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STUDY OF METHODS OF HYDROCARBON RECOVERY ENHANCEMENT FROM THE DEPLETED OIL FIELDS

1. INTRODUCTION

The current state of oil and gas industry of Ukraine is characterized by the depletion of major hydrocarbon resources for oil and gas fields from which it has been produced and is still produced the major amount of the hydrocarbons. The depleted fields still contain significant hydrocarbon reserves. With the modern level of oil-and-gas production technologies, which are used in the Ukrainian fields, the predicted ultimate oil recovery factor is near 35%, condensate recovery – 35–40%, gas recovery – 75–90%. The discovered fields in the recent years are characterized by the low hydrocarbon resources. That's why in the nearest decade, the bulk hydrocarbon production will be provided with the "old" fields, containing significant hydrocarbon resources. Thus, new technologies are needed to involve into the development the remaining hydrocarbon resources and to enhance the ultimate oil-and-gas-condensate recovery factor.

The deep drilling deposits of the Hlybynna Fold of the Boryslav oil field started at the beginning of the XIX century, when the process was without any deep drilling or development system. The deposit of the Boryslav sandstone of the Hlybynna Fold has been introduced into the industrial development since 1954. Oil deposits of the Hlybynna Fold are developed at the combined drives (dissolved gas drive and inefficient water drive. Quite intensive wells watering is the result of it).

The current state of deposit development of the Boryslav sandstone of the Hlybynna Fold of the Boryslav oil field can be characterized as unsatisfactory.

Among the methods of oil recovery enhancement which are characterized with the most effective processes rather than the traditional water flooding, we can be name the

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method of oil recovery with micellar solvents, carbon dioxide, steam, by means of fireflooding in situ combustion (Chatzis *et al.*, 1988; Safonov & Almaev, 1997; Khristianovich & Kovalenko, 1988; Surguchev *et al.*, 1991; Surguchev, 1985; Yurkiv, 1994; Zhdanov, 2001).

Very effective method of oil recovery enhancement at the final stages of oil fields development is the use of polymer flooding in addition to water flooding (Fakhretdinov, 1994; Grirorashchenko *et al.*, 1978; Shevtsov & Bakaev, 1994; Shevtsov, 1989Suleimanov *et al.*, 1998; Vlasov *et al.*, 1998). Polymer solutions are most suitable for use in heterogeneous beds and they are used to increase oil viscosity to cover it with water flooding. Such reservoir rock characteristics and physical-and-chemical properties of formation fluids are inherent to the deposit of the Boryslav sandstone of the Hlybynna Fold of the Boryslav field.

Polymer solutions with higher viscosity, better displace not only oil, but bound water, that's why they interact with the rock skeleton and cementing substance. This causes the adsorption of polymer molecules which block channels or impair filtration of water in them. But on the displacement front the inactive water shaft is formed. These two factors lead to a decrease in the dynamic heterogeneity of fluid flow and, consequently, to the increase of beds water flooding coverage (Zhang Xiaoqin *et al.*, 2013; Ali Goudarzi *et al.*, 2013; Haomin Xu *et al.*, 2013).

2. EXPERIMENTAL PROCEDURE

At the modern stage of oil-and-gas industry growth, the hydrodynamic modeling of oil fields development processes has got a wide use. To optimize the development system of the Boryslav sandstone of the Boryslav oil field the main principles of mathematical modeling of multiphase filtration flow in the porous medium have been applied.

In the basis of the mathematical task formulation the main mathematical equation of multiphase filtration process is set. The filtration process of three phases of oil, gas and water is described with the nonlinear system of equations with partial derivatives which comprises:

1. An equation of flow continuity for each phase:

$$-div\left(\frac{u_H}{B_H}\right)=\frac{\partial}{\partial t}\left(m\frac{s_H}{B_H}\right)+q_H \tag{1}$$

$$-div\left(\frac{u_B}{B_B}\right)=\frac{\partial}{\partial t}\left(m\frac{s_B}{B_B}\right)+q_B \tag{2}$$

$$-div\left(\frac{u_\Gamma}{B_\Gamma}+\frac{R\cdot u_H}{B_H}\right)=\frac{\partial}{\partial t}\left[m\cdot\left(\frac{s_\Gamma}{B_\Gamma}+\frac{R\cdot s_H}{B_H}\right)\right]+q_\Gamma \tag{3}$$

2. An equation of motion for each phase:

$$\overrightarrow{u_H} = -\frac{k_H(s_H, s_B)}{\mu_H}\overrightarrow{\text{grad}}(\text{p}_\text{H}) \tag{4}$$

$$\overrightarrow{u_B} = -\frac{k_B(s_H, s_B)}{\mu_B}\overrightarrow{\text{grad}}(\text{p}_\text{B}) \tag{5}$$

$$\overrightarrow{u_\Gamma} = -\frac{k_\Gamma(s_H, s_B)}{\mu_\Gamma}\overrightarrow{\text{grad}}(\text{p}_\Gamma) \tag{6}$$

After the equation of motion is substituted into the equation of continuity we will get the main equation of filtration:

$$div\left[K_H \overrightarrow{\text{grad}}(\text{p}_\text{H})\right] = \frac{\partial}{\partial t}\left(m\frac{s_H}{B_H}\right) + q_H \tag{7}$$

$$div\left[K_B \overrightarrow{\text{grad}}(\text{p}_\text{B})\right] = \frac{\partial}{\partial t}\left(m\frac{s_B}{B_B}\right) + q_B \qquad (8)\ \ (\text{I})$$

$$div\left[K_\Gamma \overrightarrow{\text{grad}}(\text{p}_\Gamma) + R \cdot K_H \overrightarrow{\text{grad}}(\text{p}_\text{H})\right] = \frac{\partial}{\partial t}\left[m\left(\frac{s_\Gamma}{B_\Gamma} + \frac{R \cdot s_H}{B_H}\right)\right] + q_\Gamma \tag{9}$$

whereas:

s_l – saturation of the l-st phase
B_l – volumetric factor of the 1-st phase
p_l – pressure of the 1-st phase
k_l – relative permeability of the 1-st phase
R – gas solubility in oil
$K_l = \frac{k_l(s_H, s_B)}{\mu_l \cdot B_l}$ – non-linear factor, depending on pressure
l = H(oil), B(water), Γ(gas)

On the basis of modern methods of oil and oil-and-gas-condensate fields development design by means of mathematical modeling technology, different factors influencing the fluid influx into the wells are taken into account. It is also taken into account non-isothermal filtration of unsteady many-component fluids in non-isotropic heterogeneous deformation mediums considering capillary effect. For these types of tasks, the following additional equations are required:

Fluids and gas viscosity:

$$\mu = \mu_0 \left[1 + a_\mu (p - p_0) \right] \tag{10}$$

An equation of fluid state:

$$B = \frac{B_O}{1 + \beta_p (p - p_0)} \tag{11}$$

The porosity dependence factor on pressure:

$$m = m_0 \left[1 + a_m (p - p_0) \right] \tag{12}$$

The permeability dependence factor of the porous medium on pressure:

$$k = k_0 \left[1 + a_k (p - p_0) \right] \tag{13}$$

The principle of the mathematical modeling of oil-and-gas fields development process is based on the equations system solution (I) with additional equations. At the modern stage of equations system solution the IMPES method or the method which is implicit toward the pressure but explicit toward saturation is widely used.

The principle of the method is that – instead of the continuous differential equitation they are transformed into the digital form for each unit of filtration space domain. The transformation is done by means of final volumes method.

Sampling of medium derivatives:

$$div\left[K \overrightarrow{\text{grad}}(\text{p}) \right] = \frac{1}{V_{ijk}} \left(\Delta_x K_x \Delta_x p + \Delta_y K_y \Delta_y p + \Delta_z K_z \Delta_z p \right) \tag{14}$$

$V_{ijk} = \Delta x_i \cdot \Delta y_j \cdot \Delta z$ – volume of elementary block

whereas:

$$\Delta_x K_x \Delta_x p = \left\{ \left(\frac{K_x}{\Delta x} \right)_{i+1/2} (p_{i+1} - p_i) - \left(\frac{K_x}{\Delta x} \right)_{i-1/2} (p_i - p_{i-1}) \right\} \Delta y_j \Delta z_k \tag{15}$$

$$\Delta_y K_y \Delta_y p = \left\{ \left(\frac{K_y}{\Delta y} \right)_{j+1/2} (p_{j+1} - p_j) - \left(\frac{K_y}{\Delta y} \right)_{j-1/2} (p_j - p_{j-1}) \right\} \Delta z_k \Delta x_i \tag{16}$$

$$\Delta_z K_z \Delta_z p = \left\{ \left(\frac{K_z}{\Delta z} \right)_{k+1/2} (p_{k+1} - p_k) - \left(\frac{K_z}{\Delta z} \right)_{k-1/2} (p_k - p_{k-1}) \right\} \Delta x_i \Delta y_j \tag{17}$$

Sampling of time derivatives:

$$\frac{\partial}{\partial t}\left(m\frac{s_l}{B_l}\right)=\frac{\partial}{\partial t}\left(\frac{ms_l}{B_l}\right)=\frac{1}{\Delta t}\Delta_t\left(\frac{ms_l}{B_l}\right) \tag{18}$$

$$\frac{\partial}{\partial t}\left[m\left(\frac{s_\Gamma}{B_\Gamma}+\frac{s_{\mathrm{H}}\cdot R}{B_H}\right)\right]=\frac{1}{\Delta t}\left[\Delta_t\left(\frac{ms_\Gamma}{B_\Gamma}+\frac{ms_H\cdot R}{B_H}\right)\right] \tag{19}$$

With the use of correlation:

$$\Delta_t\left(F\cdot G\right)=F^{n+1}\Delta_t G+G^n\Delta_t F$$

It is got:

$$\Delta_t\left(\frac{ms_l}{B_l}\right)=\left(\frac{m}{B_l}\right)^{n+1}\Delta_t s_l+s_l^n\Delta_t\left(\frac{m}{B_l}\right) \tag{20}$$

$$\Delta_t\left(\frac{ms_\Gamma}{B_\Gamma}+\frac{ms_H R}{B_\Gamma}\right)=\left(\frac{m}{B_\Gamma}\right)^{n+1}\Delta_t s_\Gamma+s_\Gamma^n\Delta_t\left(\frac{m}{B_\Gamma}\right)+\left(\frac{mR}{B_H}\right)^{n+1}\Delta_t s_H+s_H^n\Delta_t\left(\frac{mR}{B_H}\right) \tag{21}$$

After the achieved equations are substituted into the system (I), it is got a discretized equation for each unit:

$$\frac{1}{C_{ijk}}\left(\Delta T_B\Delta p_B+Q_{w,ijk}\right)=\left(\frac{m}{B_B}\right)^{n+1}\Delta_t s_B+s_B^n\Delta_t\left(\frac{m}{B_B}\right) \tag{22}$$

$$\frac{1}{C_{ijk}}\left(\Delta T_H\Delta p_H+Q_{H,ijk}\right)=\left(\frac{m}{B_H}\right)^{n+1}\Delta_t s_H+s_H^n\Delta_t\left(\frac{m}{B_H}\right) \tag{23}$$

$$\frac{1}{C_{ijk}}\left(\Delta T_\Gamma\Delta p_\Gamma+\Delta RT_H\Delta p_H+Q_{\Gamma,ijk}\right)=\left(\frac{m}{B_\Gamma}\right)^{n+1}\Delta_t s_\Gamma+s_\Gamma^n\Delta_t\left(\frac{m}{B_\Gamma}\right)+$$
$$+\left(\frac{mR}{B_H}\right)^{n+1}\Delta_t s_H+s_H^n\Delta_t\left(\frac{mR}{B_H}\right) \tag{24}$$

whereas: $C_{ijk}=\frac{V_{ijk}}{\Delta t}=\frac{\Delta x_i\cdot\Delta y_j\cdot\Delta z_k}{\Delta t}$

The achieved system is non-linear both toward the pressure and permeability as the equations factors depend on the needed values.

$$\frac{1}{b_B^{n+1}}[Eq(22)]+\left\{\frac{1}{b_H^{n+1}}-\frac{R}{b_\Gamma^{n+1}}\right\}[Eq(23)]+\frac{1}{b_\Gamma^{n+1}}[Eq(24)]$$

It is go the pressure equitation:

$$\begin{aligned}
&B_{\mathrm{B}}^{\mathrm{n+1}}\Delta K_B \Delta p_B+\left(B_{\mathrm{H}}^{\mathrm{n+1}}-B_{\mathrm{H}}^{\mathrm{n+1}} R^{n+1}\right) \Delta K_H \Delta p_H+ \\
&+B_{\Gamma}^{\mathrm{n+1}}\left(\Delta K_\Gamma \Delta p_\Gamma+\Delta R K_H \Delta p_H\right) \\
&+B_{\mathrm{B}}^{\mathrm{n+1}} Q_B+\left(B_{\mathrm{H}}^{\mathrm{n+1}}-B_{\Gamma}^{\mathrm{n+1}} R^{n+1}\right) Q_H+B_{\Gamma}^{\mathrm{n+1}} Q_\Gamma \\
&=\frac{V_{ijk}}{\Delta t}\left(\beta_p+a_m\right) m^n \Delta_t p
\end{aligned} \tag{25}$$

The equation (25) is non-linear and is solved with the Newton-Raphson method. This equation (25) Figures out the pressure value in each element, substituting it into the equations (22), (23) and (24) we will get the saturation values, and into the equations (4), (5) and (6) we will get the speed phase value. Thus, the task is being solved.

3. RESULTS

Nowadays the deposit development of the Boryslav sandstone of the Boryslav field is in its final stage. The current oil recovery factor during the development period (from 1954 to 2012) is 0.125 which is very low according to geological-and-commercial conditions of deposit location. It follows that at the initial stage of field development, the introduced system of development was inefficient and the methods to enhance the oil recovery factor must be introduced. At first we have to build and adapt the hydrodynamic deposit model for it.

The model building was performed with the use of the Eclipse complex program (version 2009.1) by Schlumberger.

In the Figure 1 the built hydrodynamic model of the field is shown. The geometrical dimensions of the model are 8000 × 4500 × 100 m, which is divided into 80 × 45 × 10 = 36000 elements, the dimension of each element is 100 × 100 × 10 m. On the Oz segment from the first to the forth layers are oil saturated, from the fifth to the tenth are water saturated. The layers of bed model are heterogeneous, it means that in each surface all the modeled parameters are the same and vary with the depth. Table 1 shows all the parameters of each layer.

Table 1

Modeled parameters of each layer

Layer	Kx (mD)	Ky (mD)	Kz (mD)	m	Sн
1	50	50	5	0.125	0.75
2	45	50	5	0.120	0.75
3	45	40	4	0.100	0.75
4	35	35	3	0.140	0.75

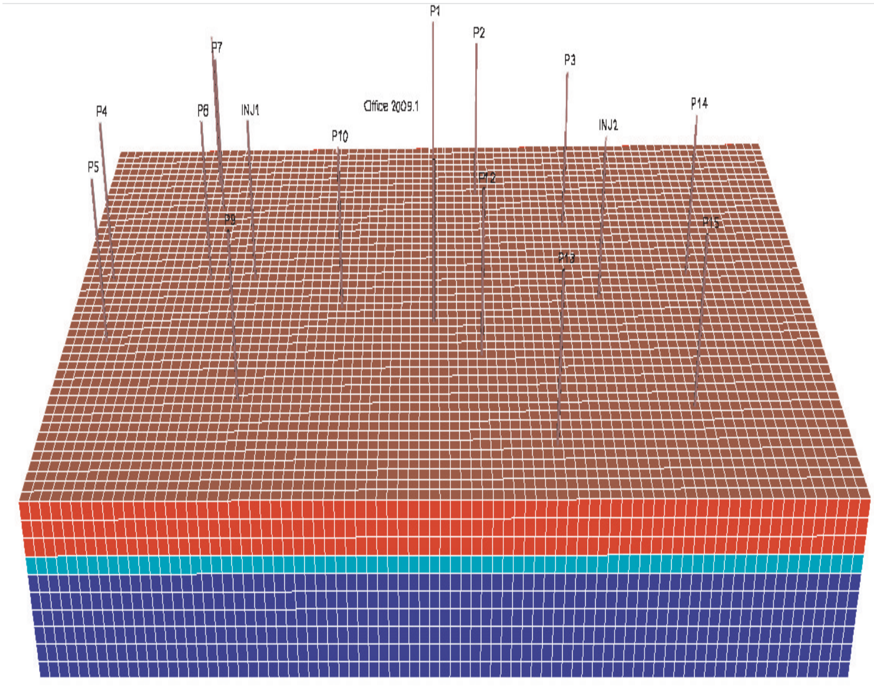

Fig. 1. Hydrodynamic field model

To build the hydrodynamic model and to perform the engineering calculations of the field development, the following data were used:

– Well data (number, location, radius, casing).
  At this deposit there are 14 producing wells P01; P02; … P14 and 2 injection wells I01; I02.
– Analysis data of core samples and formation fluids (the PVT diagrams), dependences of relative permeability factors on saturation, determination of capillary pressure.
– The distribution of initial pressure, saturation, permeability, initial position of oil-and-gas-condensate.

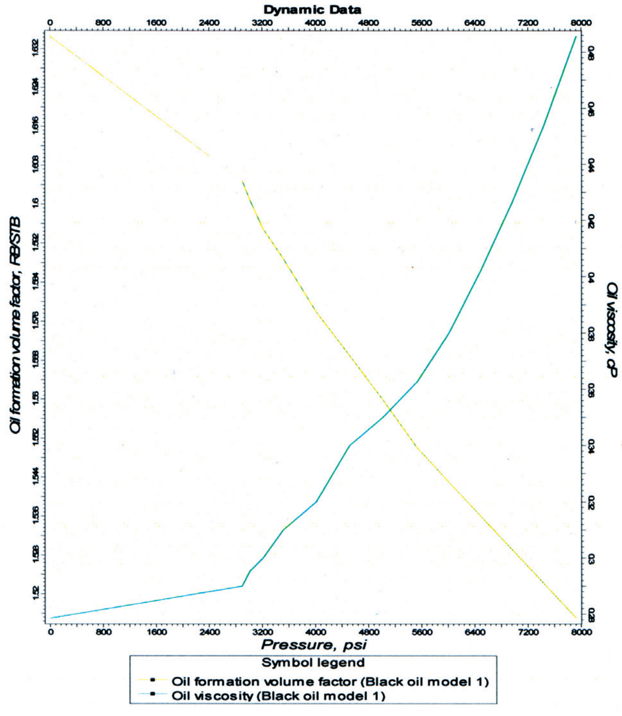

Fig. 2. The dependences of the density and the volumetric oil factor on pressure

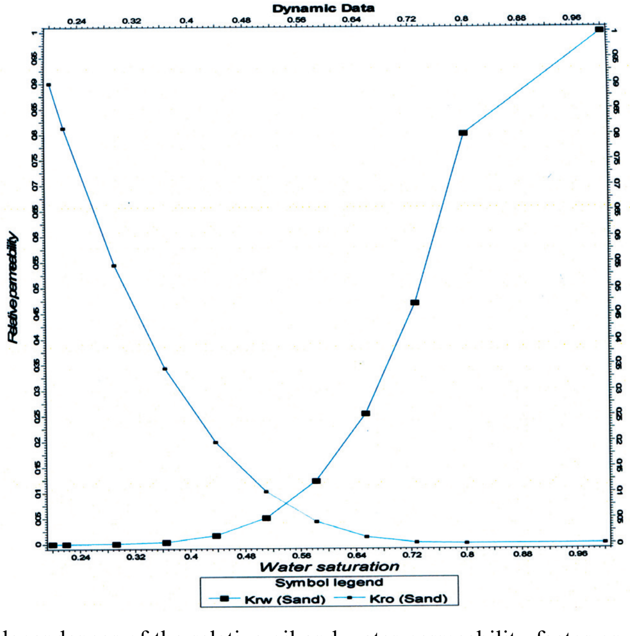

Fig. 3. The dependences of the relative oil and water permeability factor on water saturation

To choose the optimal variant of the further development of a field, the calculations for four variants were done. One of them is the basic variant and the rest three are the new variants with the additional wells drilling (vertical and horizontal). The aim of these calculations according to the basic variant is the comparison and the search of areas with high remaining oil reserves for the additional wells drilling.

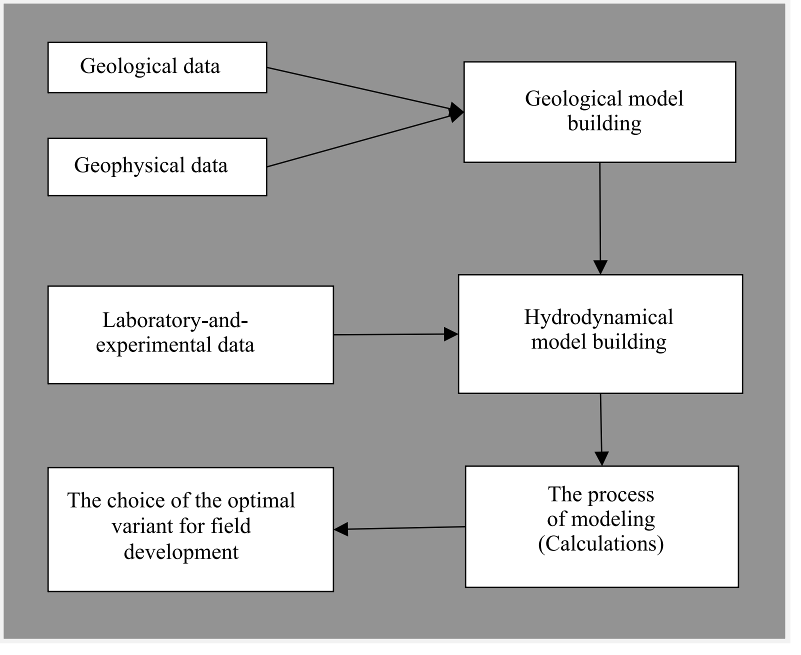

Fig. 4. Block diagram of the modeling process

Basic variant

In making the calculation for the basic variant, none of the wells haven't been drilled and the operations condition of all the wells is unchanged. The result of recovery prediction by January 01, 2025:

– Bulk oil production : 43 million m^3 of oil
– Bulk watering : 72%
– Oil recovery factor : 28% (percent)

Figure 5 shows the pictures of oil saturation distribution at the end of deposit development. Obviously, there are four zones with high remaining oil reserves for the new wells drilling.

Figure 6 presents all the indices of deposit development in accordance to the basic variant by January 01, 2025.

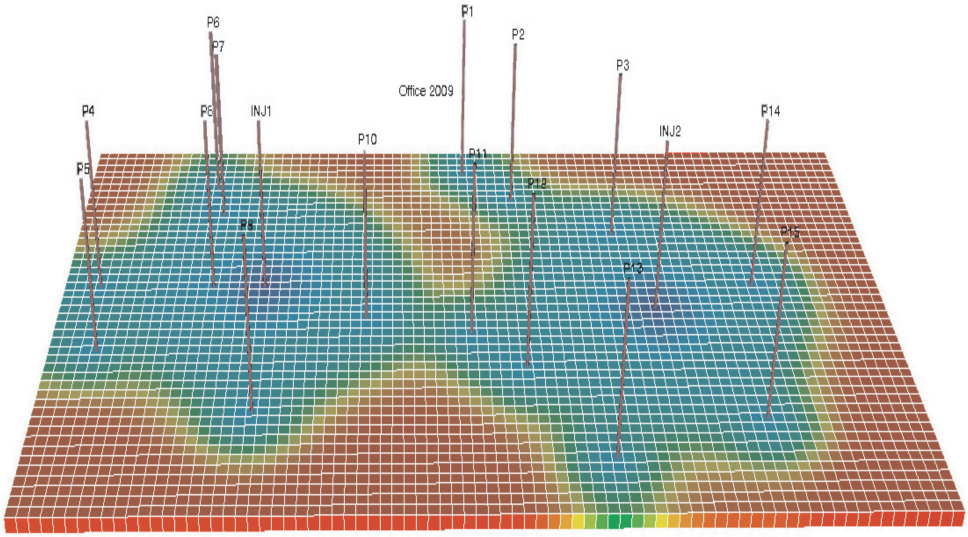

Fig. 5. Oil saturation distribution at the end of basic variant of deposit development

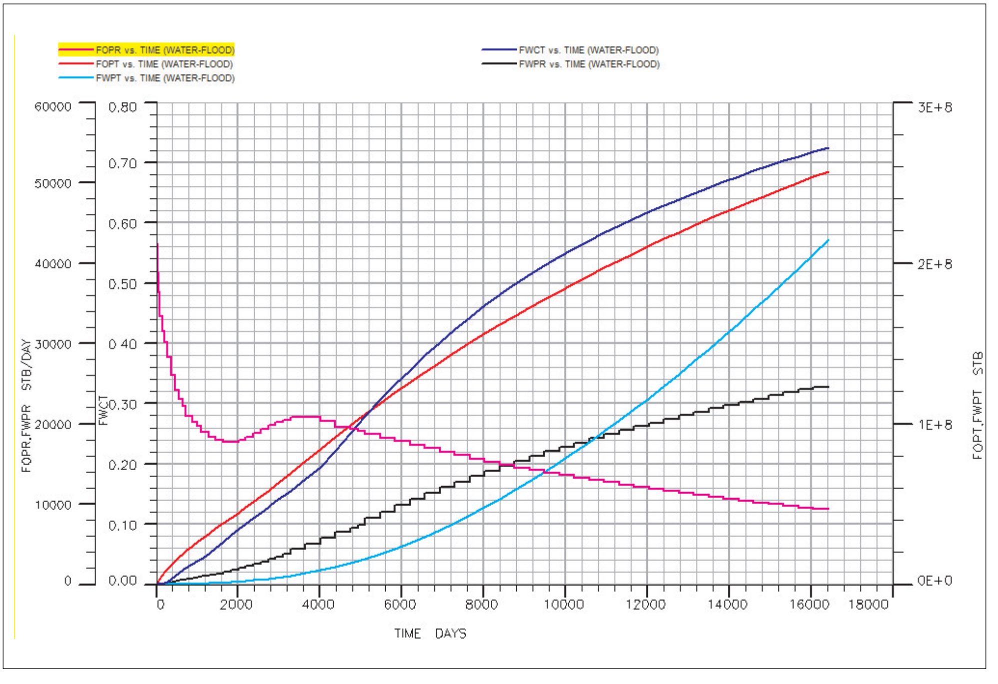

Fig. 6. The indices of deposit development regarding the basic variant of the further development of a field

First variant of the further development of a field

On the basis of the calculation results we suggested the first variant of the further development of a field to the basic variant. According to this variant it is recommended to drill six new wells – 4 producing wells (P16, P17, P18, P19) and two injection wells (INJ3, INJ4). All the wells are vertical. The wells location is shown on the Figure 6.

- The result of recovery prediction by January 01, 2025:
- Bulk oil production : 48 million m^3 of oil
- Bulk watering : 70%
- Oil recovery factor : 32%

According to the first variant of the further development of a field by 2025 we will have produced additionally 5 million m^3 of oil; oil recovery factor will be increased in 4%; water flooding will be decreased from 72% to 70%.

Second variant of development

According to the calculation results as for the basic variant of the further development of a field, it was suggested by us the second new variant of the further development of a field. According to this variant it is recommended to drill six new wells – 4 producing wells (P16, P17, P18, P19), whereas two of them are horizontal (P16 and P19), and two injection wells (INJ3, INJ4). The length of each horizontal well is 1000 m. The wells location is shown on the Figure 9.

- The result of recovery prediction by January 01, 2025:
- Bulk oil production : 51 million m^3 of oil
- Bulk watering : 69%
- Oil recovery factor : 33%

According to the second new variant of the further development of a field by 2025 we will have produced additionally 8 million m^3 of oil; oil recovery factor will be increased in 5%; water flooding will be decreased from 72% to 69%.

Third new variant of further development of a field

To choose the means of oil recovery enhancement factor, we considered the peculiarities of the geological conditions and injected oil and water properties. As the bed is heterogeneous and the oil is high-viscous so these characteristics affect the water flooding process. Thus, flooding productive beds flooding factor decreases. To increase both the water flooding efficiency and field water flooding coverage factor, we suggested to use the polymeric solvent with the concentration of 0.05% vol. The polymeric solvent is advised to be injected into the productive bed through four injection wells, starting on January 01, 2012 till January 01, 2013. The data development after the implementation of technological process are given in the Figure 11.

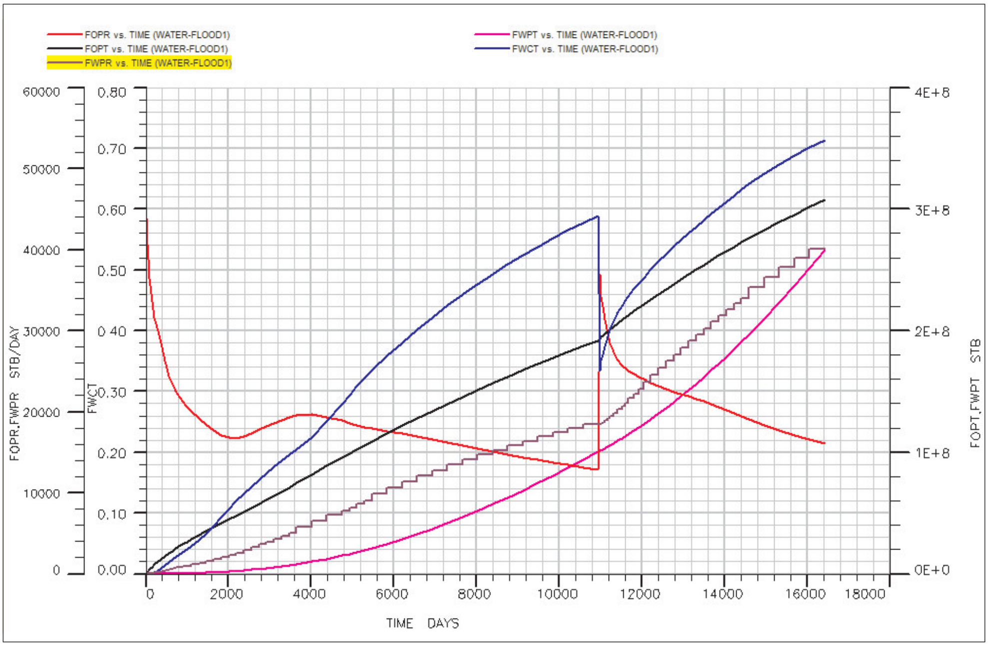

Fig. 7. The indices of the deposit development according to the first new variant

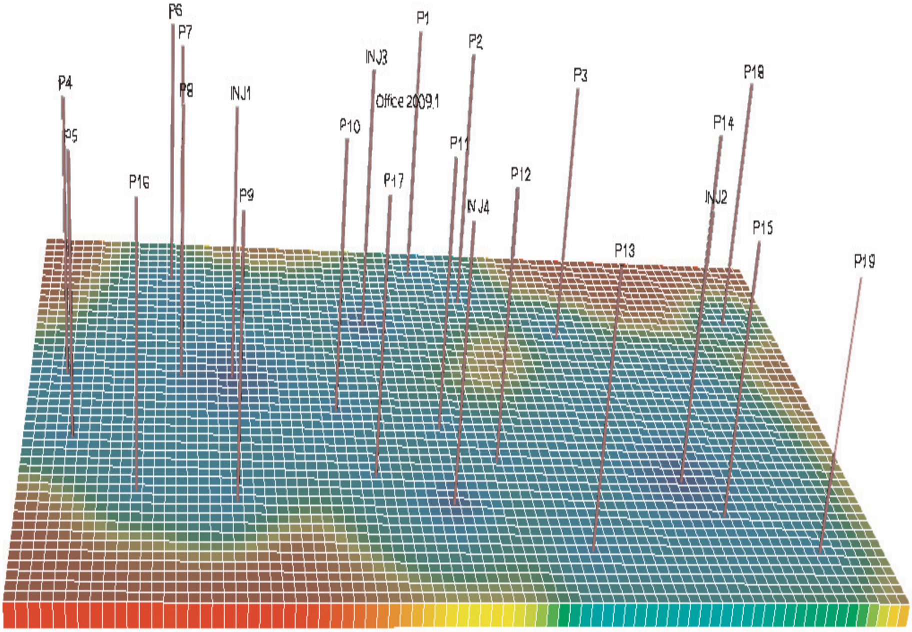

Fig. 8. The location of new additional wells and oil saturation distribution at the end of the deposit development according to the first new variant

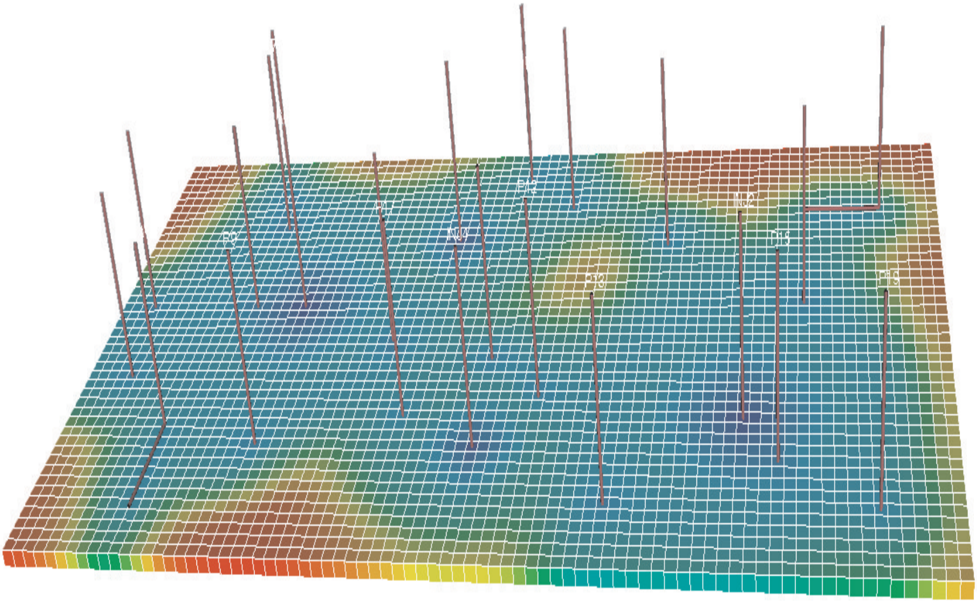

Fig. 9. The location of new additional wells and oil saturation distribution at the end of the deposit development according to the second new variant

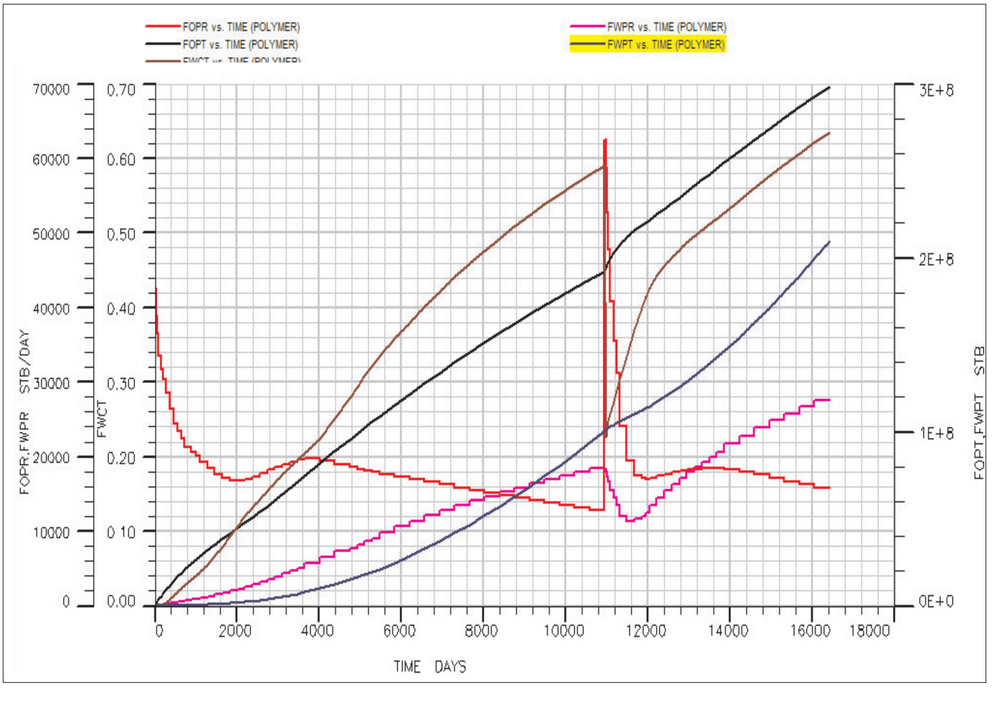

Fig. 10. The indices of the deposit development according to the second new variant

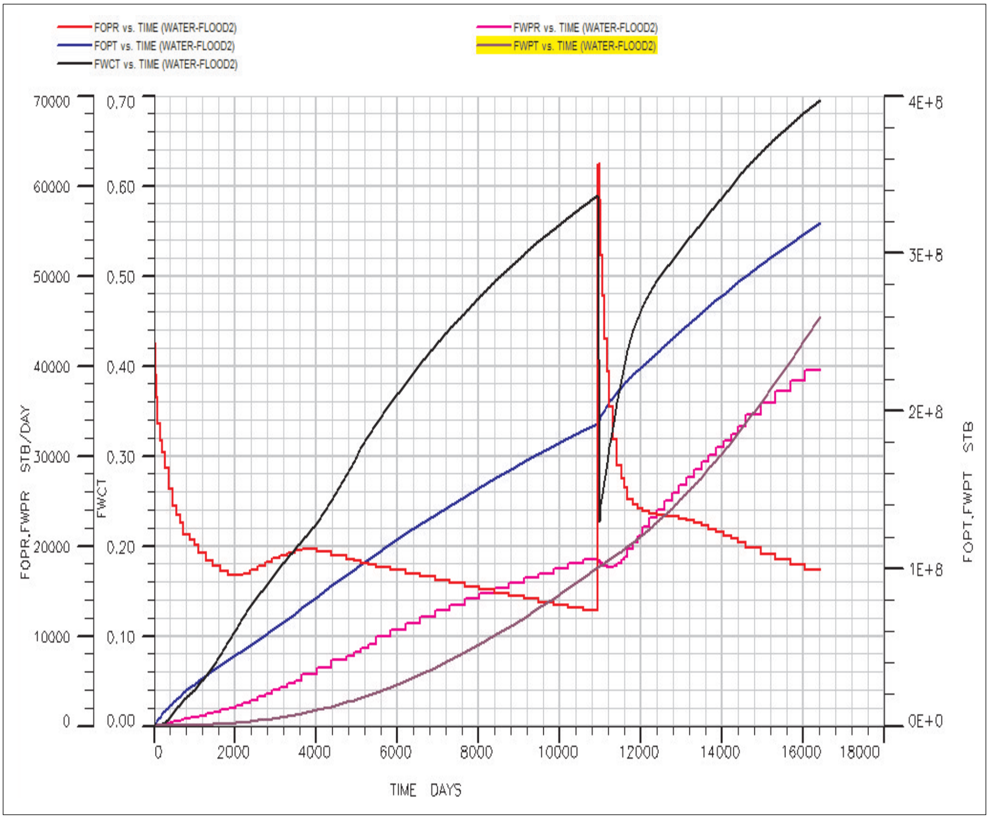

Fig. 11. The indices of deposit development with the use of polymeric solvent according to the third new variant of further development of a field

- The result of recovery prediction by January 01, 2025:
- Bulk oil production : 55 million m^3 of oil
- Bulk watering : 67%
- Oil recovery factor : 37%

According to the third new variant of the further development of a field by 2025 we will have produced additionally 12 million m^3 of oil; oil recovery factor will be increased at 9%; water flooding will be decreased from 72% to 67%.

4. ANALYSIS OF THE CALCULATIONS RESULTS AND RECOMMENDATION ON THE CHOICE OF THE OPTIMAL VARIANT OF THE FURTHER DEVELOPMENT OF A FIELD

The Figures 12, 13 and 14 show the comparison of main indices of field development for four variants of further development.

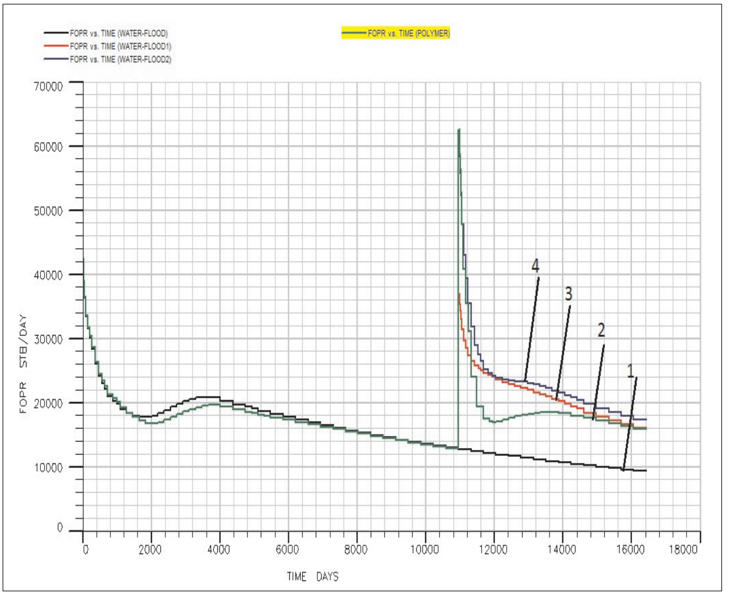

Fig. 12. The comparison of the current oil production for four variants of further development of a filed: 1 – Basic variant, 2 – First new variant of development, 3 – Second new variant of development, 4 – Third new variant of development with the use of polymeric flooding

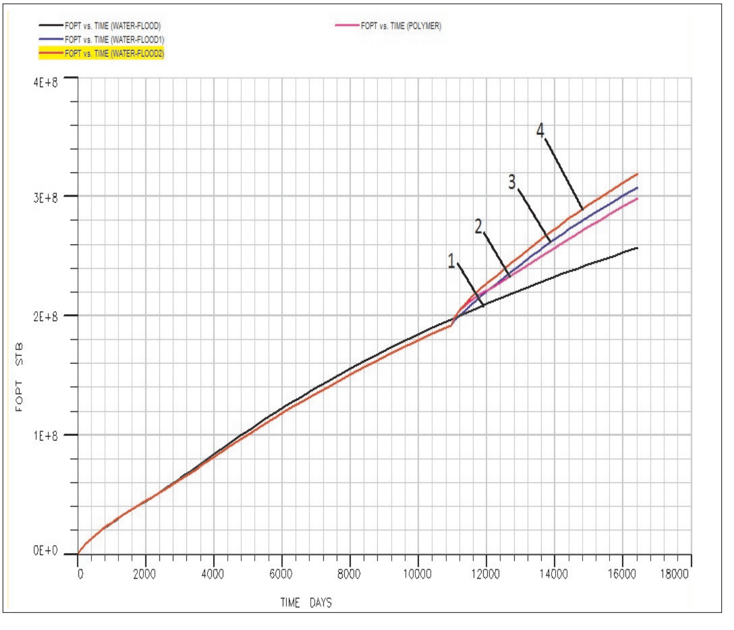

Fig. 13. The comparison of the bulk oil production for four variants of further development of a filed: 1 – Basic variant, 2 – First new variant of development, 3 – Second new variant of development, 4 – Third new variant of development with the use of polymeric flooding

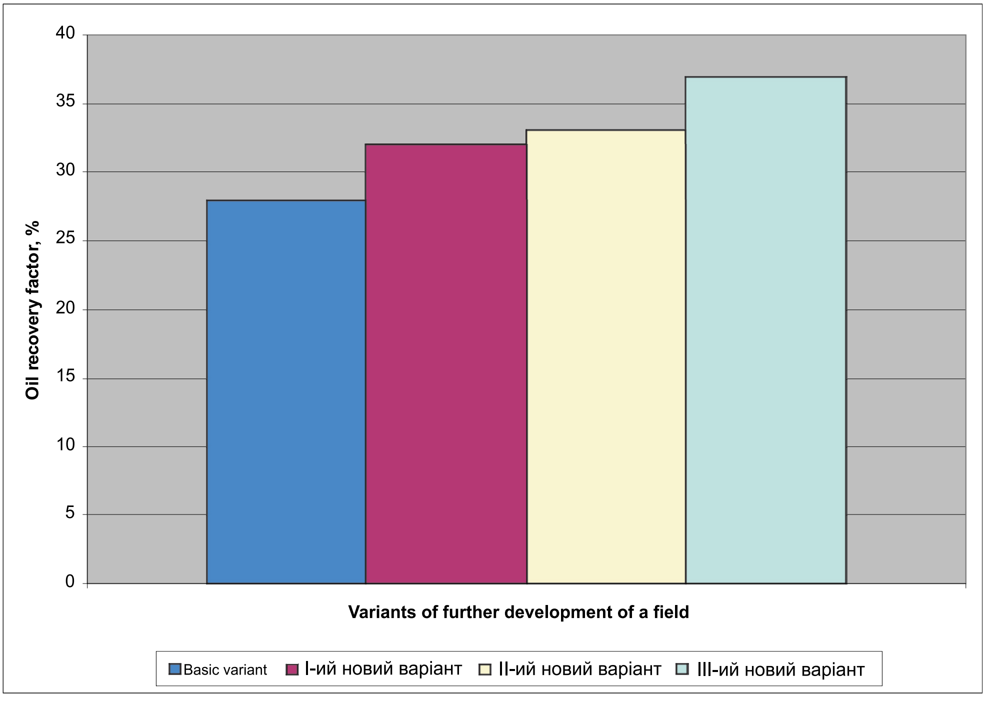

Fig. 14. The comparison of the design oil recovery factor for four variants of further development of a filed

5. CONCLUSIONS

According to the performed calculations at the deposit of the Boryslav sandstone of the Boryslav oil field, it is recommended to introduce the third variant of the further development of a filed. According to this variant it is necessary to drill additionally six new wells to drill six new wells – 4 producing wells (P16, P17, P18, P19), whereas two of them are vertical (P17 and P18) and two horizontal wells (P16, P19) and two injection wells (INJ3, INJ4). The further field development is suggested to be made by the pumping of the polymeric solvent with the concentration of 0.05% vol. through all the injection wells.

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