, two injection-production well groups existing wormhole and extra wormhole in Gudong Oilfield are taken as an example. The parameters of injection-production well group are shown in Table 1. After a long period of water flooding, the wormhole is full of injected water, so the fluid viscosity and density can be given the value of 1 mPa·s and 1 g/cm^3 respectively.

The $Be_1=0.5696$ and $Be_2=0.9655$ are obtained from the Eq. 3. According to the criterion of $Be_c=0.0526$, the flow rule in the wormhole and extra wormhole belongs to a high speed Non-Darcy flow. Then, the Forchheimer equation and Darcy's law are both used to calculate the flow speed in the wormhole or extra wormhole, the results are shown in Table 2.

Table 1. The Parameters of Injection-Production Well Group

Wormhole type	Porosity	Permeability / μm^2	Well spacing /m	Pressure differential /MPa	Actual speed /(cm/s)
Wormhole	0.3	10	279	20	0.156
Extra wormhole	0.35	25	212	20	0.348

Table 2. Calculation Results of Darcy and Non-Darcy Flow

Wormhole type	Actual speed /(cm/s)	Non-Darcy flow /(cm/s)	Error /%	Darcy flow /(cm/s)	Error /%
Wormhole	0.156	0.1542	1.15	0.2389	53.14
Extra wormhole	0.348	0.3428	1.49	0.6739	93.65

It is clear that, the error between calculated speed and actual speed is very little based on the Forchheimer equation, but which is more than 50% in wormhole and 90% in the extra wormhole based on the Darcy's law. Therefore, it is reasonable that the Forchheimer equation is used to describe the flow rule in wormhole and extra wormhole.

3. COMPARISONS OF FORCHHEIMER MODEL WITH OTHER MODELS

3.1. Exponent Model

The idea of non-integer exponents for the relationship between pressure gradient and flow rate was introduced by White [23] and generalized by Missbach [24].

$$v = -C \left(\frac{dP}{dL} \right)^n \tag{4}$$

Where, C is a constant, related to porous media and fluid properties, and it is assigned as k/μ in this paper; n is the flow index, its value is between 0.5 and 1.

3.2. Mazaheri Model

Mazaheri *et al.* [25] obtained a novel model to represent that the pressure drop increase deviates from the linear variation by fitting the simulation data,

$$-\frac{dP}{dL} = \frac{\mu}{k} v + \frac{\rho}{\eta} v^2 \tag{5}$$

3.3. Model Comparisons

The well groups of Gudong Oilfield are taken as an example again. Then, the exponent model, Mazaheri model and Forchheimer model is used to predict the flow rate based on the reservoir parameters respectively. The results are shown in Table 3.

From Table 3, when the n of exponent model equals 0.8 for wormhole and 0.7 for extra wormhole, the results are satisfactory, but the errors are large in other cases. The n is difficult to be determined in the process of practical application. The errors of Mazaheri model are 24.27% and 8.45%, which are both larger than that of the Forchheimer model. It can clearly be seen that the Forchheimer model is superior to the exponent model and Mazaheri model on representing the flow rules in wormhole or extra wormhole.

4. PRODUCTIVITY EQUATION FOR POORLY CONSOLIDATED RESERVOIR

It is assumed that a positive rhythm reservoir with a total effective thickness H , the thickness of wormhole h , and the width of high permeability strip is B . The injection-production well spacing is L , and the injection-production pressure difference is Δp . The permeability of wormhole is k_w , and the fluid viscosity and density are μ_w and ρ_w respectively. The permeability of non-wormhole is k_n , and the fluid viscosity and density are μ_n and ρ_n respectively. Also, the one-dimensional displacement from injector to producer is assumed. The Be_c is also used to judge the flow rule, when the Be in the wormhole is lower than Be_c , the flow rule in the wormhole will transform into Darcy flow. The productivity of wormhole is,

$$Q_1 = v_1 A_1 = \begin{cases} Bh \left(\frac{\sqrt{\left(\frac{\mu_w}{k_w} \right)^2 + 4\rho_w \beta_f \frac{\Delta p}{\Delta L}} - \frac{\mu_w}{k_w}}{2\rho_w \beta_f} \right) & Be \geq 0.0526 \\ \frac{k_w Bh \Delta p}{\mu_w \Delta L} & Be < 0.0526 \end{cases} \tag{6}$$

The productivity of non-wormhole is,

$$Q_2 = v_2 A_2 = \frac{k_n B(H-h)\Delta p}{\mu_n \Delta L} \tag{7}$$

Table 3. Comparisons of Forchheimer Model with Exponent Model and Mazaheri Model

Wormhole type	Actual value /(cm/s)	Models	Parameter	Calculation value /(cm/s)	Error %
Wormhole	0.156	Exponent model	$n=0.5$	0.0892	42.79
			$n=0.6$	0.1087	30.34
			$n=0.7$	0.1323	15.17
			$n=0.8$	0.1611	3.30
			$n=0.9$	0.1962	25.79
			$n=1.0$	0.2389	53.17
		Forchheimer model	0.1542	1.15	
Extra wormhole	0.348	Exponent model	$n=0.5$	0.2194	36.96
			$n=0.6$	0.2746	21.09
			$n=0.7$	0.3437	1.24
			$n=0.8$	0.4302	23.61
			$n=0.9$	0.5384	54.71
			$n=1.0$	0.6739	93.64
		Forchheimer model	0.3428	1.49	
		Mazaheri model		0.3185	8.45

Table 4. Yield Distributions of Wormhole and Non-Wormhole

Flow rule	Yield in wormhole (cm ³ /s)	Yield in non-wormhole (cm ³ /s)	Total yield (cm ³ /s)	Yield percentage in wormhole /%
Darcy flow	67.669	4.308	71.977	94.015
Non-Darcy flow	43.123	4.308	47.431	90.917

The total productivity is,

$$Q_t = Q_1 + Q_2 = \begin{cases} Bh \left(\frac{\sqrt{\left(\frac{\mu_w}{k_w}\right)^2 + 4\rho_w\beta_t \frac{\Delta p}{\Delta L} - \frac{\mu_w}{k_w}}}{2\rho_w\beta_t} \right) + \frac{k_r B(H-h)\Delta p}{\mu_n \Delta L} & Be \geq 0.0526 \\ \frac{k_r B H \Delta p}{\mu_n \Delta L} & Be < 0.0526 \end{cases} \quad (8)$$

Based on the tracer production curve of an well group in Gudong Oilfield, the thickness of wormhole is only several centimeters, but the permeability may reach up to 10-1000 μm². As a result, only 1-8% of the total effective thickness is occupied by the wormhole, but 90% of the production volume is occupied [26]. According to the field data, the well spacing is 266 m. The total effective thickness is 2 m, and the thickness of wormhole is 0.09 m which occupies 4.5% of the total effective thickness. The width is about 1 m. The oil viscosity is 50 mPa·s, and the injection-production pressure difference equals 20 MPa. The permeability of wormhole is 10 μm², and the permeability of non-wormhole is 1.5 μm². The porosity is 0.3. The yields of wormhole and non-wormhole are calculated by the Eqs. 6 and 7, and the results are shown in Table 4.

It is shown that the wormhole thickness occupies 4.5% of the total effective thickness, but the yield percentage reaches up to 90.917%. This result is consistent with the statistical value in the oilfield, which proves the rationality of using Forchheimer equation to represent the flow rule in wormhole or extra wormhole once again.

5. SENSITIVE ANALYSIS AND IMPROVEMENT MEASURES FOR DEVELOPMENT OF POORLY CONSOLIDATED RESERVOIR

5.1. Viscosity of Displacing Fluid

Increasing the viscosity of displacing fluid is an emphasis for enhancing oil recovery, and it is also important for developing the poorly consolidated reservoirs. In fact, it is only the displacing fluid in the wormhole, but a mixed system of displacing fluid and crude oil in the non-wormhole. Then, the effect of viscosity ratio of crude oil to displacing fluid on yield percentage of wormhole is studied based on the productivity equation, and as shown in Fig. (2).

It is shown that the viscosity ratio of crude oil to displacing fluid has a significant effect on the yield distribution. As the viscosity ratio increases, the yield percentage of wormhole increases rapidly. When the viscosity ratio of crude oil to displacing fluid equals 1, the yield percentage in non-wormhole can increase to about 85%, a large number of remaining oil will be produced. Therefore, the EOR technology such as polymer flooding

and cross-linked polymer flooding can be used to develop the poorly consolidated reservoirs in high water-cut stage.

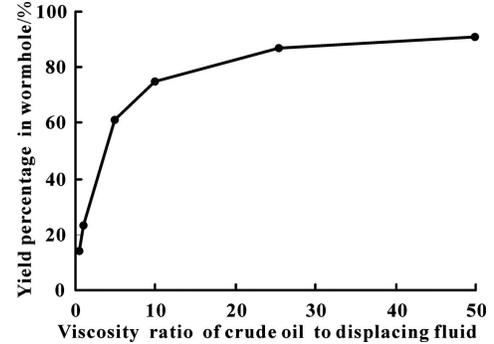


Fig. (2). Effect of viscosity ratio of oil to displacing fluid on yield percentage in wormhole.

5.2. Permeability of Wormhole

The main reason for the high flow speed in the wormhole is the excessive permeability. And it also affect the heterogeneity of injection profile. The effect of permeability ratio of wormhole to non-wormhole on yield percentage is studied based on the productivity equation, and as shown in Fig. (3).

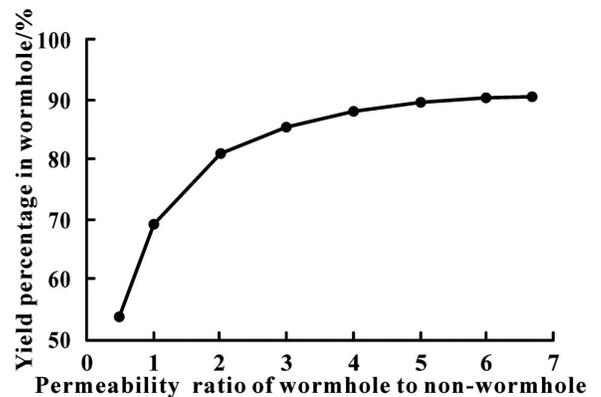


Fig. (3). Effect of permeability ratio of wormhole to non-wormhole on yield percentage in wormhole.

It is shown that the permeability ratio of wormhole to non-wormhole also has a significant effect on the yield distribution. As the permeability ratio increases, the yield percentage of wormhole increases. When the ratio of wormhole to non-wormhole equals 1, the yield percentage in non-wormhole can increase up to about 30%. Therefore, the EOR technology such as body gel blocking, pre-gelled particles flooding and foam flooding can be used to develop the poorly consolidated reservoirs in high water-cut period.

5.3. Inject-Production Pressure Gradient

Adjusting the operation parameters is another way to enhance oil recovery. In this section, the effect of injection-production pressure gradient is discussed. The effect of injection-production pressure gradient on yield percentage is shown in Fig. (4).

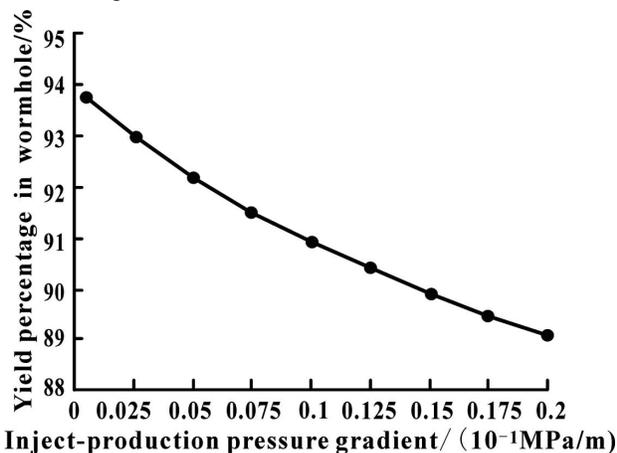


Fig. (4). Effect of inject-production pressure gradient on yield percentage in wormhole.

It is shown that the influence degree of injection-production pressure gradient is weak. As the injection-production pressure gradient increases, the yield percentage of wormhole reduces gradually. Therefore, a larger pressure differential should be used in the development process if the condition is permitted.

6. CONCLUSIONS

The flow rule in the wormhole or extra wormhole can be regarded as a high speed Non-Darcy flow, and modelled by the Forchheimer equation. And it is superior to the exponent model and Mazaheri model. The productivity equation is obtained based on the Forchheimer equation. and then the sensitivity analysis of viscosity ratio of crude oil to displacing fluid, permeability ratio of wormhole to non-wormhole and injection-production pressure gradient are studied,

- The viscosity ratio of crude oil to displacing fluid has a significant effect on the yield distribution, as the viscosity ratio increases, the yield percentage of wormhole increases rapidly. Polymer flooding or cross-linked polymer flooding can be used to develop the poorly consolidated reservoirs in high water-cut stage;
- The permeability ratio of wormhole to non-wormhole has a significant effect on the yield distribution. As the permeability ratio increases, the yield percentage of wormhole increases. But the influencing degree is much weaker than that of viscosity ratio. Body gel blocking, pre-gelled particles flooding and foam flooding can be used to develop the poorly consolidated reservoirs with wormhole or extra wormhole.
- The injection-production pressure gradient has the weakest influence on the yield distribution. As the injection-production pressure gradient increases, the yield percentage of wormhole reduces gradually. But it is

also necessary to use a larger pressure difference in the development process if the condition is permitted.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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