ABSTRACT

The paper presents a successive improvement of the technology on non-stationary waterflooding by the example of East-Suleevsky and Alkeevsky areas of Romashkino field, including the following stages and elements:

- cyclic water injection into separate injection wells in operation of producing wells under stationary conditions (1968-1972);
- cyclic water injection into rows of injection wells of latitudinal direction also under stationary conditions of producing wells operation (1973-1985);
- determination of blocks by creation of additional rows of injection wells of meridional direction and alternate cyclic water injection into wells of latitudinal and meridional rows. Stationary regime of producing wells operation retains (1986-1989);
- realization of the injection technology of the previous stage with alternation of injection and producing wells operation (1989 - up to present time).

An important novelty in realization of mentioned technological processes was substantiation and application of production/injection conditions and duration of cyclic stimulation elements, corresponding to characteristics of formations.

Application of the named technology in Alkeevsky and Suleevsky areas allowed to provide stable levels of oil production during 7 and 11 years respectively, achieve current oil recovery factors 48 and 46.6% with practically stable water cut during recent 10-12 years to be 81-86%.

INTRODUCTION

Considerable practical experience of non-stationary waterflooding is gathered, theoretical investigations for evaluation of this method efficiency under different geologic conditions are accomplished, though the results of the latters are often conflicting. Thus, by modeling the heterogeneous formation as a medium with double porosity, taking into account an exchange of wetting and non-wetting fluids between media of different permeabilities, using experimental saturation functions similar to relative permeabilities, the following has been obtained [1]:

- With designated duration of the cycle the most value of pressure differential amplitude ($\Delta P$) between different permeability media is achieved at variations of flow rates in galleries in opposed phases;
- With increase of the cycle period amplitude $\Delta P$ between media is at first increasing, and after that it becomes practically stable;
- With increase of the distance between galleries the amplitude of pressure differential between high- and low-permeable layers is decreasing, at the same time the amplitudes of the pressures themselves are decreasing.
For investigation of the cyclic stimulation technology at the stage of considerable water encroachment of wells product in reference [2] the multilayer model of the formation is replaced by two-layer one. The 1-st layer includes completely flooded interlayers, the 2-nd layer - unflooded and partially flooded. The influence of parameters, quickly changing during cyclic stimulation, on the results has been studied and the following is concluded:

- It is reasonable to start cyclic stimulation of formations at early stages of development. As duration of the method application increases, its efficiency falls: the share of oil in product approaches the share in stationary waterflooding. Change of specific water flow rate in oil production has similar character, increment of current oil recovery is decreasing;

- The efficiency of cyclic stimulation method is increasing with increase of formation heterogeneity and oil viscosity;

- Even on retention of constant averaged $\Delta P$ for stationary and cyclic methods of waterflooding, current fluid withdrawals for the second method become lower compared with the first one, while oil production remains without change or somewhat increases.

Different conditions of non-stationary waterflooding of heterogeneous formations have been studied by numerical solution of equations on 2-phase filtration of immiscible liquids taking into account compressibility of phases and rock [3]. Heterogeneity of formation was modelled by specifying five interlayers with a set of permeabilities according to the given distribution. Each complete cycle included 2 periods: in the 1-st period water at $P_{btm}=\text{const}$ was injected with simultaneous production of product from producing wells also at $P_{btm}=\text{const}$. In the 2-nd period $P_{form}$ was sharply decreased by cease of injection and proceeding production with fixed $P_{btm}>P_{sat}$ at well bottom of producing row.

Judging by these studies it is clear that early beginning of cyclic stimulation leads to considerable losses in rates of oil recovery regarding the case of stationary waterflooding. However too late application extends the period of development. Recommendations for evaluation of cycle duration are obtained: with lesser duration the reserve of formation elastic energy is not completely used, with greater duration the intensity of fluid crossflow between interlayers is decreasing. The expected increase of ultimate oil recovery comprises about 5%. Subsequent calculations on this model allowed to specify the range of oil viscosity change, when the most increase of oil recovery is achieved [4]: 5-10 mPa$\cdot$sec. It is shown that efficiency of non-stationary waterflooding method is increasing, if surfactant slug is preliminarily injected, thanks to increase of oil mobility. Economic efficiency is made more exact, depending on the period of beginning of the method application: the technology is efficient at early stage, if reserve in injection and recovery is available, and average fluid flow rate is the same as with stationary injection. In case such reserve is not available and it can not be realized in practice, then the technology is more efficient at late stage.

References [5,6,7,8] also present contradictory results, which are similar to the above mentioned ones. It is explained by the fact that at present there are no analytical methods, which could describe the essence of the technology with sufficient adequacy, especially in change of filtration flows and pulse stimulation. Therefore, analysis and generalization of the results of application in practice of different variants of non-stationary waterflooding technology becomes especially interesting.

**BRIEF CHARACTERISTICS OF THE STRUCTURE UNDER INVESTIGATION**

Major Romashkino field was brought in development by its dividing into separate areas of independent development by rows of injection wells [9]. The main structures for commercial development here are producing formations of Pashiysky horizon ($D_1$) and formation $D_0$ of Kynovsky horizon. Horizon $D_1$ is presented by interbedding of sandy, aleurolite and argillite rocks. Frequent change of sandy-aleurolite rocks by clayey ones both by section and area is
characteristic. For example, figures 1 and 2 show profile and a map of propagation of different type reservoirs in small areas of the field, depicting multilayering (from top down: D0, a1, b1, b2, b3, v, g, d) and layer-by-layer and zonal heterogeneity for one of the formations. Wide range of changing filtration parameters of formations in stationary waterflooding leads to nonuniform displacement of oil by water, low coverage of macro- and micro-heterogeneous structure of development by displacement process.

The issues of increasing coverage by stimulation on the whole of separate heterogeneous formations are solved by improvement of development system (subdivision of producing formation, optimization of well pattern density, bottomhole pressure of water injection and recovery of product, etc.). As for problems of increasing coverage by displacement taking into account micro-heterogeneity of separate formation, they are most successfully solved by methods of non-stationary waterflooding.

For integral comparative evaluation of the technological effect on successive improvement of non-stationary waterflooding in East-Suleevsky and Alkeevsky areas let us consider main geologic characteristics of still more areas of Romashkino field, a priori close to the parameters of areas under study (Table 1).

Even for these areas the range of changing parameters is wide and not unidirectional. Therefore, for transfer to approximate quantitative comparisons of selected areas let us use 5-point system. For example, the highest coefficient of arenosity, equal to 0.480 for Pavlovsky area, corresponds to maximum point, equal to 5; minimum for Beryozovsky area, equal to 0.279 - corresponds to 1. Other areas will have intermediate points. As for variation coefficient - vice versa: the greater is its value, the more heterogeneous is the structure by the investigated parameter. In this instance, variation coefficient for Beryozovsky area, equal to 0.825, is accepted as 1 point, minimal value of 0.332 for Pavlovsky area - as 5 points. In the same way total porosity, permeability, oil saturation and distribution of reserves in different groups and classes of reservoirs is estimated.

Being studied areas in the table are arranged in the order of increasing points or improving their combined characteristics.

We have a right to expect that areas under study as for technological indices shall be arranged in the above mentioned order. However, it turned out to be not so. For brevity sake let us compare only current factors of oil recovery and water cutting of product, corresponding, for example, to dimensionless time, equal to 1 (Fig. 3). In reality for being analysed East-Suleevsky, Alkeevsky areas the current oil recovery factors are higher than for 3 best areas. Certainly, also higher than for the worst Pavlovsky area. More detailed analysis of these diagrams will be further.

THE TECHNOLOGY OF NON-STATIONARY WATERFLOODING REALIZATION

Alkeevsky and East-Suleevsky areas have been put in development in 1959 and 1955 respectively. Operation of areas began by stationary water injection into formation through injection wells of dividing rows. Of course, some elements of unorganized non-stationary filtration always took place because of accidental shutdowns of injection and producing wells for different reasons. Only in 1968 systematic periodic shutdown of single injection wells began, which served as a source of accelerated water encroachment of the product of certain producing wells. Positive technological effect, achieved in this case, allowed to subsequently increase the number of injection wells, operating under cyclic conditions, including all wells of cluster pumping station (CPS).

At this stage for different filtration properties of formations there were determined experimentally volumes and pressure of injection, durations of cycles provided oil recovery rates for producing wells retain at designed level.
Since 1973 a new stage began when in central dividing rows of East-Suleevsky and Alkeevsky areas all wells of CPS-55 and CPS-106 and later all CPS-s were shifted to cyclic regime of injection. The process of cyclic water injection began through injection rows of latitudinal direction in operation of producing wells under stationary conditions. Also injection under cyclic conditions began through spot wells into lower formations, which do not have hydrodynamic communication with wells of injection rows.

The regimes of injection wells operation were established in such a way that:
- water injection pressure at wells bottom corresponded to optimum one, when opening of fissures was only in restricted areas near wells bottom;
- dynamic formation pressure between zones of injection and recovery did not exceed critical values, when new fissures are created or opening of the existing ones is increasing;
- duration of injection was established in such a way that compensation of fluid recovery by a volume of injected water was achieved for this period.

The above mentioned conditions were determined by special well researches (injection of tracers; pulse testing; step-rate testing; pressure build-up (fall off) curves).

However, duration of cyclic stimulation according to this technology was followed by gradual decrease of its efficiency. Therefore, since 1986 transfer to improved technology began, which included:
- creation of additional dividing rows of meridional direction in base formations;
- subdivision of producing formation and creation of new rows by application of previously created spot wells for injection into lower formations;
- alternation of injection and shut-down cycles using injection wells in rows of latitudinal and meridional directions.

This technology allowed to obtain a new effect: change of the direction of filtration in the formation, which resulted in considerable decrease of water cutting of well production and increase of production rates.

However, technological effect fell off again, since under change of the filtration direction, primarily, the same high permeability interlayers took water and pressure gradients reached under these regimes proved to be inadequate to provide efficient change of fluids between high- and low permeability interlayers. In 1986 a new stage began, the essence of which consisted in the following.

During the period of injection into injection wells producing wells are shut down, which leads to increase of formation pressure for some time and development of elastic reserve of energy. At the next stage producing wells are placed on production while injection wells are shut down: accumulated formation energy is being consumed. Low permeability zones are covered by development, while stationary and cyclic flooding have no action upon them. This pulsing method of water injection and fluid withdrawal allows to cover drainage zone by stimulation more fully, which finally reduces water cutting of well production and increases ultimate recovery of formations.

Specific feature of realization of this stage of the technology of non-stationary method consists in establishing of operation regime differentially for each injection and producing well:
- maintenance of optimum formation pressure and water injection pressure in rows of injection wells;
- recovery of design volume of fluid from producing wells, therewith providing for optimum regime of operation of pumping equipment in the range of variation of formation pressure values from maximum to minimum in the zone of recovery; these conditions determine time of wells’ operation;
- establishing of time of injection wells operation to provide compensation of the volume of fluid recovery by water injection.
The fulfillment of these conditions results in the change of parameters of cyclic stimulation on a wide scale. Regime of operation of wells is established for each month on the basis of calculations made every quarter.

ANALYSIS OF RESULTS OF NON-STATIONARY WATERFLOODING

To evaluate integrally the efficiency of different technologies of non-stationary flooding at Alkeevsky and East-Suleevsky areas one can compare some critical indices of development for close in geological characteristics areas (See Fig. 3). It is evident that apart from geological factors and non-stationary process of stimulation, a large number of other technological parameters affect these indices, namely, well spacing, ratio of producers and injectors, absolute values of formation pressure, etc. For this reason it is rather difficult to evaluate uniquely quantitative effect of being applied technologies. Besides, very often actual information accumulated over these years may contain different errors. However, one can see that for Alkeevsky and East-Suleevsky areas:

- time of plateau production at a maximum level is longer if compared to others, but with less rate of recovery of reserves;
- current oil recovery indices are higher if compared to the best areas. The exception is South-Romashkinsky area at initial stage (0.2-0.75 dimensionless time), which may be accounted for higher formation pressures. Higher rates of water cutting of production of wells of South-Romashkinsky area can be accounted for the same reason;
- higher water cutting of well production noted in the beginning of recovery (to dimensionless time about 0.5 for East-Suleevsky area and 0.45 for Alkeevsky area) began to decrease and was noted as the least at dimensionless time 0.85.

Evaluation of absolute values of increment of new reserves of oil brought into development and increase of oil recovery factor at Alkeevsky and East-Suleevsky areas due to non-stationary methods of development alone has been made for different years and stages as of beginning of 1996. In ascending order they are as follows:

<table>
<thead>
<tr>
<th>Area</th>
<th>Accumulated increment of oil recovery factor (%) by stages</th>
<th>Current oil recovery factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>II III IV</td>
<td></td>
</tr>
<tr>
<td>Alkeevsky</td>
<td>1.6 2.6 3.8</td>
<td>48.0</td>
</tr>
<tr>
<td>East-Suleevsky</td>
<td>1.3 2.4 4.3</td>
<td>46.6</td>
</tr>
</tbody>
</table>

For the period 1973-1994 at Alkeevsky and East-Suleevsky areas the volumes of water recovery were reduced by 3847 and 3582 thous. tons, respectively, due to realization of non-stationary methods of development. This implies also decrease of volumes of water injection on these areas per the same volume of oil recovery. Pictorially one can see it in Figure 4, where actual and design values of specific volume of injected water per recovery of 1 ton of oil are shown. In the period of 1962-1976 slow increase of this index for Alkeevsky area took place. Shift to the new regime of non-stationary waterflooding resulted in the sharp decrease followed by more rapid increase of specific consumption of water per 1 ton of oil (1978-1988). By subsequent introduction of improved technology the same tendency repeated again. During the whole stage, beginning from 1976 when the Third general project of development of Romashkino oil field was made, and from 1984, when the last Design of the development of the area was drawn up, design values of specific consumption of water were considerably higher, if compared to actual one. For the section of CPS-106 (cluster pumping station), where introduction of non-stationary methods at Alkeevsky area began, this ratio is even better.
The character of monthly change of water cutting of well production demonstrates reaction of producers to non-stationary process of injection at early stages, and more dynamic reaction at the last stage when both injectors and producers began to work in cyclic regime (since 1988-1989). Let us call attention only to the following (Fig. 5):

- average water cutting of well production at both areas considerably decreased (by 5-6%) compared to water cutting prior to the shift to the new technology;
- range of variation of monthly value of water cutting of well production varies over a wide range (from fractions to 5-6%);
- tendency to increase of water cutting of well production remains under the last modification of non-stationary process of development. By this is meant that, on the one hand, the effect of hydrodynamic methods of stimulation decreases at the late stage of development, on the other hand, it is necessary to investigate the variants of combination of hydrodynamic methods with other physico-chemical or gas methods of enhanced oil recovery.

One can see the character of operation of separate producers under non-stationary methods of development by the example of well # 10292 (Fig. 6). In the beginning of 1980 it produced oil with monthly average production rate about 1 ton/day with water cutting of production about 95-96%. In the beginning of application of non-stationary methods of stimulation monthly average oil production rate increased to 25-30 tons/day, water cutting decreased to 5-10%. It is evident that with time the efficiency of the process falls off: so, in the period from 1990 to 1997 water cutting has been slowly increasing (from 60-70% to 70-80%), production rate - decreasing (from 10-15 to 2.5-7.0 tons/day). Sufficiently close correlation connection exists between these parameters of wells' operation.

Thus, analysis of results of different variants of non-stationary methods of development by the example of Alkeevsky and East-Suleevsky areas of Romashkino oil field convinces that for heterogeneous reservoirs being applied technological process are rather efficient. The efficiency is expressed not only in increase of current oil recovery and ultimate oil recovery factor, but also in considerable decrease of specific and summary consumption of injected water and recovered fluid, which helps both to reduce current operational costs, and improve ecology.

**CONCLUSIONS**

1. Powerful method of cyclic waterflooding aimed at increase of current oil production and oil recovery factor of heterogeneous oil fields loses its efficiency with increase of the number of cycles and degree of water cutting of well production.
2. By the example of Alkeevsky and East-Suleevsky areas of Romashkino oil field experience of sequential improvement of the technology of cyclic waterflooding is shown, which allowed to obtain good enough results, if compared to other areas characterized by close geological and filtration properties.
3. The sequence of non-stationary technological processes, including change of filtration and pulsing stimulation which has been applied, has no solution of adequate filtration equations. Since, field experience and worked out methodical approaches are of great importance and can be applied in other oil fields at any stage of their development by waterflooding methods.
REFERENCES


Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Pavlovsky</th>
<th>East-Suleevsky</th>
<th>Alkeevsky</th>
<th>South-Romashkinsky</th>
<th>North-Almetyeysky</th>
<th>Beryozovsk y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity, %</td>
<td>19,6</td>
<td>19,9</td>
<td>20,2</td>
<td>19,7</td>
<td>19,9</td>
<td>19,7</td>
</tr>
<tr>
<td>Permeability, mkm²</td>
<td>0,474</td>
<td>0,545</td>
<td>0,590</td>
<td>0,544</td>
<td>0,578</td>
<td>0,615</td>
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<tr>
<td>Oil saturation, %</td>
<td>82,5</td>
<td>82,6</td>
<td>85,3</td>
<td>83,7</td>
<td>83,0</td>
<td>83,8</td>
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<tr>
<td>Arenosity factor, fractions</td>
<td>0,480</td>
<td>0,339</td>
<td>0,333</td>
<td>0,475</td>
<td>0,337</td>
<td>0,275</td>
</tr>
<tr>
<td>Variation of arenosity factor</td>
<td>0,332</td>
<td>0,468</td>
<td>0,484</td>
<td>0,394</td>
<td>0,381</td>
<td>0,815</td>
</tr>
<tr>
<td>Multilayering factor</td>
<td>4,325</td>
<td>4,047</td>
<td>3,381</td>
<td>4,217</td>
<td>4,997</td>
<td>3,444</td>
</tr>
<tr>
<td>Variation of multilayering factor</td>
<td>0,387</td>
<td>0,388</td>
<td>0,420</td>
<td>0,399</td>
<td>0,357</td>
<td>0,447</td>
</tr>
<tr>
<td>Reserves by groups of rocks, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>high-productive</td>
<td>84,77</td>
<td>77,49</td>
<td>71,52</td>
<td>79,13</td>
<td>71,10</td>
<td>65,63</td>
</tr>
<tr>
<td>high-productive clayey</td>
<td>5,76</td>
<td>13,64</td>
<td>21,28</td>
<td>11,83</td>
<td>13,23</td>
<td>23,92</td>
</tr>
<tr>
<td>low-productivity</td>
<td>9,47</td>
<td>8,87</td>
<td>7,20</td>
<td>9,04</td>
<td>15,67</td>
<td>10,45</td>
</tr>
<tr>
<td>Reserves of oil-water zone</td>
<td>20,28</td>
<td>11,79</td>
<td>6,73</td>
<td>9,95</td>
<td>13,90</td>
<td>9,48</td>
</tr>
<tr>
<td>Integral characteristics, points</td>
<td>2,89</td>
<td>3,14</td>
<td>3,39</td>
<td>3,42</td>
<td>3,49</td>
<td>3,67</td>
</tr>
</tbody>
</table>

Fig.1 - Cross section. Part of Romashkino oil field.
Fig. 2 - Map of formations D1A and D1B in Alkeevsky area.

Formation D1A

Formation D1B

- well No
- thickness of reservoir group of rocks
- high-producing reservoir
- high-producing layey reservoir
- low-producing reservoir
- merging with lower formation
- merging with upper formation
Fig. 3 - Dynamics of main operating characteristics of areas in dimensionless time.
Fig. 4 - Comparison of practical and actual specific water flow rate with oil production, t/t

Fig. 5 - Dynamics of production water cutting at different stages of non-stationary development of areas.
Fig. 6 - Averaged monthly operating indicates of producing well No10292.

Regime of well operation:

- stationary
- cyclic