IMPROVEMENT OF GAS UNDERGROUND STORAGE PERFORMANCE BY ADDITIONAL PRODUCTION OF OIL RIM USING MODERN COMPUTER-AIDED TECHNOLOGIES

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ABSTRACT

The report covers a problem of recovering residual oil from oil rim during cyclic operation of gas storage.

The Yelshano-Kurdyum gas field was put into operation in 1943. After three years an oil rim was discovered by continuing exploration drilling. Then, after gas resources got exhausted, a gas underground storage (GUS) was created in the pore volume of gas cap.

Oil rim was operated in parallel with gas production. Then oil production was carried out in cyclic mode of GUS operation.

GUS impact on the oil rim development showed in dramatic increase of gas factor in oil wells production. As a result, the oil rim development was stopped in the middle of 80-s. Over this period the gas storage was brought to commercial inflows, and its operation continues until now.

In recent years the idle oil wells were investigated. The investigations indicated at commercial oil inflow. Moreover, oil carry-over was observed in border zones of a number of the GUS gas production wells. This meant that a study of the further oil rim development possibility is necessary to reduce its negative influence on efficiency of the GUS gas wells operation.

The oil rim is characterized by complex geologic structure. Two most important blocks of the oil rim were investigated.

For northern and eastern blocks, 3D geological and technological models of the oil rim were built on the basis of advanced software system. Procedure of the models adaptation was executed. Prediction calculations were carried out for many alternatives of oil reserves additional production in parallel with GUS operation.

From a number of investigated alternatives, the results of calculations for three ones are presented as an example. The first one is additional oil production with the old oil wells stock. The second alternative is to put into oil production operation abandoned wells. As the third alternative, a possibility was considered to develop oil rim by horizontal wells.
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INTRODUCTION

A developed system of gas underground storages was established in Russia in the middle of 50-s. OJSC «Gazprom» operates 24 GUSes in the territory of Russia [1]. All the underground storages are located in maximum possible proximity to the main consumers, in the junction points of the integrated transport system. It allows one to promptly send the gas flows to consumers in any situation.

The history of establishment and development of gas industry in the USSR is closely connected with Saratov region [2]. During the Second World War, commercial gas was recovered from Yelshan-Kurdyum structure, and in 1946 the first in the former USSR main gas pipeline Saratov-Moscow was laid, which gave a start to establishment of gas industry.

Yelshan-Kurdyum field was discovered in 1943. Some time later, oil bearing capacity of the facility has been discovered. After that, parallel development of gas and oil resources was carried out. After gas supplies were exhausted, Yelshan-Kurdyum GUS was created in the gas cap of the field. The location of the GUS may be found at Fig. 1.

Operation of the field and gas storage was complicated by the fact that it was actually situated within the city limits. The field territory is occupied by garden plots, city buildings and industrial plants. It accounts for not universal drilling-out of the gas bearing area. (see Fig. 2).

The figure symbols: 1 – GUS gas production wells; 2 – oil rim wells; 3 – GUS gas wells that carry over the oil; 4 – observation wells; 5 – inside gas-oil contact; 6 – outside gas-oil contact; 7 – inside water-oil contact; 8 – outside water-oil contact; and 9 – zones of reservoirs replacement with impermeable blocks. In the southern part of the storage, living headquarters zones are located.
2. FIELD AND GUS HISTORY

Recovery of Yelshan-Kurdyum resources began already in the forties of the last century. During the war, accelerated gas production started. Only three years after, the oil rim was discovered and oil resources started to be drilled-out and recovered.

The oil rim does not have commercial oil reserves in every part of its bed. So, it was conventionally divided into eight blocks, some of which are separated from each other by a zone without reservoirs. For further research, two main blocks were discovered that hold up to 95% of all oil reserves. These are the northern and eastern blocks (Fig.3).

In 1966 GUS creation started in the gas cap. Oil production rates gradually decreased. Increase of gas factor in production of oil wells told negatively on the oil rim development. Oil production was stopped by the middle of the 80-s (see Fig.3).

As a result of cyclic operation of GUS, the maximum reservoir pressure in the gas cap at the end of the injection season became comparable to the pressure at the beginning of field resources recovery, i.e. in the 40-s. Oil carry-over was observed in production of a number of production gas wells at the GUS near the oil rim. That is why in the beginning of 2000 it was decided to carry out additional investigations of idle wells for oil inflow. Moreover, laboratory investigations of oil composition of the oil rim were carried out.

The investigations results showed that the oil became more gas-saturated over the last twenty years and, consequently, more movable. It appeared that the contemporary oil flow rates of the investigated oil wells are comparable to the flow rates at the beginning of oil rim commercial recovery. (Fig.4).
Over the period from the end of oil rim operation, all the GUS design wells were drilled. The gas storage is operated in cyclic mode. Its parameters are quite stable. Nevertheless, they differ from the design ones, first of all by the commercial gas volume. So, for example, annual gas withdrawal is 20-25% lower than the design active gas volume. One of the reasons lies in decommissioning of a number of gas wells due to oil carry-over.

In order to examine the current condition of the oil rim during GUS operation, as well as to determine the possibility of additional production of residual oil reserves, it was necessary to carry out 3D geological and technological simulation. In accordance with the current requirements [3,4], permanent action geologic-technological models of oil rim blocks were built.

3. 3D – GEOLOGICAL MODEL

Let us briefly characterize the object of investigation.

Production section of Yelshano-Kurdyum GUS belongs to the deposits of coal system of Paleozoic erathem. Production reservoirs are deposited at the depth of 700 - 800 m. The reservoir beds are hereinafter referred to as bed «A» and «B».

Reservoirs of upper horizon A are sandstones, which include well-sorted quartz grains, fine-grained with medium-grained blocks and interlayers, semiconsolidated with interlayers of sands and clays. The thickness of reservoirs varies from 0 to 9 m. The total thickness of the horizon A varies from 2 to 15 m.

The lower horizon B is represented by carbonate rocks. It is not universally divided by impermeable interlayer of clays that in some places reach 8 meters. The thickness of productive part of the horizon reaches 27 meters. The total thickness of the horizon reaches 35 meters.

The diagram of geologic structure of the oil rim in blocks is shown at Fig.5.

On the basis of existing geologic-geophysical information, detail 3D models of separate sections of Yelshano-Kurdyum GUS were constructed.

All the existing geologic-geophysical data were systematized and processed. Structural geologic maps were digitized according to the productive horizons, as well as the maps of general and efficient thicknesses. All the information that is available on wells was taken from the specialized software data base. The data base was developed by GUS Department of OJSC «VNIPIgazdobycha». It includes GIS interpretation, systematized petrophysical data. The information on wells was adapted to the corresponding geologic simulation program formats. The capabilities of IRAP RMS software complex by Norwegian company ROXAR were used for simulation [7].
For wells spacings and digitized isolines of tops and bases of horizons reservoirs, surfaces of productive horizons A and B were constructed.

On the basis of these surfaces and data about the nature of rocks forming the productive horizons, network models were created for the northern and eastern blocks. For them, Corner point grid type was used, as its cell nodes may be shifted from ideal 3D box. It allows one to adapt the network model with more flexibility and accuracy to the structure of the simulation object. The unit cell of the grid has the lateral size of 10x10 meters. The vertical size of the grid element is determined by the ratio of general thickness of the horizon to the number of network layers. The number of layers for each horizon is determined by average number of permeable and impermeable sublayers as registered by GIS-investigation of wells.

The network model of blocks has all the necessary permeability and porosity properties simulated. The initial well data are averaged by the Blocked Wells procedure. The procedure is to fill the grid unit cells (units), through which the well passes, with values. With the help of interpolating algorithms, a model was created of initial data distribution among the overall volume of network model of blocks.

That is the way for construction of lithologic models of blocks, models of reservoir permeability and porosity distribution, including initial oil saturation.

As the model was constructed, borders of gas- and water-oil contacts were specified for each horizon at all the oil rim blocks.

There is a difference in location of water-oil contact along horizon A for the northern and eastern blocks. The water-oil contact along the northern block was fixed at the actual elevation of «-754.5 m», along the eastern one – at the actual elevation of «-744 m». Gas-oil contact of the horizon was identical for both blocks and was fixed at the elevation of «-737 m». For the lower horizon, gas-oil contact of the northern and eastern blocks is at the single elevation of «-740 m». Water-oil contact is also fixed at the common for both blocks elevation of «-758 m».

Thus, taking into consideration these peculiarities, it is possible to state the disconnection of the northern and eastern blocks of the oil rim within horizon A. On the contrary, identical water-oil contacts of horizon B point to technological connection between the blocks within this horizon.

Average properties of the northern and eastern blocks are presented in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Northern block</th>
<th>Eastern block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net oil thickness, m</td>
<td>4.43 15.80</td>
<td>5.90 14.90</td>
</tr>
<tr>
<td>Porosity, unit frac.</td>
<td>0.18 0.08</td>
<td>0.18 0.08</td>
</tr>
<tr>
<td>Permeability, mDarcy</td>
<td>717 465</td>
<td>856 570</td>
</tr>
<tr>
<td>Oil saturation, unit frac.</td>
<td>0.76–0.81 0.71–0.85</td>
<td>0.76–0.81 0.71–0.85</td>
</tr>
</tbody>
</table>

Table 1. Average properties of the northern and eastern blocks

In order to calculate oil reserves in the oil rim model, a factor of oil liberation of gas during gas cap operation was also used, it constituted 0.891, along with oil volume factor, which is 0.910 for the northern block, and 0.917 for the eastern one at horizon «A», and 0.864 at horizon «B». The specific gravity of oil is 0.837 according to the results of chemical analyses.

Oil reserves in geological models satisfactorily correspond to the actual ones – relative error of calculations is between 5.8E-7 and 0.14. It proves that the built geological models of the oil rim are correct.
4. 3D – SIMULATION MODEL

4.1. Brief Description

The simulation model was built on the basis of geological model. Software package Tempest MORE by the same Norwegian company ROXAR was used as a technological simulator [8]. The following data were transferred into the model – lithologic structure, porosity, permeability, saturation models, gas-oil and oil-water contacts.

Black Oil non-volatile oil model type was selected for simulation calculations [8]. At that, the fluid system is represented by three phases – water, oil and gas. Volume factors, gas factor, and viscosity were introduced into the program for oil and gas in the form of tables in dependence on saturation pressure. For water – compressibility, viscosity, and density. According to the results of laboratory tests, the oil from the field is undersaturated, that is why its volume factor and viscosity are in linear dependence on pressure.

Phase permeabilities for the rims three-phase system were calculated following the second Stone model [8]. The model supports hysteresis of relative phase permeabilities for all the three phases. The model allows one to modify function of relative phase permeabilities (FRPP) for different blocks of the rim. In the course of phase permeabilities values adjustment, current provisions on FRPP were taken into consideration [9].

The model is characterized by equilibrium initialization at the beginning of calculations. At that, the simulator has adapted the gas factor of oil phase to set the change of saturation pressure with depth.

Simulation model of the eastern and northern blocks is a 33-layer 3D grid. 19 layers belong to horizon A, 14 layers – to horizon B. The model of the eastern block includes 75x65 units along the lateral, the northern one - 112x56 units correspondingly.

The blocks models include all the three simulation areas – gas, oil, and water. On the gas part side, the models are open for gas outflow and inflow by means of “pseudowells” creation on the border units of the grid. These wells control reservoir pressure changes in the oil rim model. At that, the historic data of reservoir pressures change in the gas part were taken into consideration both in gas-oil field development mode, and in the GUS cyclic operation mode. On the water-bearing zone side, different methods of aquifer basin model connection were tested.

4.2. Adaptation

Oil rim history was represented in the form of set oil inflows. The historic data for each well contains flow rates of oil, gas, and water, as well as operation factor, location, and structure, along with skin-factors.

Historic development of reserves was mainly carried out at reservoir A, with the exception of the northern block, for its geologic structure has lithologic gaps between reservoirs A and B.

The main purpose of oil rim history representation was to specify the parameters of heterogeneities of reservoirs permeability. It is necessary to assure reliability of process parameters forecast for oil rim additional recovery. An important result of adaptation was also determination of current condition of oil saturated blocks of the oil rim.

The main adaptation alternatives of oil rim model based on the actual historic operation data were at first tested by the example of eastern block and then taken into consideration during adaptation of the northern block with adjustments for peculiarities of its geologic structure and some differences in water properties (higher density).

The adaptation period constituted 60 years. The eastern block was actively developed for oil from 1946 to 1984. The northern one - from 1948 to 1975. From the moment of development completion, oil rim was only influenced by cyclic pressure differences from the gas underground storage.
The first adaptation alternative consisted in adjustment of 3D model to the development history during connection of aquifer horizon following Karter-Tracy type [8,9]. Average parameters of aquifer basin were set as initial data, i.e. depth, permeability, porosity and general compressibility, as well as propagation angle, initial pressure and water viscosity. Aquifer horizon was connected to the selected open cell faces inside the set regular domain.

During simulation of phase crossflows it was discovered that the model of aquifer basin connection has one significant flaw. During connection of the aquifer horizon model in the process of adaptation to the development history, premature flooding of wells is observed. Besides, the process of water intrusion into the reservoir had constantly increasing unidirectional character irrespective of the storage operation cycles. Under conditions of cyclic operation of GUS, the so-called “breathing” of the oil rim is found at gas-oil contacts. Phase crossflows are bidirectional.

In order to eliminate the constantly increasing flooding, and to take into consideration the cyclic process of storage operation, a network model of aquifer horizon was simulated. The aquifer dimensions were adjusted according to the rate of water influx into the oil rim. This was registered by the speed of oil wells flooding. Aquifer area was simulated in this case by irregular grid. The sizes of its units vary from 50х50 m to 25х25 km. It allowed one to avoid excessive awkwardness of the model and preserve high speed of processor calculations.

Another important issue for using such model of aquifer is to adjust the reservoir properties to the parameters of the studied deposit. In this case, the parameters are not set by average values. All the reservoir properties are transferred to the aquifer area. Total size of the network model is about 250 km².

Adaptation of gas-technological model of the oil rim was carried out both at each block, and at each well. All the oil wells were adapted according to oil production. Adaptation according to gas and water was carried out as follows. With the help of scaling of endpoints of relative phase permeabilities for gas and water, gas and water production from wells was brought into satisfactory correspondence with the historic figures. This is well represented by Fig.6 where adaptation results for well № 304 are shown.

During oil production adaptation in accordance with the historic parameters, parameters of lithologic heterogeneities of reservoirs were corrected, values of absolute permeabilities of reservoirs were specified.

By analogy with the eastern block, in the northern one, horizon A is described with 19 network layers, horizon B – with 14 layers. However, geologic structure of the northern block of the oil rim differs from that of the eastern block by presence of lithologic gaps between main reservoirs. In other words, impermeable layer between reservoirs is not spread universally.
As a result of this difference, adaptation of the northern block development to the operation history in some way differed from adaptation of the eastern block. First of all, it showed in incongruity of estimated and historic flow rates of oil in the oil wells.

A study of alternatives for modification of functions of relative phase permeabilities for corresponding horizons was carried out. Absolute permeabilities were corrected by block. Operation of pseudowells group was regulated. The elongated network model of aquifer was created.

However, at a specific point of development, estimated flow rates biased downward from the historic figures. It took place at all wells of the northern block, irrespective of their location and adjustments of permeability properties of the technological grid. It resulted in the conclusion about not enough reservoir model permeability properties to reach the actual historic figures of oil production.

Correspondence of estimated and actual parameters of oil production was achieved by alteration of communication between the grid cells at the border of A and B horizons. After that, gas and water production performance was adapted. As an example, Fig.7 shows operation performance of well № 224.
The results of technological simulation of the northern block at the stage of adaptation proved the supposition about lithologic gaps. It fostered crossflows of oil phase from horizon B to horizon A and gave additional potential to productivity of oil wells.

In general, adaptation results of simulation model of the northern block in accordance with the history of its development showed satisfactory correspondence of estimated and actual parameters of oil, gas, and water production.

On the basis of carried out simulation calculations that follow the history of oil rim development, models of oil saturation were built for each year of development. The current condition of average oil saturation models by blocks is represented by Fig. 8,9.

4.3. Oil Production Forecast

The forecasting calculations purpose is to predict the future 12 years’ behavior of integral production data for the considered oil rim blocks as well as for separate wells.

During the calculations the storage cyclic operation impact was considered by application of corresponding boundary data. On the one hand these were pressure fluctuation in the GUS depending on extraction/pumping periods of the GUS gas. On the other hand they were the aquifer basin behavior. In addition, limitations of the oil wells operating modes were applied. We considered the oil wells production indexes obtained from the last years’ investigations. The oil wells structure data was used in the simulation. During the research a number of forecasting calculation alternatives were carried out. The consideration of some of them is below.

Alternative I

The first alternative of the oil rim additional production calculations was for the old oil wells – three wells of the eastern block and 12 wells of the northern one. Also a gas well of the eastern block with oil carry-over was involved in the development.

During forecasting the GUS influence (by setting of limitation for bottom-hole pressure) as well as the influence of aquifer basin were considered as boundary data for the block. Critical pressure drawdown values obtained from the last investigations are the basic boundary data of oil wells.

All wells are vertical. Production strings perforate a reservoir A.

The forecasting calculation period of additional production is partial of 12 years.

In the alternative all wells are operated with sufficiently high gas factor and with initial oil output according to set points. All wells have minor water production during the whole calculation period.
The dependence of oil outputs on reservoir pressure fluctuation is observed in wells. As a result of cyclic fluctuation of reservoir pressure the gas content in oil wells production is changed and water production is somewhat increase in the periods of low reservoir pressure.

Oil output in each well of the oil rim is gradually reduced during the calculation period. It is due to general reduction of reservoir pressure in oil rim within the calculation period.

It is assumed that within the calculation period of additional production in the eastern block using the given alternative the oil extraction factor (OEF) of oil wells will reach 0.5 from initial oil reserves.

In the given alternative a calculation factor of oil extraction in the northern block is 0.4.

Alternative II

In this alternative of the oil rim additional production each old oil well, including the abandoned, is used for oil production. Abandoned wells are to be reconstructed. At that the 4-in. string is pulled down in an old string. An absolute sealing of an old borehole is carried out through it cementation from the bottomhole to the wellhead. Then the 2.5-in. lifts are lowered and perforated with the intervals of reservoirs A and B deposition. The wells are operated at their own accepted values of drawdown.

In this alternative of additional production of the eastern block oil rim OEF equal to 0.7 is reached. For the northern block the oil extraction factor is 0.72.

Alternative III

In this alternative of oil rim additional production except from vertical old oil wells the horizontal wells are brought into service. A horizontal part of the borehole has a height of 500m. The wells are perforated along the whole height of horizontal part at the reservoir B level. To determine an optimal disposition of horizontal wells the geologic simulation results were used.

As an example the horizontal well PR28 performance is considered (see Fig.12). The well is located in the eastern block. Pressure in the block is regulated from the gas cap side through pseudo-wells located in the corresponding border cells of the model. It is modified synchronically depending on the GUS operating period. At the beginning of development its average value is about 8 MPa. As the additional production of oil reserves continues, oil rim pressure will decrease. Its variation range is 3 – 5 MPa. In the production data diagram there is distinctly shown the dependence of oil, gas and water production on reservoir pressure fluctuation in the GUS. Maximum values of gas, oil and water production are reached at maximum peak values of reservoir pressure.
In total for the eastern block with usage of the old oil wells and horizontal wells the oil extraction factor reaches 0.82, for the northern one - 0.85.

5. CONCLUSION

Investigations show that additional production of oil rim in conditions of gas underground storage operation is practicable.

Reservoir pressure behavior in an oil rim is influenced by reservoir pressure difference in the gas cap. The oil production history changes in synchrony with reservoir pressures dynamics.

At the same time oil production from the oil rim promotes increasing of GUS active gas volume (see Fig.11). The figure presents annual volumes of gas extraction from GUS production wells and oil rim wells. The lower values are for annual gas extraction from GUS production wells. The upper values are for gas extraction in parallel with oil rim wells operation. They correspond to oil rim additional production alternatives considered previously. Gas production of oil rim wells and GUS production wells is summarized.

Thus, the operated gas underground storage has positive influence on oil reserves extraction from an oil rim. And vice versa, oil reserves extraction promote increasing of the GUS active gas volume.

Methodology of the 3D –geologic-technological models creation for oil rims under conditions of the certain GUS operation was developed. At that the experience of geologic-technological models creation for gas-and –oil fields [9-11] was taken into account. At the same time fundamental difference of a GUS as such from a field was considered. Mainly, it consists of the more limited operating time and cycling of intensive gas extraction and pumping. Impact of GUS operating modes upon oil rim production values was proved during simulation.

Then the given technology can be used for solving the similar tasks in other facilities of underground storage that have oil rims.
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