Enhanced Oil Recovery of the Anisotropic Reservoir

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ABSTRACT

Usually, productive formations of oil and gas fields are anisotropic on their reservoir properties. Most scientists paid attention to determination and taking into consideration the anisotropy of permeability in vertical direction. Theoretical studies and real data confirm that such type of anisotropy renders the significant influence on the development processes of oil and gas fields. But attention to take into account the lateral anisotropy is not enough. Therefore in this paper the attempt is made to consider the influence of lateral anisotropy on the indices of the oil displacement under water flooding at different well pattern and their configurations.

INTRODUCTION

For a long time the geological investigations show the fact of anisotropy of the reservoir properties in productive formations. In particular it concerns carbonate rocks^{1,2}.

There are a lot of publications which take into account the anisotropy of reservoir properties in vertical direction. Especially it concerns the papers which consider the oil and gas inflow problems for wells with partial penetration, the formation of gas and water cones³⁻⁵. Approximate solution for system of the vertical wells in anisotropic reservoir could be found in work⁶ as applied to the steady-state flow regime.

In connection with wide application of the horizontal wells in practice of oil and gas production, some solutions⁷⁻⁹ for horizontal well draining the

anisotropic reservoir were obtained and pointed the ways of taking into consideration the formation anisotropy in numerical simulation of the horizontal well¹⁰. Of course, the analytical solutions deal with single-phase flow.

Some publications consider that there are reasons to improve several ideas of multiphase flow theory in anisotropic reservoirs¹¹⁻¹⁴.

Thus, there are the different consumers of information on the reservoir anisotropy. It needs not only qualitative, but also quantitative data about anisotropy. Therefore different methods were worked out to determine the formation anisotropy both in vertical direction¹⁵⁻¹⁷ and along productive area^{16,18}. Besides, the injection of some indicators is used in order to estimate parameters of the lateral anisotropy^{19,20}.

At the same time taking into account the anisotropy in processes of displacing one fluid by another is needed investigations. It's evident that the lateral anisotropy should affect the injection and producing well pattern, the water-cut dynamics and the ultimate oil recovery factor(ORF).

The configuration of injection and producing well pattern, well pattern density are the subject of the steadfast studies long ago. It's connected with their influence on ORF and the expenses for the recovery of oil resources. There are a lot of publications on the clearing of ORF dependance from the configuration of well pattern and well pattern density^{3,21-28}. As authors know, the preceding investigations concerned, basically, the cases of isotropic reservoir or they took into account

the different types of heterogeneity, wedging out of bed and so on. In the present paper the processes of oil displacement by working agents are considered as applied to the anisotropic reservoir, and the corresponding comparison with isotropic formations is given. Very interesting results are observed under the well pattern deformation both in isotropic and anisotropic reservoirs.

Fig. 1. Example of linear well system deformation.

PROBLEM STATEMENT

The regularities and quantitative characteristics of the one fluid by another displacement processes are examined under different lateral anisotropy and various configurations of the considered well patterns.

In this connection the oil by water displacement processes are investigated for two characteristic well pattern - linear and five-spot well system. Probably, some well patterns, such as seven-spot well system, nine-spot well system and so on, are not useful in the anisotropic formation since some of the operating wells appear under unfavourable conditions from the viewpoint of premature water cutting.

It's supposed that the main axes of the permeability tensor are directed along Ox and Oy axes respectively. Permeability along Ox axis is denoted by Kx and along Oy axis - Ky . Investigations are fulfilled for different Kx/Ky ratios. Comparisons are given for the cases when $Kx/Ky = 1; 10; 100$. In the case of the five-spot well system the obtained results for the mentioned Kx/Ky ratios are correct also for the cases when $Ky/Kx = 10; 100$ since we have symmetry of flow scheme. In the case of linear well system we have to consider the mentioned cases of Ky/Kx ratios separately.

Three variants differed by phase permeability and mobility ratio are examined. In the first variant the phase permeabilities are linear function of saturation.

This case is of interest as applied to miscible displacement processes. In the second variant the phase permeabilities are polynomial relations of saturation. Herewith water gets mobility at saturation equal to 0.25, and residual oil saturation is equal to 0.23. In the third variant the phase permeabilities are taken as quadratic relations of saturation starting from the coordinate beginning and from the point with water saturation equal to 1, accordingly to water and oil.

Absolute value of permeability is uniform and equal to 0.2 D in the cases with isotropic formation. In the case of anisotropic reservoir this permeability value is minimum of two main values of permeability tensor. We will not become confused by high permeability values Ky as sometimes permeability attains 10 D, for example, in the case of North Sea fields. Porosity and formation thickness are taken the same in all variants and equal to 0.2 and 15 m respectively.

In the first and second series of variants the mobility ratio is equal to 1 and oil viscosity in formation conditions - 3.64 mPa.s. Therefore, for instance, thickened water could be considered as injected fluid. In the third series of variants the unfavourable case is studied when the mobility ratio of oil and displacing agent is equal to 10. At the same oil viscosity the viscosity of injected agent is equal to 0.364 mPa.s that corresponds to water in formation conditions: initial formation pressure is equal to 15.2 MPa and formation temperature - 65°C.

In the case of linear well pattern the basic variant is characterized by the equal distance between wells in rows and between rows. This distance is 500 m. Basic five-spot well pattern also has equal sides. They are 1000 m.

The well pattern density is not changed in all cases of linear and five-spot well systems. But well pattern deformation is carried out by the change of the sides' ratio (see fig. 1). The oil rate of the operating well and the injection rate of well are constant in all considered variants and equal to 100 m³/day.

The parameter for comparison of considering variants is not obvious. Evidently, the considering variants will be characterized by various development duration, different water-cut dynamics and ORF. Frequently they want to get back as soon as possible the used up capital charges since oil production. From this connection the current ORF at 50% wells' water-cutting is of some interest. As applied to offshore fields the 70% water-cutting is rather critical because of limited opportunities to treat the water cut production. Usually oil production is made until 98% water-cutting at onshore fields. Therefore at the outset we will analyze the development figures under achievement of 50% water-cutting. Then the analysis is completed by results for cases of water-cutting at 70% and 98%.

Stated below results are obtained with use of 2D two-phase numerical simulator. Herewith new solving algorithm of respective problem is employed which provides less numerical dispersion as compared with

Fig. 2. Isolines of water saturation under oil-by-water displacement in II variant.

another methods²⁹.

LINEAR WELL PATTERN

Considering formation element is oriented in this case so that the producing and injection wells are disposed at Oy axis and displacement takes place upwards (see fig. 1). Here and far the following indices achieved at the moment of 50% water-cutting deserve the most attention:

- oil recovery factor;
- pressure difference ΔP between grid points where the operating and injection wells are located;
- development duration T when mentioned water-cut takes place.

Calculation results for linear well pattern are given in table I when distance between wells and rows is equal to 500*500 m. First of all it's noted that the difference in development indices in cases of isotropic and anisotropic formations is explained by various character of phase permeability in corresponding variants.

Table 1. Development indices for linear well pattern.

Variants		Anisotropy parameter, K_x/K_y				
		100	10	1	1/10	1/100
I	ORF	.9271	.8937	.7110	.3132	.1117
	$\Delta P, \text{MPa}$	0.72	0.95	1.62	0.36	0.06
	T, days	7320	7170	6020	2890	870
II	ORF	.6600	.6504	.5675	.2483	.0818
	$\Delta P, \text{MPa}$	3.98	4.85	7.6	1.7	0.34
	T, days	5000	4940	4480	2080	620
III	ORF	.6385	.6090	.5255	.2332	.0934
	$\Delta P, \text{MPa}$	0.15	0.18	0.32	0.07	0.012
	T, days	7850	7310	6900	3070	1040

Analysis of table 1 allows to remark very strong dependance of considered development indices from formation anisotropy degree.

It's obviously that if the most permeable direction coincides with displacement direction then ORF sharply decreases by growth of K_y/K_x ratio. So, for example, in variant I the ORF, which equals to 0.7110 in the case of isotropic formation, reduces to 0.3132 and 0.1117 at $K_y/K_x = 10$ and 100 respectively. Naturally, the development duration T and pressure loss ΔP are shortened.

The correct taking into consideration of formation anisotropy by well disposing leads to considerable increase of ORF. In the same variant if displacement is organized along direction with the less permeability then ORF grows up from 0.7110 to 0.8937 and 0.9271 accordingly when $K_x/K_y = 10$ and 100. It's explained by that the displacement front is complicated by water

fingering in considerable less degree as compared with the case of isotropic formation. This circumstance is connected with that injected fluid is of favourable condition for spread in direction along Ox axis. Therefore the possibility of forming the stagnant zones is decreased. Here the growth of development durations

Fig. 3. Isolines of water saturation in deformed linear well patterns at the same time in II variant.

takes place due to more ORF succeed in corresponding subvariants. It's important that energetic losses are reduced as well. It's explained by the pressure losses ΔP decrease due to high permeability along direction which coincides with direction of main axis of permeability tensor with the most main value. Calculation results for II and III variants are explained by the same way. Low pressure losses ΔP in III variant are connected with that the injected fluid viscosity is less by 10 times in comparison with II variant. The given in table 1 ΔP values correspond to ultimate time T.

Figure 2 allows to understand the flow process

peculiarities in considered both isotropic and anisotropic reservoirs and the obtained numerical indices too. Here isolines of water saturation, as applied to II variant, are presented at the same date for cases when $Kx/Ky = 1$; 100 and 1/100 respectively. Evidently, fig. 2 does not need additional explanations as it illustrates properly the said above statements.

It's revealed in the course of present studies that the well pattern deformation can render considerable influence on the development indices as well as the formation anisotropy. Let's deform the considered development element, namely will change the ratio of sides b/a from 1 to 4 or 1/4 as applied to isotropic

formation(see fig. 1). Here and far a - length of element side along Ox axis, b - along Oy axis. Calculation results are given in table 2 for these cases.

Table 2. Development indices under different well pattern deformations.

Variants		Ratio of sides, b/a		
		1	4	1/4
I	ORF	0.7110	0.9065	0.2574
	$\Delta P, \text{MPa}$	1.62	3.3	1.05
II	ORF	0.5675	0.6540	0.2150
	$\Delta P, \text{MPa}$	7.6	18.25	5.0
III	ORF	0.5255	0.6175	0.1904
	$\Delta P, \text{MPa}$	0.32	0.77	0.21

The case, when $b/a=1/4$, does not deserve any attention. It's presented only to emphasize the role and meaning of the well pattern deformation factor. The case, when $b/a=4$, shows it's useful to reduce distance between wells into row and to increase distance between rows, having the same number of wells (at invariable well pattern density). The increase of distance between operating and injection wells is favourable for growing of ORF. Herewith the energetic expenses increase in such cases. For example, ΔP value enlarges from 1.62 MPa to 3.3 MPa in I variant.

Figure 3 permits to trace the influence of well pattern deformation factor on sweep efficiency. Here the isolines of water saturation are presented at the same time, as example, for the II variant. We can see that larger productive area is embraced by displacement process at $b/a=4$.

Dependencies of the well water-cut and ORF from time are given at fig. 4 and 5 for different formation anisotropy degree in the case of linear well pattern when $b/a=1$. These dependencies show that the formation anisotropy is the important factor and it predetermines all peculiarities of water-cut and ORF values.

We can't say that the deformation problem of development element is new. For example, it's spoken about in work²⁸. But there the author doesn't feel the required assurance in such matter as the stretching of well pattern at fixed ΔP leads to reduction of oil rate. Unlike the work²⁸ the fulfilled investigations show more exactly the expediency of well pattern deformation. As a result the ORF could be increased, the same oil rates could be kept under the growth of ΔP value, i. e. the growth of energetic expenses.

There is a need to give some numbers in order to feel really with what well spacing we would deal in the course of deformation of initial development element with 500×500 m size. At the invariable well pattern density the side a is equal to 250 m and side b

Fig. 4. Water-cut dynamics in the case of linear well pattern.

Fig. 5. ORF dynamics at different formation anisotropy in the case of linear well pattern.

is equal to 1000 m when the ratio of sides is equal to 1/4. When the ratio of sides $b/a=16$, we have $a=125$ m, $b=2000$ m. Probably such stretching of development element sides would be very useful in the cases of offshore field mastering since it would allow to increase the distance between platforms and might reduce their number.

FIVE-SPOT WELL PATTERN

Calculation results for isotropic and anisotropic formations as applied to five-spot well system are presented in table 3. Besides, the data of table 3 reflect the influence of well pattern deformation factor on the development indices.

Let's consider at first results obtained for isotropic formation as they represent an independent interest.

1. In the case of isotropic reservoir the symmetrical results take place as applied to the stretching of the five-spot well pattern along Ox axis or Oy axis.

2. The stretching of examined well pattern is

Fig. 6. ORF as a function of sides' ratio of five-spot pattern.

favourable for ORF in the I variant of phase permeabilities and mobilities. ORF increases from 0.8161 to 0.9214, 0.9399 and 0.9404 respectively when the ratio of sides b/a is changed from 1 to 4, 8 and 16. Here we can see that the well pattern deformation factor acts irregularly. Thus, the greatest ORF growth takes place at increasing the ratio of sides from 1 to 4. Like the previous case moving of the producing well away from the injection one leads to increase of pressure losses ΔP between wells and to increase of duration T of displacement process. Nevertheless it's obvious that well pattern deformation could be effective method. For example, ORF increases from 0.8161 to 0.9214 by enlarge of sides' ratio b/a from 1 to 4 and pressure losses ΔP growth from 3.25 MPa to 4.3 MPa. In a word the determination of optimal well pattern deformation degree is both technical and economical problem.

It's deserved to be underlined the constant dependence of ORF growth from well pattern deformation degree in II variant. Besides ORF increase the reduction of development time is achieved in III

variant.

3. Formation anisotropy, when $b/a=1$, acts positively on ORF in the considering five-spot well system orientation case relatively to the main axes of permeability tensor. In the series of first(I) variants ORF increases from 0.8161 to 0.9094 and 0.9407 by growth of K_x/K_y to 10 and 100 respectively. In second(II) series of variants we have sequentially values of ORF equal to 0.6297, 0.6434, 0.6582. In third(III) variants we have the analogous tendency in figures - 0.6214, 0.6333, 0.6392.

4. In the case of anisotropic formation the considering dependencies of ORF from well pattern deformation character differ by new peculiarities. If the well pattern deformation is made in direction, where $b/a < 1$, it results in significant ORF decrease. For instance, in I variant, when $K_x/K_y=10$, ORF reduces from 0.9094 at $b/a=1$ to 0.8244 at $b/a=1/4$. But ORF at $b/a=1/16$ reaches 0.9311. When $K_x/K_y=100$, the minimum value of ORF is occurred at $b/a=1/8$: ORF decreases from 0.9407 to 0.8240. Some dependencies of ORF from well pattern deformation character are given in fig. 6. They testify that in each particular case the well pattern both in isotropic and anisotropic reservoir demands more careful investigations. Herewith the five-spot well pattern should be stretched in direction with the smallest permeability, though some growth of energetic expenses (ΔP value) takes place.

ORF - WATER-CUTTING

The criterion of production water-cutting influences on conclusions following from simulation data. Some of the calculation results of ORF under different water-cutting given in the fig. 7-9 confirm this idea in case of five-spot well pattern.

The mentioned above figures allow to express the fairly important practical conclusion. Under considerable output water-cutting (98%) the five-spot well pattern is small sensitive to

- possible their deformation, i. e. it is no need of any stretching;
- degree of formation anisotropy.

These conclusions as applied to large water-cutting are fair when direction of that well pattern coincides with main axes of permeability tensor. If diagonal connecting producer and injector coincides with one of permeability tensor axes the conclusions mentioned above for linear well system are becoming just to considered well pattern.

CONCLUSIONS

1. Formation anisotropy renders the large influence on the indices of the process of oil displacement by different agents. Incorrect taking into account of formation anisotropy could lead to sharp reduce of ORF. By correct taking into consideration of reservoir anisotropy one could achieve the ORF increase as compared with the case of isotropic reservoir.

2. The well pattern deformation factor provides

Table 3. ORF values for five-spot well pattern at different phase permeabilities, mobilities, anisotropy and the ratio of element sides.

Variants		Ratio of sides, b/a						
		1/16	1/8	1/4	1	4	8	16
Anisotropy parameter, $K_x/K_y=1$								
I	ORF	.9413	.9402	.9222	.8168	.9222	.9402	.9413
	$\Delta P, \text{MPa}$	11.7	6.57	4.32	3.24	4.32	6.57	11.7
	T,days	7350	7350	7260	6540	7260	7350	7350
II	ORF	.6645	.6584	.6491	.6305	.6491	.6584	.6645
	$\Delta P, \text{MPa}$	64.8	36.7	23.9	19.0	23.9	36.7	64.8
	T,days	5050	5000	4930	4770	4930	5000	5050
III	ORF	.4165	.4162	.4129	.3840	.4129	.4162	.4165
	$\Delta P, \text{MPa}$	5.58	3.10	2.02	1.56	2.02	3.10	5.58
	T,days	3300	3320	3330	3110	3330	3320	3300
Anisotropy parameter, $K_x/K_y=10$								
I	ORF	.9316	.8921	.8249	.9102	.9413	.9403	.9402
	$\Delta P, \text{MPa}$	1.54	1.16	1.03	1.24	3	5.7	11.2
	T,days	7305	7080	6615	7200	7350	7335	7335
II	ORF	.6543	.6399	.6318	.6451	.6637	.6623	.6642
	$\Delta P, \text{MPa}$	8.55	6.22	6.04	6.88	16.5	31.2	61.2
	T,days	4935	4840	4780	4900	5050	5020	5040
III	ORF	.4156	.4069	.3874	.4010	.4163	.4170	.4171
	$\Delta P, \text{MPa}$	0.724	0.548	0.496	0.583	1.43	2.72	5.37
	T,days	3340	3310	3150	3320	3300	3300	3300
Anisotropy parameter, $K_x/K_y=100$								
I	ORF	.8443	.8245	.8905	.9409	.9403	.9402	.9402
	$\Delta P, \text{MPa}$	0.334	0.326	0.364	0.78	2.8	5.6	11.17
	T,days	6750	6615	7065	7350	7335	7335	7335
II	ORF	.6372	.6318	.6399	.6607	.6633	.6643	.6646
	$\Delta P, \text{MPa}$	1.96	1.9	1.96	4.34	15.3	30.4	61.7
	T,days	4820	4780	4840	5020	5030	5040	5040
III	ORF	.3925	.3873	.4067	.4163	.4172	.4172	.4172
	$\Delta P, \text{MPa}$	0.160	0.157	0.172	0.369	1.34	2.67	5.33
	T,days	3190	3150	3310	3310	3300	3300	3300

Fig. 7. ORF as a function of the sides' ratio of five-spot pattern when $K_x/K_y=1$.

Fig. 8. ORF as a function of the sides' ratio of five-spot pattern when $K_x/K_y=10$.

Fig. 9. ORF as a function of the sides' ratio of five-spot pattern at $K_x/K_y=100$.

the ORF increase in both isotropic and anisotropic formations. Optimal well pattern deformation degree could be established as the result of statement and solving of corresponding technic-economic problem, since ORF growth is accompanied by the increase of energetic expenses when we increase the distance between the producing and injection wells.

3. Not all the traditional well patterns are applicable in the case of anisotropic reservoirs. The application of development elements with large number of producing wells per one injector could result in ORF loss expressed in premature water-cutting of some wells. The five-spot well pattern is the least sensitive system from formation anisotropy under high water cutting, if its sides direction coincides with main axes of permeability tensor.

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