Cyclic impact on productive formations of high-viscosity oil deposits

Yu A Kotenev¹, V Sh Mukhametshin², Sh Kh Sultanov¹ and A Yu Kotenev²

¹ Department of Geology and Exploration of Oil and Gas Field, Ufa State Petroleum Technological University, SASI “Institute of strategic research of the Republic of Bashkortostan”, Ufa, Republic of Bashkortostan, Russia
² Department of Oil and Gas Field Exploration and Development, Ufa State Petroleum Technological University, Branch of the University in the City of Oktyabrsky, Oktyabrsky, Republic of Bashkortostan, Russia

E-mail: geokot@inbox.ru, vsh@of.ugntu.ru, ssultanov@mail.ru, kotenov@mail.ru

Abstract. It is shown that the priority condition for reliable forecasting of the cyclic impact on productive formations of high-viscosity oil is the joint research and study of rheological and filtration properties of high-viscosity oils, including thixotropic properties, as well as mathematical calculations to choose the right mode of the working fluid injection. For the Stepnoozerskoe field conditions, the optimal injection period is 10 days.

1. Introduction
The main task of the oil industry of the country is to create a scientific and methodological basis regarding geological and technological justification to increase the development efficiency of hard-to-recover deposits [1–11].

The peculiarity of the present and forthcoming development stage of oil and gas industry is the development of high-viscosity, heavy oil, super-heavy oil deposits in order to increase the resources of hydrocarbon raw materials and create technologies for their production. The prospects for the development of high-viscosity oil deposits can be determined by a methodological approach, including the detailed study of geological structure; the study of the experience of similar fields; numerical, laboratory and experimental adaptation of working fluids to specific geological-technological conditions of the deposit.

Domestic reserves of high-viscosity and heavy oil account for ~ 13 % of the total oil resources in Russia. According to the Institute of Oil Chemistry of the Siberian branch of the Russian Academy of Sciences, the total reserves of the Volga-Ural and West Siberian oil and gas deposits account for more than 71 % of the all-Russian reserves of heavy oil. Volga-Ural types of high-viscosity oil, compared to West Siberian, contain more sulphur, paraffin, resin, vanadium, but less dissolved gas. More than 450 deposits and natural bitumen and high-viscosity deposits are found on the territory of the Republic of Tatarstan. They are mainly located on the west and south-east slopes of the South Tatar Vault. Relative to the balance of initial reserves in Tatarstan, the share of high-viscosity oil reserves (more than 30 mPa·s) accounts for about 43 % [1]. The main share of high-viscosity oil reserves is found in the deposits of lower and middle Carboniferous period. It was found that as the depth productive formations...
decreases, the weighting of degassed oil, increase of sulphur content in them, reduction of gas factor and content of light hydrocarbons are observed.

2. Methods and materials
The development of high-viscosity oil fields has its peculiarities, and in conditions of complex geological structure the choice of oil production technology requires the detailed study. The Stepnoozerskoe oil field located in the Republic of Tatarstan is characterized by the specific structure of lower Carboniferous deposits, extensive development of erosion cuts of both area and channel types. Two important points shall therefore be borne in mind. First, the development of many deposits of the western slope of the South Tatar Vault revealed hydrodynamic interaction of oil deposits of the Tournaisian and the Visean stages. Since the erosion cuts filled with loose sand or slightly cemented sandstone are nothing more than natural oil storage caverns having a considerable size and therefore draining a large volume of carbonate reservoirs, it is obvious that the flow of oil from carbonates should be the more significant the better the reservoir properties of the terrigenous formation and the larger the area of the cavern. Second, there is a considerable multiple formation effect in the terrigenous thickness of the Stepnoozerskoe field. At the same time, natural modes of the Bobrikovian formations development are different: if in erosion cuts the formations can be operated quite effectively in a rigid natural mode, the lying mantle-like formation \( B_4 \) is not developed effectively without the hydrodynamic modes. It shall also be noted that high viscosity of oil may reach up to 620 mPa·s. Any solution in the development of such deposits needs detailed preliminary study and justification. The problems related to the definition of technological effects from the application of enhanced oil recovery methods and experimental investigations of rheological and filtration characteristics of oils are particularly highlighted. At present, a feasible method of field development is the effective maintenance of formation pressure. Systematic research and development of scientific bases of non-stationary impact technology were laid down in the works of I.N. Sharbatova, M.L. Surguchev. The most common technology implies that the water injection is periodically stopped at the site while maintaining the average injection rate for a long period, i.e. during the first half-period the injection wells are shut down, and then during the second half-period the water is injected at increased flowrates. Together with K.M. Fedorov (TumSU), the cyclic impact was justified, calculated and modeled.

3. Results
Effective application of cyclic action is possible in case of heterogeneity of formations along the vertical section and the presence of sufficient vertical relationship in the formation. In order to analyze the efficiency of cyclic impact, it is necessary to clarify the parameters of formations in section for each analyzed horizon. Geological-statistical sections of horizons are given in Table 1.

The preliminary analysis of this data shows that the development object of the lower Carboniferous of the Stepnoozerskoe deposit meets the conditions of successful cyclic flooding.

The parameters of cyclic action were calculated using two-dimensional numerical model of two-phase filtration in laminar- heterogeneous formation. It was assumed that the formation is developed by a row of wells, with the distance between injection and production rows equal to 300 m. The task was solved in a two-dimensional version along the vertical section without taking into account capillary and gravitational forces. The vertical permeability of the formation, which determines the hydrodynamic bond of interlayers in the oil-saturated horizon, was 0.01 times of the horizontal component. The cyclic impact period consisted of equal half-periods corresponding to the shutdown mode of only injection wells. During the half-cycle of water injection, the injection pressure was increased by 30 %, which ensures the execution of the injection plan. The initial saturation of the formation with water and oil was determined from the problem of flooding until the moment of reaching the current water cut of the product within the studied formation (70 %). The calculations were made for several dozen exposure cycles until 97 % water cut was achieved.

Figure 1 shows the example of oil production rate calculations during normal flooding and cyclic impact.
Table 1. Geological-statistical sections of oil-saturated horizons

| Formation       | Weighted average net oil thickness, m | Porosity, unit fraction | Hydrocarbon saturation, unit fraction | Permeability, µm² |
|-----------------|---------------------------------------|-------------------------|---------------------------------------|------------------|
| Kashirskian-3   | 1.57                                  | 0.18                    | 0.71                                  | 0.151            |
| Kashirskian-1   | 1.9                                   | 0.22                    | 0.60                                  | 0.151            |
| Vereiskian-5     | 0.91                                  | 0.131                   | 0.73                                  | 0.089            |
| Vereiskian-4     | 1.13                                  | 0.145                   | 0.754                                 | 0.157            |
| Vereiskian-3     | 2.10                                  | 0.151                   | 0.761                                 | 0.351            |
| Vereiskian-2     | 1.47                                  | 0.147                   | 0.732                                 | 0.274            |
| Vereiskian-1     | 0.80                                  | 0.143                   | 0.745                                 | 0.253            |
| Baskirian-2      | 2.31                                  | 0.14                    | 0.75                                  | 0.235            |
| Baskirian-1      | 5.18                                  | 0.14                    | 0.75                                  | 0.345            |
| Bobrian-10       | 1.04                                  | 0.206                   | 0.866                                 | 0.320            |
| Bobrian-01       | 4.71                                  | 0.239                   | 0.938                                 | 1.185            |
| Bobrian-02       | 3.0                                   | 0.242                   | 0.95                                  | 1.878            |
| Bobrian-03+04    | 4.7                                   | 0.271                   | 0.948                                 | 5.144            |
| Tournaisian      | 3.73                                  | 0.154                   | 0.702                                 | 0.053            |

The accumulated oil production during flooding and cyclic impact is equal to the area under the corresponding curves (Figure 1). The difference of accumulated volumes of oil at cyclic impact and flooding constitutes additional oil production from impact. This difference for the entire development period is shown for different impact periods in Figure 2 (area of the design section ~1000 m²). As the period increases, the additional production increases to a maximum of 10 days and then drops to negative values (Figure 2). Thus, the optimal cycle period and additional oil production for the analyzed polygon object are determined. The maximum value of additional oil production (10000 t/Ha) corresponds to 3.5% of the oil recovery factor increase of the impact area.

![Figure 1. Example of oil production rate calculation during flooding (solid curve) and cyclic impact (dashed curve) on the second object](image)

The performed numerical calculations require additional studies of rheological and filtration properties of the formation oil. In order to ensure the cyclic effect, it is important to study the thixotropic properties of oil. Together with M.K. Rogachev (Mining University), the experimental studies covered rheological and filtration properties of oil samples taken from 14 wells, which opened productive horizons of lower and middle Carboniforous, including 10 wells of the Stepnoozerskoe field. The research was limited to obtaining experimental relations between bulk oil flows through a capillary or rock sample and pressure drops at their ends. The experiments were conducted under “fixed volume...
flow rates – changing pressure drops”. The pressure drop was measured under steady-state oil flow conditions.

![Graph](image)

**Figure 2.** Additional oil production at cyclic impact limited to a full period of exposure.

With the help of rheological lines and filtration curves, the main rheological and filtration parameters of degassed and formation oil were determined: yield point (YP), structure destruction yield point (SDYP), dynamic pressure shear gradient (DPSG), structure destruction yield point gradient (SDYPG), oil viscosity anomaly and mobility anomaly indices (VAI and MAI).

The results of these studies for one of the wells are presented in Tables 2 and 3, as well as in Figure 3.

**Table 2.** Results of experiments on rheological properties of formation oil of the Stepnoozerskoe field

| Shear rate γ · 10², s⁻¹ | Shear stress τ, Pa | Effective viscosity μ, mPa·s |
|--------------------------|-------------------|-----------------------------|
| Forward stroke           | Return stroke     | Forward stroke              | Return stroke              |
| 1.12                     | 0.018             | 0.010                       | 1610                      | 893                       |
| 1.46                     | 0.021             | 0.012                       | 1440                      | 822                       |
| 2.94                     | 0.028             | 0.017                       | 952                       | 578                       |
| 5.11                     | 0.031             | 0.020                       | 607                       | 391                       |
| 11.2                     | 0.042             | 0.042                       | 375                       | 375                       |
| 14.6                     | 0.054             | 0.054                       | 370                       | 370                       |

**Table 3.** Results of experiments on filtration properties of formation oil of the Stepnoozerskoe field

| Filtration velocity ν · 10⁻¹⁰, m/s | Pressure gradient grad p, MPa/m | Effective motion (κ/μ) · 10⁻⁵, μm²/mPa·s |
|-------------------------------------|---------------------------------|--------------------------------------------|
| Forward stroke                      | Return stroke                   | Forward stroke                             | Return stroke |
| 1.47                                | 0.062                           | 0.24                                       | –             |
| 1.92                                | 0.066                           | 0.29                                       | –             |
| 3.91                                | 0.122                           | 0.32                                       | –             |
| 6.78                                | 0.212                           | 0.32                                       | –             |
| 14.7                                | 0.459                           | 0.32                                       | –             |

With the help of obtained results for each well the rheological and filtration parameters of studied reservoir oils are determined as shown in Table 4.

Experimental studies of rheological and filtration parameters of the Stepnoozerskoe oilfield showed the following distinctive features:

- high density and viscosity of degassed oils, which is explained by increased content of asphalt-resin substances in their composition;
- high viscosity of formation oils at low gas factor;
- high nitrogen content in associated gas at low formation oil gas factor.
The samples of studied oils at a temperature equal to the formation temperature have viscosity and mobility anomalies, and they can be classified as non-Newtonian oils. This behavior of oils is caused by the presence of a spatial structure of asphaltenic particles in them.

Filtration of studied oils through natural rock samples takes place at high values of boundary pressure gradients, low and variable values of oil mobility, which will certainly have a negative impact on the process of its extraction from the formation and should be taken into account when planning the development of these oil deposits. Besides, all studied oil has thixotropic properties, which are expressed in the increase of the boundary shear stresses and pressure gradients when the oil is at a standstill due to strengthening of its spatial structure. These properties should be taken into account when designing the cyclic impact methods on the productive formation, as well as when planning the operation of wells in periodic modes.

4. Conclusion
Thus, the priority condition for reliable forecasting of the cyclic impact on productive formations of high-viscosity oil is the joint research and study of rheological and filtration properties of high-viscosity oils, including thixotropic properties, as well as mathematical calculations to choose the right mode of the working fluid injection. For the Stepnoozerskoe field conditions, the optimal injection period is 10 days.
Table 4. Rheological and filtration parameters of degassed oil of the Stepnoozerskoe field

| Indicator                        | 2462 | 2172 | 2220 | 637 | 2233 | 2129 | 687 | 2245 | 2252 | 132 |
|----------------------------------|------|------|------|-----|------|------|-----|------|------|-----|
| YP at forward stroke, Pa        | 0.026| 0.015| 0.023| 0.014| 0.019| 0.019| 0.019| 0.025| 0.026| 0.018|
| YP at return stroke, Pa         | 0.014| 0.008| 0.012| 0.007| 0.010| 0.010| 0.010| 0.013| 0.013| 0.010|
| SDYP at forward stroke, Pa      | 0.036| 0.021| 0.031| 0.019| 0.026| 0.026| 0.026| 0.034| 0.035| 0.025|
| SDYP at return stroke, Pa       | 0.019| 0.011| 0.017| 0.010| 0.014| 0.014| 0.014| 0.018| 0.019| 0.014|
| Viscosity of oil with broken     | 230  | 375  | 200  | 220 | 364  | 516  | 220 | 575  | 370  | 274 |
| structure, mPa·s                |      |      |      |     |      |      |     |      |      |     |
| Viscosity of oil with unbroken   | 982  | 1250 | 890  | 893 | 1430 | 1700 | 982 | 1960 | 1610 | 1160|
| structure, mPa·s                |      |      |      |     |      |      |     |      |      |     |
| VAI                             | 4.3  | 3.3  | 4.4  | 4.1 | 3.9  | 3.3  | 4.5 | 3.4  | 4.4  | 4.2 |

| Filtration parameters           |      |      |      |     |      |      |     |      |      |     |
|----------------------------------|------|------|------|-----|------|------|-----|------|------|-----|
| Permeability of rock sample, μm² | 0.010| 0.010| 0.010| 0.010| 0.003| 0.003| 0.003| 0.010| 0.003| 0.010|
| DPSG at forward stroke, MPa/m    | 0.025| 0.014| 0.021| 0.013| 0.036| 0.018| 0.037| 0.023| 0.049| 0.017|
| DPSG at return stroke, MPa/m     | 0.012| –    | 0.011| 0.006| –    | –    | –    | –    | –    | –    |
| SDYPG at forward stroke, MPa/m   | 0.033| 0.019| 0.029| 0.017| 0.049| 0.024| 0.050| 0.032| 0.067| 0.024|
| SDYPG at return stroke, MPa/m    | 0.017| –    | 0.015| 0.009| –    | –    | –    | –    | –    | –    |
| Mobility of oil with broken       | 2.17·10⁻⁵ | 1.33·10⁻⁵ | 2.51·10⁻⁵ | 2.27·10⁻⁵ | 0.33·10⁻⁵ | 0.98·10⁻⁵ | 0.54·10⁻⁵ | 0.87·10⁻⁵ | 0.32·10⁻⁵ | 1.88·10⁻⁵|
| structure, μm²/mPa·s              |      |      |      |     |      |      |     |      |      |     |
| Mobility of oil with unbroken     | 0.67·10⁻⁵ | 0.86·10⁻⁵ | 0.74·10⁻⁵ | 1.05·10⁻⁵ | 0.30·10⁻⁵ | 0.70·10⁻⁵ | 0.33·10⁻⁵ | 0.52·10⁻⁵ | 0.24·10⁻⁵ | 0.77·10⁻⁵|
| structure, μm²/mPa·s              |      |      |      |     |      |      |     |      |      |     |
| MAI                             | 3.2  | 1.5  | 3.4  | 2.2 | 1.1  | 1.4  | 1.6 | 1.7  | 1.3  | 2.4 |

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