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Studying the efficiency of implementation of enhanced oil recovery technologies based on field data statistical processing

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Изучение эффективности реализации технологий повышения нефтеотдачи пластов, основанное на статистической обработке промысловых данных

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tracer studies, polymer flooding, field data, correlation coefficient, efficiency, statistical analysis, hydrodynamic connection.

Polymer flooding technology is an effective tool for enhancing oil recovery of highly watered deposits. The high cost of practical implementation of this technology necessitates a thorough critical analysis of the accumulated experience in order to effectively plan its further use. This article is devoted to the analysis of the results of polymer flooding at the Shagirtsko-Gozhanskoye field in the period from 2012 to 2014. Tracer studies performed at the field before and after polymer flooding did not allow an unambiguous assessment of its results. The reason for the ambiguity of the assessment was the insufficient duration of the tracer sampling period. This article proposes a method for evaluating the results of polymer flooding based on statistical analysis of field data. The main idea of the approach is as follows: a polymer injected into a reservoir is a kind of barrier, and the period of its passage should be accompanied by a violation of the hydrodynamic connection between the injection well into which the polymer was injected and the production well that responds to injection. A sign of the emergence of such a barrier may be a decrease in the correlation coefficient between the performance of production and injection wells. In turn, the fact of a decrease in the correlation coefficient can be interpreted as the passage of a polymer in the area of the deposit between these wells. The proposed approach was used to evaluate the results of polymer flooding in the Shagirtsko-Gozhanskoye field. It was established that the injection of the polymer was implemented effectively only in one injection site.

Ключевые слова:
трассерные исследования, полимерное заводнение, промысловые данные, коэффициент корреляции, эффективность, статистический анализ, гидродинамическая связь

Эффективным инструментом повышения нефтеотдачи высокообводненных залежей является технология полимерного заводнения. Высокая стоимость практической реализации данной технологии обусловливает необходимость тщательного критического анализа накопленного опыта проведения мероприятия с целью эффективного планирования дальнейшего его использования. Настоящая статья посвящена анализу результатов проведения полимерного заводнения на Шагиртско-Гожанском месторождении в период с 2012 по 2014 г. Трассерные исследования, выполненные на месторождении до и после полимерного заводнения, не позволили однозначно оценить его результаты. Причиной неоднозначности оценки является недостаточная продолжительность периода отбора трассирующих веществ. В настоящей статье предложен способ оценки результатов полимерного заводнения, основанный на статистическом анализе промысловых данных. Основная идея подхода заключается в следующем: полимер, закачанный в продуктивный пласт, является неким барьером, и период его прохождения должен сопровождаться нарушением гидродинамической связи между нагнетательной скважиной, в которую полимер закачан, и добывающей, реагирующей на закачку. Признаком возникновения такого барьера может быть снижение коэффициента корреляции между показателями эксплуатации добывающей и нагнетательной скважин. В свою очередь факт снижения коэффициента корреляции можно трактовать как прохождение полимера на участке залежи между этими скважинами. Предложенный подход использован для оценки результатов полимерного заводнения на Шагиртско-Гожанском месторождении. Установлено, что закачка полимера реализована эффективно только в одном очаге нагнетания.

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Introduction

Currently, most of the world's oil production comes from mature fields that are developed through secondary displacement techniques. The amount of water which is filtered (injected and extracted) into the reservoir increases significantly over time until a water-to-oil ratio is reached that makes further production unprofitable [1]. Recovery of oil remaining in the reservoir after secondary recovery methods (e.g. waterflooding with water, gas or others) is accomplished by applying enhanced oil recovery techniques, which include various technologies such as thermal and non-thermal [2]. Polymer flooding is one of the most promising non-thermal enhanced oil recovery methods. Polymer flooding has been used in industry for more than 50 years [3-7]. It has several advantages, including increased mobility of the injected fluid, improved vertical and area coverage efficiency, less water required compared to waterflooding, and low cost compared to other enhanced oil recovery methods [8–15].

The polymer increases the viscosity of the aqueous phase, helping to reduce the mobility coefficient and improve the displacement efficiency. In addition, depending on the type of polymer, the permeability to water in the zones covered by the polymer can be reduced [16-19]. This permeability reduction can have a favorable additional secondary effect by sealing the formation and restoring some of the pressure of the highly permeable zones through which the polymer is preferentially filtered in heterogeneous reservoirs. The effect of these two mechanisms, which generate the so-called resistance and residual resistance factors, are combined with the effect of increased viscosity of the injected water, which further reduces the mobility factor in displacement of the water-oil ratio, and hence increases the recovery factor. These are widely accepted fundamental mechanisms [20]. Other mechanisms have been proposed to explain macroscopic and microscopic effects of polymer flooding processes, which are described in detail in [21].

It is known from the literature review that the probability of success in secondary polymer injection projects is higher than in tertiary polymer injection [22, 23]. Tertiary polymer flooding requires more polymer per ton of oil production. Since the 1990s, it has been known to increase the performance of the polymer flooding process in high water cut conditions due to the use of higher concentration and higher total injected mass [24]. These fluid characteristics can lead to lower injectivity depending on the reservoir and pressure-limited conditions [25].

The evaluation of polymer flooding efficiency has been widely studied both in experimental works [26-29] and by numerical modeling [30, 31]. Numerical modeling and simulation of the recovery efficiency of polymer flooding can be performed using traditional simulators. Current flow simulators require a huge number of input parameters (initial saturation, pressure distribution, multiphase flow functions, etc.). Matching these parameters is difficult in terms of simulation run time, while accurate measurements for these parameters are often not available. In addition, numerical modeling may require a large number of physical assumptions for prediction future characteristics of the underlying process. Provided that the input and output parameters of the target functions have extremely nonlinear relationships, the computation time is also extremely long.

Although numerous studies have been widely reported in the literature [32-35] to examine the profound effects of polymer flooding characteristics, this study proposes a new approach to evaluate the results of this intervention.

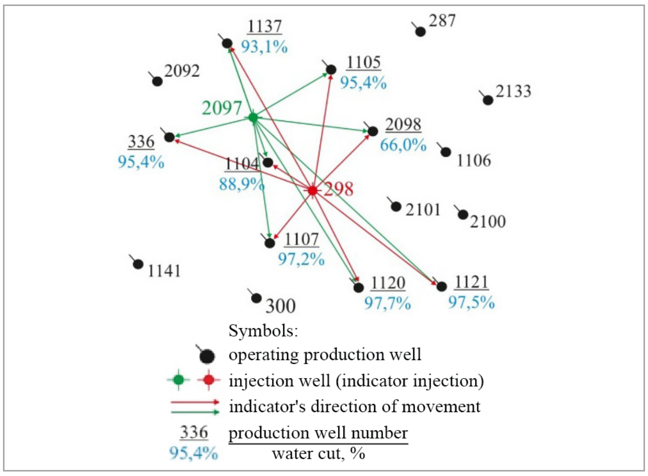

Fig. 1. Scheme of the study area of the Shagirtsko-Gozhanskoye field, Tl-Bb reservoir (at the beginning of polymer flooding)

Geological and physical characteristics of the Tl-Bb formation of the Shagirtsko-Gozhanskoye field

Parameter	Indicator
Average depth of occurrence, m	1330.0
Average total reservoir thickness, m	13.4
Average oil saturated thickness of the reservoir, m	3.0
Permeability according to hydrodynamic studies of wells, μm^2	1.233
Sandiness coefficient, fractions of units.	0.4
Dissection factor, fractions of units	2.37
Reservoir temperature, °C	28.0
Oil viscosity in reservoir conditions, mPa-c	36.46
Gas factor, m^3/day	21.3

Object of Study

In order to improve the displacement ratio and increase the final oil recovery factor under conditions of highly viscous oil and significant water cut of the produced products, polymer waterflooding works were carried out at the Tl-Bb object of the Shagirtsko-Gozhanskoye field.

The studied area of the deposit is characterized by unfavorable geological and physical characteristics of the productive formations, what contributes to rapid flooding of the produced products, reduction of oil withdrawals and oil recovery factor. Tracer studies were carried out to identify the presence of hydrodynamic connection, assess the distribution of injected water flows and clarify the degree of influence of injection wells No. 298 and 2097 on watering of the surrounding reactive production wells at the stage preceding polymer injection..

The analysis of well operation modes together with the results of tracer studies (Fig. 1) and sample analysis indicates the presence of good hydrodynamic connection between production and injection wells of the analyzed area, as well as between formations B_{b1}, Tl_{2a}, Tl_{2b} and Bb_2. The geological and physical characteristics of the study area are presented in the table.

Tracer studies revealed the presence of zones of low filtration resistance at the object of research. The main output of indicators was observed in the first-second day after injection into injection wells. The appearance of "labeled" liquid in the control production wells indicates that they are flooded by water injected into the deposit. Most of the injected water filtered through low filtration resistance channels both from well No. 2097 and well No. 298 flows towards production wells No. 1104, 1105, 1107, 1120 (Fig. 2). Wells No. 1105, 1107, 1120 are characterized by maximum current watercut (95–98 %) and high water/oil ratio (20–40).

The most significant influence of injected water was found in the section of injection well No. 2097. The zone of low filtration resistances for this section is characterized by the highest proportion of water filtered through high conductivity channels. The presence of multiple peaks of indicator output concentration (high permeability filtration channels) in the control production wells in the section of injection well No. 2097 indicates a developed fracture system in this section and a high degree of permeability heterogeneity in the reservoir thickness.

According to the available literature [36-38], we can conclude that the formation of low filtration resistance channels (fractures) is predominantly technogenic in nature – hydraulic fracturing, deep depressions and high repressions during drilling, development and operation of wells obviously exceed the critical values of opening of dynamo-stress zones and thus contribute to the formation of fractures. Practice shows that at certain water injection pressures, called critical (0.55–1.47 of the vertical mountain pressure), in reservoirs representing frequent interlacing of sandstones, clays and shales, formation or increase in the number and volume of fractures extending from injection to production wells is possible.

The use of enhanced oil recovery methods for the purpose of colmatation of channels with low filtration resistance makes it possible to eliminate their influence by an average of 50–60%. However, within some time after the destruction of the compositions, the number and volume of channels of low filtration resistance increase. This indicates the need for periodicity and consistency of enhanced oil recovery methods.

Pilot Works on Polymer Flooding

Pilot works on polymer flooding have been carried out at the Shagirtsko-Gozhanskoye field (Tl-Bb object of the North Shagirt uplift) since December 2012. Polymer injection was started on 28.12.2012 in injection wells No. 298 and 2097.

Polymer injection was accompanied by preliminary and subsequent short-term tracer studies.

According to the results of a comparative analysis of tracer studies for both injection centers, a redistribution of filtration volumes is noted both over the area, and in terms of permeability ranges (in the volume of characterized high-permeability filtration channels) after the completion of polymer injection (Fig. 2). The redistribution of filtration volumes has taken place in the direction of reducing the share of highly permeable channels and increasing the share of less permeable ones, which entails an increase in the coverage of intervals that have not previously participated in the waterflooding process, what should ultimately have a positive effect on the oil displacement process.

In addition, there is a decrease in the indicator arrival rate for production wells before and after pilot work. Thus it is possible to judge about the possible effect of polymer flooding injection, which influenced the change of hydrodynamic connection between the investigated injection and production wells and the mobility of displacing agent through high-permeability channels.

Despite the visible change in the filtration pattern, during the engineering support there were difficulties in assessing the results of the technology implementation in the field under consideration. The technology is conditionally recognized as effective [39].

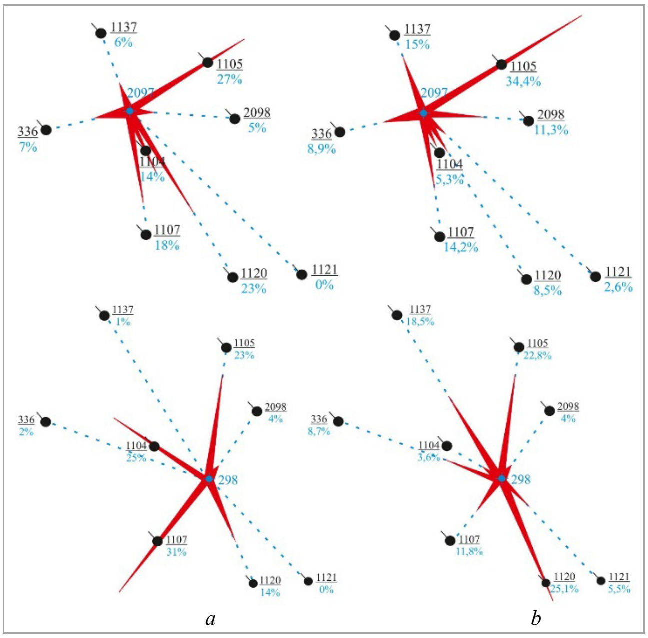

Fig. 2. Distribution of injected water according to the results of tracer studies: *a* – before injection of the polymer composition; *b* – after injection of the polymer composition

It should be noted that the low duration of the sampling period after injection of tracer agents (three months) may contribute to low reliability of the results assessment based only on tracer studies. In this regard, it seems advisable to conduct additional analysis aimed at a detailed assessment of the results of polymer flooding technology implementation at the considered object.

Evaluation of the Results of Polymer Flooding based on the Processing of Field Material

The target of polymer injection into the reservoir is to increase the amount of oil displaced; An increase in the oil flow rate of reactive wells should be considered a sign of effective implementation of the technology. Therefore, at the first stage of the study, a joint analysis of the dynamics of this indicator was carried out for wells located in the immediate vicinity of injection wells – injection centers (Fig. 3).

As follows from the analysis of Fig. 3 all wells located near the polymer injection centers show the growth of oil flow rate for about one year. At the same time, the increment growth of the flow rate varies from 0.7 to 8.9 t/d, averaging about 5 t/d. The maximum growthe is typical for wells located in the northern and northeastern parts of the development system element.

At the next stage of the study, the change in the degree of interaction between the injection wells and the production wells located in the immediate vicinity was assessed [40–44]. For this purpose it was calculated the coefficients of pairwise correlation between the injectivity of injection wells into which the polymer composition was injected (wells No 298 and 2097) and fluid flow rates of neighboring production wells. The correlation coefficient r is often used in the practice of solving engineering problems to estimate the measure of interaction between random variables. This approach has been successfully tested in assessing the results of measures to affect productive layers. For example, some researchers analyze in detail the behavior of an element of the development system before and after hydraulic fracturing on one of its wells. Obviously, similar studies can be carried out in relation to many other technologies for influencing

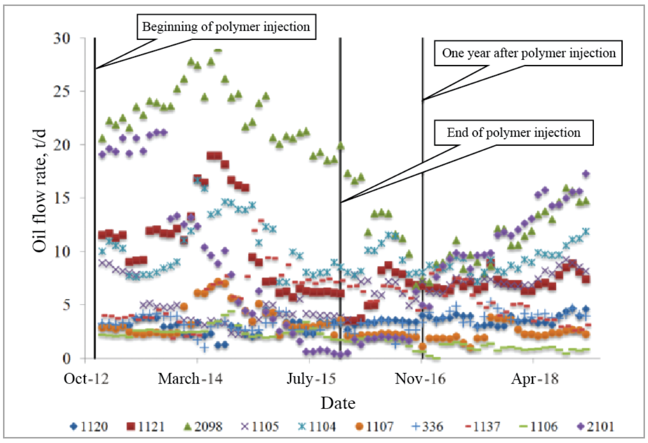

Fig. 3. Oil flow rate dynamics by wells in the polymer injection zone

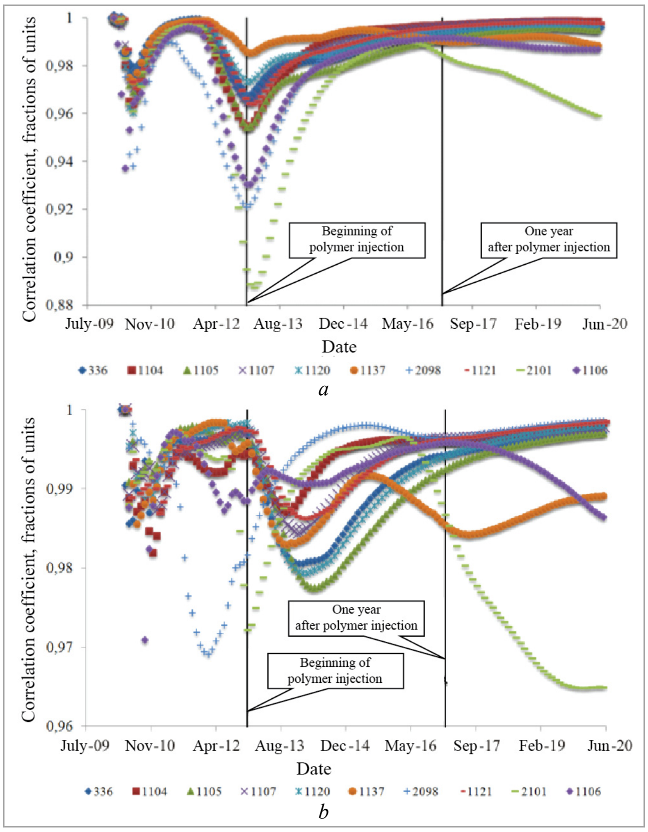

Fig. 4. Dynamics of the correlation coefficient for producing wells of the injection center: *a* – well No. 298; *b* – well No. 2097

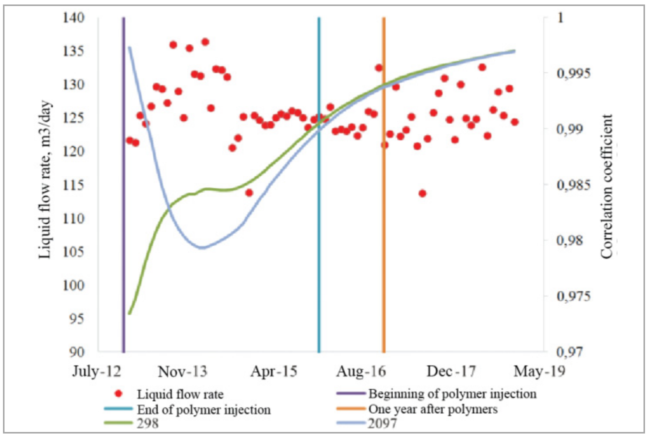

Fig. 5. Combined diagram showing the graph of fluid flow rate of well No. 1120 and correlation coefficients of this well with two injection centers – wells No. 298 and 2097

productive formations that can lead to a change in the interaction between wells.

The possibility of correlation of average daily flow rates is caused by high permeability of reservoirs at the object under consideration and, as a result, by the fast response time of the reacting well to changes in the operating mode of the perturbing well. For low-permeability reservoirs correlation of average daily flow rates may lead to unreliable results, and therefore it seems appropriate to use other approaches.

In the article [45] it is proposed an approach to assessment of the degree of interaction between production and injection wells, based on the correlation of accumulated indicators (fluid production and injection). The reliability of the proposed method is confirmed by the authors with the materials of direct field studies. In this regard, the final stage of this study is devoted to the use of this tool to solve the target task of assessing the efficiency of polymer injection [46].

The essence of the method is to analyze the behavior of the correlation coefficient between accumulated injection and production for a pair of wells. It is assumed that a sharp change in the behavior of the coefficient r indicates a change in the patterns of oil displacement. Graphs illustrating the dynamics of the correlation coefficient for the wells of the considered element are presented in Fig. 4.

The main idea of the approach is as follows. The polymer injected into the productive formation is a kind of barrier, and the period of its passage should be accompanied by a disruption of the hydrodynamic connection between the injection well, into which the polymer is injected, and the production well reacting to the injection. A sign of such a barrier may be a decrease in the correlation coefficient between the performance indicators (accumulated production and injection) of the production and injection wells. The fact of the correlation coefficient decrease, in turn, can be interpreted as the polymer passing in the deposit area between these wells.

It follows from Fig. 4 that for all production wells located near the injection source - well No. 298, similar behavior of the correlation coefficient in time is characteristic: the period of the beginning of polymer injection is characterized not by a decrease, but by an increase of the r coefficient. That is, the fact of hydrodynamic connection violation and polymer barrier formation is not determined. The probable reason for the improvement of the connection between the wells and the growth of the r coefficient can be considered to be the reaction of the producing wells to the increase in injectivity of the injection well No. 298, which took place after the polymer flooding was organized.

In turn, injection well No. 2097 is characterized by a different situation. The period of the beginning of polymer injection is characterized by a decrease in correlation with practically all neighboring producing wells, which indicates a violation of hydrodynamic connection due to the passage of the polymer barrier.

For clarity of interpretation of the behavior of the coefficient r on the displacement processes, Fig. 5 shows a combined graph reflecting the dynamics of fluid flow rate of well No. 1120 and correlation coefficients of this well with two injection centers – wells No. 298 and 2097.

The combined graph shows that the period from the beginning of polymer injection until February 2014 is characterized by deterioration of hydrodynamic connection (decrease of correlation coefficient) between this production well and injection well No. 2097. After February 2014, the correlation coefficient increases, which indirectly indicates the resumption of interaction between these wells. Obviously, the time period from early December 2012 to February 2014 is the period of polymer passage in the deposit area between these wells. No deterioration of the interaction between this well and injection well No. 298 was found, hence it can be concluded that the polymer injected into well No. 298 did not enter the productive formation operated by well No. 1120.

Similar graphs were constructed for all production wells located in the immediate vicinity of polymer injection centers, their analysis allowed obtaining exactly the same result: polymer injected into injection well No. 298 did not form a barrier and did not break the hydrodynamic connection with any production well. In its turn, polymer injection into well No. 2097 should be considered successful, since the fact of changing the filtration pattern in the direction of practically all neighboring producing wells has been established.

The probable cause of ineffective polymer injection into well No. 298 should be considered as its vertical movement due to leaky cement stone.

Thus, the construction and analysis of correlation graphs of accumulated indicators (injection and production) also makes it possible to study in detail the results of the implementation of various enhanced oil recovery technologies, which is demonstrated by the example of an element of the Shagirtsko-Gozhanskoye field development system, where polymer flooding technology has been implemented.

Conclusion

Assessment of the technological efficiency of a number of implemented enhanced oil recovery technologies is often difficult for a number of objective reasons. Thus, the impossibility of an unambiguous assessment of the effectiveness of polymer flooding at the Shagirtsko-Gozhanskoye field was noted during the engineering support of this event.

Tracer studies are an objective and effective tool for assessing the results of polymer flooding, but reliable results can be obtained only with a sufficient duration of the period of their implementation, which, in turn, significantly increases the total cost of the event.

In this article the method for assessing the results of polymer flooding based on statistical analysis of field data has been proposed. The initial data for the analysis are the accumulated and current production (injection) indicators, which are regularly determined in practice. It should also be noted the simplicity of the applied mathematical apparatus.

The proposed approach is used to assess the results of polymer flooding at the Shagirtsko-Gozhanskoye field. It was found that polymer injection was implemented effectively only in one injection center.

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