Запропоновано і досліджено ймовірносно-статистичну модель прогнозування ефективності гідророзриву пласта. Досліджено вплив кількісних критеріїв на вибір параметрів тріщини по довжині, висоті і кількості закачаного пропанту. З використанням результатів аналізу статистичних показників застосування багатостадійного ГРП показано, що застосування на горизонті АС12-3 цієї технології забезпечує її більш високу ефективність у порівнянні з технологією одностадійного ГРП

Ключові слова: одностадійний розрив пласта, багатостадійний ГРП, продуктивний пласт, потужність пласта, коефіцієнт глинястості

Предложена и исследована вероятностно-статистическая модель прогнозирования эффективности гидроразрыва пласта. Исследовано влияние количественных критериев на выбор параметров трещины по длине, высоте и количеству закачанного проппанта. С использованием результатов анализа статистических показателей применения многостадийного ГРП показано, что применение на горизонте АС12-3 данной технологии обеспечивает её более высокую эффективность по сравнению с технологией одностадийного ГРП

Ключевые слова: одностадийный разрыв пласта, многостадийный ГРП, продуктивный пласт, мощность пласта, коэффициент глинистости

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A PROBABILISTIC AND STATISTICAL APPROACH AS A MEANS OF PREDICTING THE EFFICIENCY OF HYDRAULIC FRACTURING

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1. Introduction

The trends of the last decade are such that the technologies of improving the efficiency of petroleum production include hydraulic fracturing (HF) since it allows enhancing the inflow of petroleum. The technology is based on the mechanism of forming and developing cracks in rocks. Given that an effective use of such technologies requires an acceptable model to describe the perspective process, it is highly expedient to apply a probabilistic and statistical approach to researching the efficiency of HF. In particular, this would help solve the problems of determining the optimal number of HF stages and, subsequently, of estimating the distances between the cracks. Therefore, it is necessary to have a probabilistic and statistical approach in working out new criteria for a successful use of multiple HF among the technologies of integrated impact on the petroleum layer in field conditions.

2. Analysis of previous studies and statement of the problem

In studies that examine the efficiency of HF, especially when it concerns hard-to-recover petroleum reserves, many researchers consider ways to improve multistage fracturing technologies that are used in heterogeneous anisotropic petroleum-rich reservoirs [1–4].

The authors of [5] describe the possibilities of evaluating the productivity ratios of deposits on the basis of indirect data at the stage of drawing up the first project documents and planning petroleum recovery with the use of experience in long-exploited oil fields.

In [6], the researcher uses a method of determining the volume of injected proppant. The author introduces new constitutive equations to describe the process of a fracture closing and analyse the effect of the fluid viscosity and density as well as the layer size and permeability. The research findings can be useful in selecting the proppant composition.

The authors of [7] base their study on the statistical analysis to group the oil fields in the latitudinal segment of the Ob River area. The multivariate analysis allowed the researchers to reveal the geological features that affect the efficiency of field exploitation.

Simulation of an elastic and plastic stress field around a wellbore is suggested in [8], where a new elastic and plastic model of HF initiation is developed in conjunction with a maximum tensile strength, which is important in determining the stress field of hydraulic fracturing.

The efficiency of HF can be enhanced with the use of an impulse technology of sand fracturing proposed in [9]. The authors introduced the concept of discrete multilayer grinding inside cracks. Their research proved that the impulse duration affects the layer, considerably enhances the well productivity, and reduces the volume of fracturing proppant.

The authors of [10] suggest a mathematical model that helps both accurately assess the fracturing effectiveness and determine the optimal parameter design in horizontal wells. The laboratory tests were applied in the field and showed good results.

However, it should be noted that despite the substantial research in the field of enhancing the layer productivity with single-stage and multistage HF technologies, there are still some unsolved problems. We have used the experience described in the previous studies and manuals [12, 13] as well as the research findings based on mathematical statistics and the oil fields in the latitudinal segment of the Ob River area to specify the purpose and objectives of the study that allow resolving a number of problems.

3. The purpose and objectives of the study

The purpose of the study is to identify the criteria of HF efficiency by applying a probabilistic and statistical approach. To achieve the goal, it is necessary to fulfil the following tasks:

– to make a statistical analysis of the existing fracturing technologies;

– to study the effectiveness of single-stage and multistage HF operations;

– to specify the criteria of an efficient HF technology.

4. The findings of the petroleum geology research on the Ob River area

The study is based on a probabilistic and statistical analysis of the performed HF operations, which allows selecting the method of intensifying oil production on the basis of a single-stage fracturing technology as well as the filtration and capacitive properties of the AC-12-3 horizon that contribute to the formation of hard-to-recover reserves in it. Having processed the statistical data on the field efficiency, we specified quantitative criteria of selecting fracture parameters such as its length, height, and the amount of proppant pumped into it. Implementation of the research findings resulted in an enhanced field exploitation efficiency of using a single-stage hydraulic fracturing, and the annual increments of cumulative production increased by at least 10–15 % [6]. However, after some time (4 years), the field efficiency of the single-stage hydraulic fracturing began to decline, which required finding ways to improve it via introducing its multistage modification. Analysis of the field testing results helped obtain quantitative criteria of a multistage hydraulic fracturing optimization on the basis of a well-grounded choice of the length and size of the cracks as well as their quantity, which allowed achieving the planned oil recovery factor in the exploitation of the AC-12-3 horizon within the terms earlier specified and agreed with the State Committee of the Russian Federation for State Reserves.

The unique Ob River area oil field is part of the large Khulym-Ob oil and gas zone that stretches as a broad band from north to south in the central part of the West Siberian Plain [4].

According to the geological field research, the oil-rich thickness of the deposit has a stratum composition represented by the main productive layer horizon AC-12-3 of the Cherkashina (Cherkashinskaya) formation. The capacity increases (up to 16–18 m) towards the arch of the field and decreases (down to 5–4 m) at its edges.

Fig. 1 shows a histogramme of an effective oil-saturation distribution in the AC-12-3 layer, from which it is clear that it comprises not more than 50 % of the actual capacity of the deposit, its prevailing value of 3–7 m is about 60 %, and the remaining capacities of 1–3 m and of 8–10 m are less than 40 %.

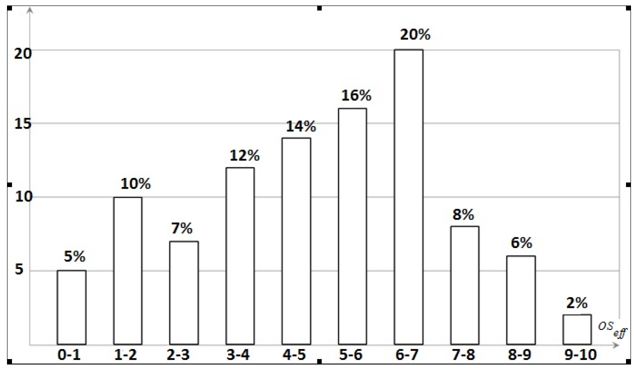


Fig. 1. A histogramme of an effective oil-saturation distribution in the layer AC-12-3 [2]

In addition, the layer AC-12-3 is characterized by a relatively high dissection, up to 80 % or more if there are 2–6 interlayers (Fig. 2).

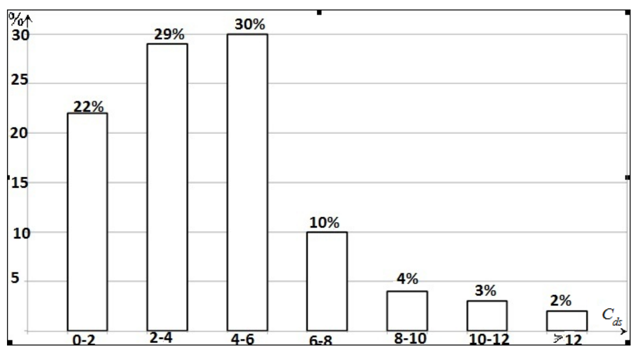


Fig. 2. A histogramme of dissection distribution in the productive AC-12-3 formation [2]

The productive layer has a relatively low coefficient of sand content, whose fraction up to 0.4 is about 90 % (Fig. 3). This is due to a relatively high coefficient of clay content (5.0–8.0 %), despite a relatively high average intergranular porosity of the formation (19 %) (Fig. 4), which is the cause of its low permeability (45–90 mpc) at an average oil saturation of 62–76 %.

Ultimately, the above filtration and capacitive properties of the AC-12-3 formation allow classifying therein oil deposits as hard-to-recover, which leads to their uneven exploitation in the deposit area.

According to previous studies [6, 11], the long-term exploiting of the AC-12-3 formation (since 1986) has resulted in an uneven redistribution of the remaining reserves across the area of its occurrence. Thus, the minimum content of the residual reserves appears to coincide with the zones (areas) of the formation with minimal dissection and a maximum sand content, whereas a significant proportion of the remaining reserves is concentrated in the areas of the reservoir with maximum ruggedness and minimal sandiness and, accordingly, with a minimum permeability. However, the water cutting effect on the AC-12-3 layer is of the opposite nature: the productivity is higher where there is less dissection but more sand content, and the productivity is reversely lower where there is more dissection and less sand content.

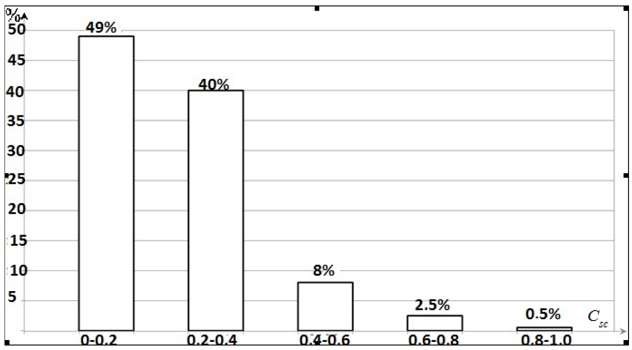


Fig. 3. A histogramme of sand content distribution in the productive AC-12-3 layer [2]

The deposit structure of the AC-12-3 deteriorated in the process of its intensive development. Thus, despite the increase in the number of the operating wells by 1991 to 80 sites, there was a rapid fall in the amount of the annual production (Fig. 5), which induced a search for more effective methods of enhanced oil recovery (EOR). By early 2000, various methods of intensification had been tested (including hydrochloric acid injection (HCI), thermal injection, horizontal well (HW) and sidetrack horizontal well (SHW) development), and, after a thorough analysis of the submissions received, the option chosen was to apply a single-stage hydraulic fracturing technology [3].

According to the project task, the HF mode was selected with the expectation of receiving a single crack with the height of the productive thickness (Hcr) in the stratum of up to 0.8–0.9 Hstr, the crack length (Lcr) of about 70–80 meters, and the crack disclosure (W) of 3–5 mm.

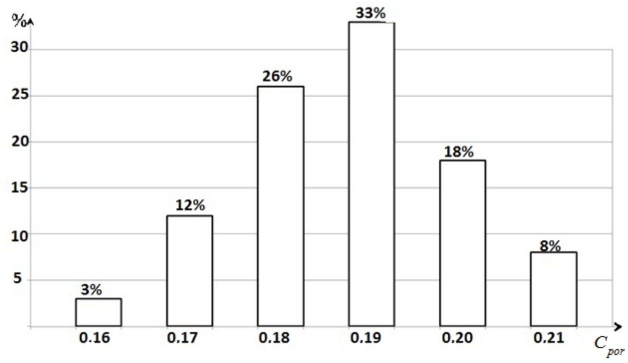


Fig. 4. A histogramme of porosity distribution in the productive AC-12-3 formation [2]

The commercial efficiency of HF was estimated as about 50 %. Analysis of the results of failed HF showed that they were usually accompanied by low production rates and increasing water content compared to the original, although the selected wells were located in the zone of relatively high residual reserves.

The study of the deposit structure and its comparison with the direction of the underlying cracks in its foundation showed that in the wing areas of the sedimentary depth there were plots of the stress state of rock accompanied by the formation of natural fractures of a predominantly axial (along the mound-shaped field structure) direction.

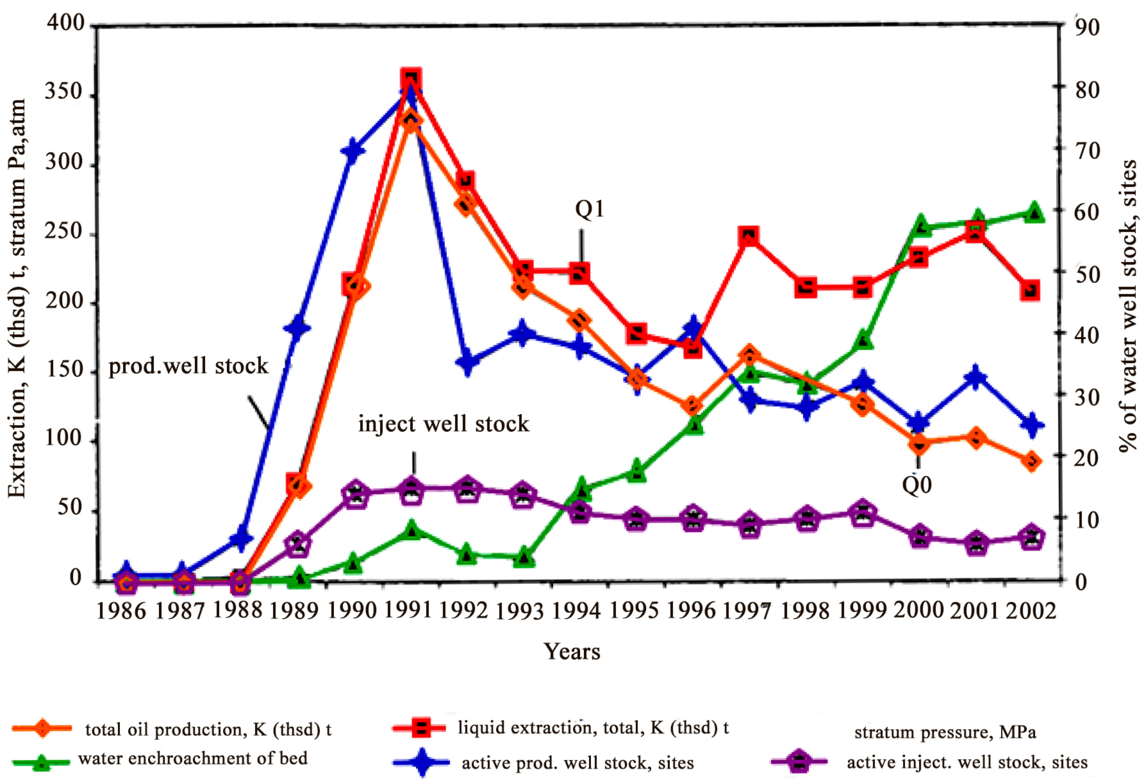


Fig. 5. The operating dynamics of the AC-12-3 formation in the Ob River area oil field

A comparison of the data on the failed HF in the wells located in the areas of concentrated residual reserves and on the direction of the natural fracture showed that the second wing of the crack coincided with a depleted reserve zone that had a high water content, which could explain the low operational efficiency [2].

At the stage of pilot testing of the single-stage HF technology, the wells were chosen by the following criteria [4]:

– an oil saturated reservoir capacity of not less than 3 m;

– a potential flow rate (the maximum flow rate for the entire operating history) of at least 10 tonnes per day;

– the initial oil saturation factor $F_{sat} > 0.4 + 0.15 \cdot (1 - \sqrt{\alpha_{nc}})$;

– a capacity of the overlying and underlying displays of at least 3 m;

– a ratio of the active stratum pressure to the initial reservoir pressure of at least 0.9;

– a good state of the cement stone in the perforation interval of ±20 m;

– the well should not have casing flows;

– the water cut should not exceed 50 %;

– the angle deviation of the wellbore from the vertical in the interval of the formation should not be more than 10°;

– the water content of the surrounding wells of no more than 70 %.

In order to investigate the dependence of technological efficiency of HF on the technology of its implementation, it was expedient to use the previously proven methods of studying the influence of such fracture parameters as: length, height, width, and the amount of proppant.

As a result, it was found that if the crack length increased, the initial oil production rate increased too, but the water cut index went down, which is reflected in the graphs shown in Fig. 6, 7.

It was determined that with an increasing height of the crack on the effective capacity of the reservoir, the oil flow rate declined, but the water content, on the contrary, increased, as is obvious from the graphs given in Fig. 8, 9. Such behaviour can be clearly associated with a decrease in the effective oil-saturated reservoir capacity as development of the reserves was in the course of continuous operation.

We further determined that with an increase in the mass of the injected proppant, the post-fracturing oil production rate also increased (Fig. 10), which was well correlated with the graph in Fig. 6 for the flow rate depending on the length of the crack. The obtained dependencies given in Fig. 6–10 helped substantially correct the application of the single-stage hydraulic fracturing technology with regard to increasing its both technological and economic efficiency.

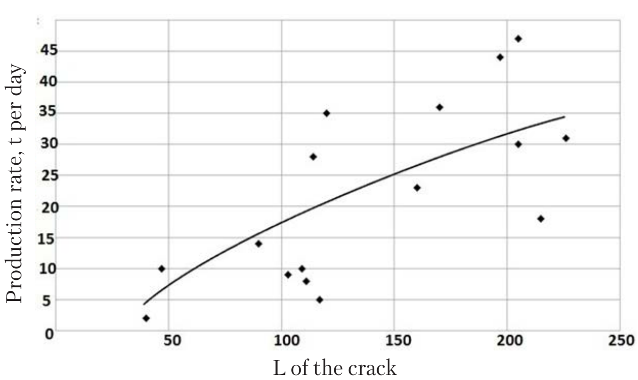


Fig. 6. The dependence of the oil well production rate after a single-stage HF on the length of the crack

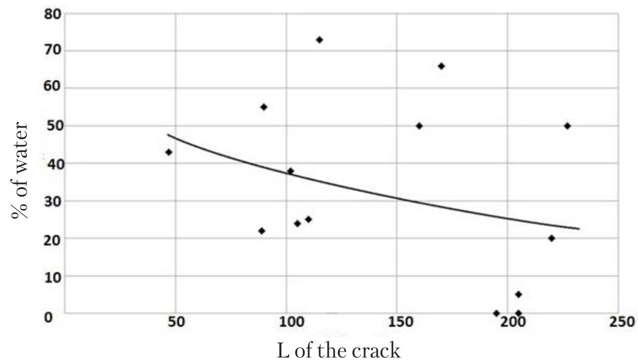


Fig. 7. The dependence of the well water-cut after a single-stage HF on the length of the crack

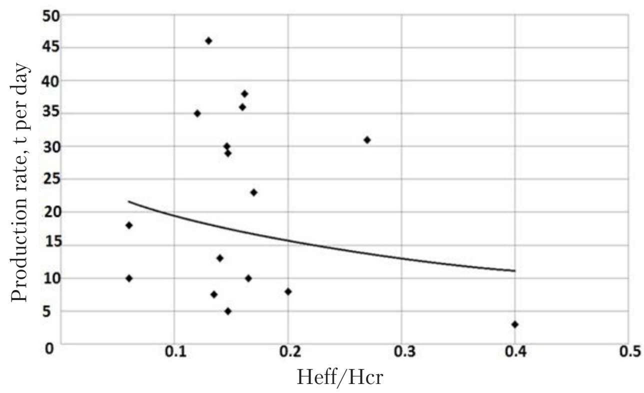


Fig. 8. The dependence of the oil well production rate after a single-stage HF on the effective capacity of the reservoir to the height of the crack

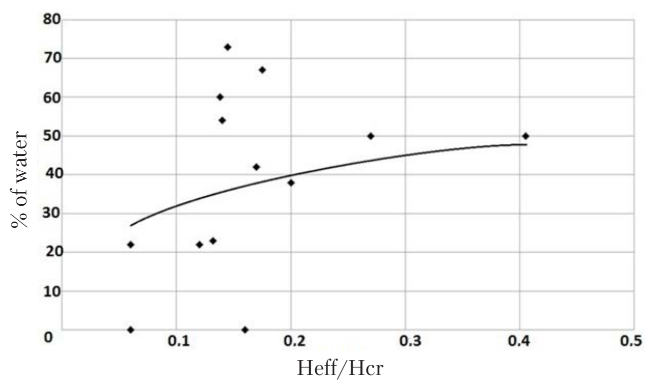


Fig. 9. The dependence of the water cut after a single-stage HF on the effective capacity of the reservoir to the height of the crack

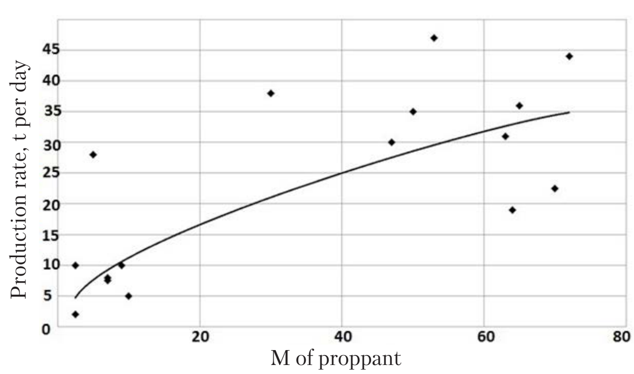


Fig. 10. The dependence of the oil well production rate after a single-stage HF on the amount of proppant injected into the crack

By using the obtained criteria to select rational parameters of the optimal single-stage fracturing technology, it was possible not only to stop the incipient slowdown accumulated during the operation of the BC-8-1 formation, but also to ensure its increase by 2006 (Fig. 11). However, graphs 6–10 show that after 2006 there has been another decline in the cumulative current oil production.

5. The effectiveness of a multistage HF

A multistage HF technique was developed as an alternative of the single-stage HF to be employed when a horizontal bore is drilled in the formation and, therein, with the help of special equipment, the technology is used to create multiple fractures that are separated by a certain interval from one another [4, 11].

Fig. 12 shows a range of the oil production rates from the wells in which multistage HF was conducted, from primary flow rates before the multistage HF to the calculated (predicted) and actual flow rates immediately after the hydraulic fracturing (launching), then in 3 months after the fracturing, and finally after 6 months past the HF.

The illustrated dependencies show that the range of the estimated production rates and the launch yields virtually coincide, which testifies in favour of the almost perfect method of predicting the commercial effect on the basis of the multistage hydraulic fracturing [4].

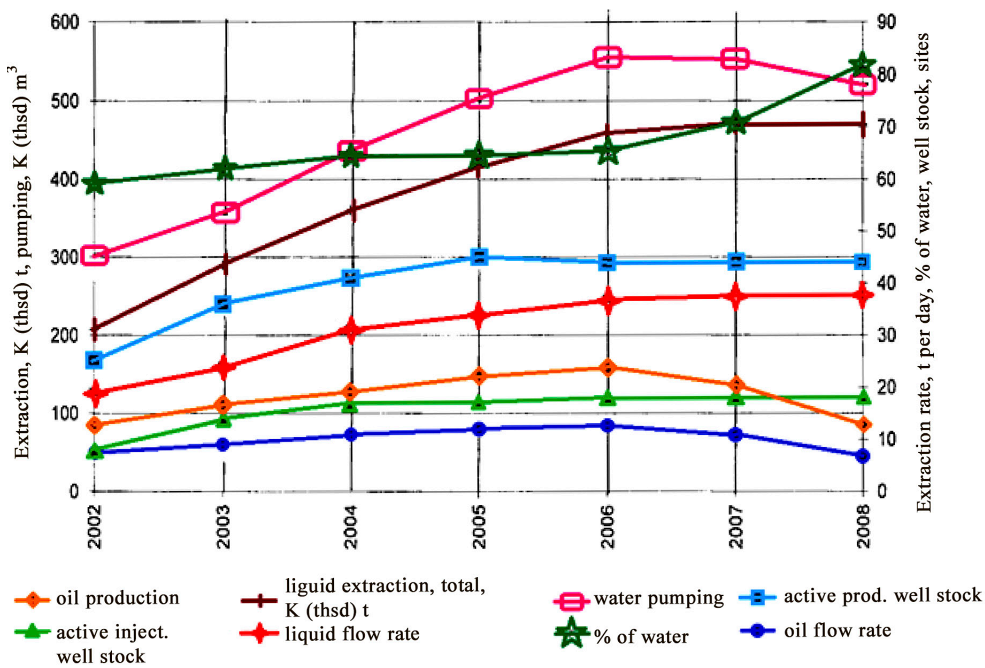


Fig. 11. The dynamics of developing the AC-12-3 formation from 2002 to 2008

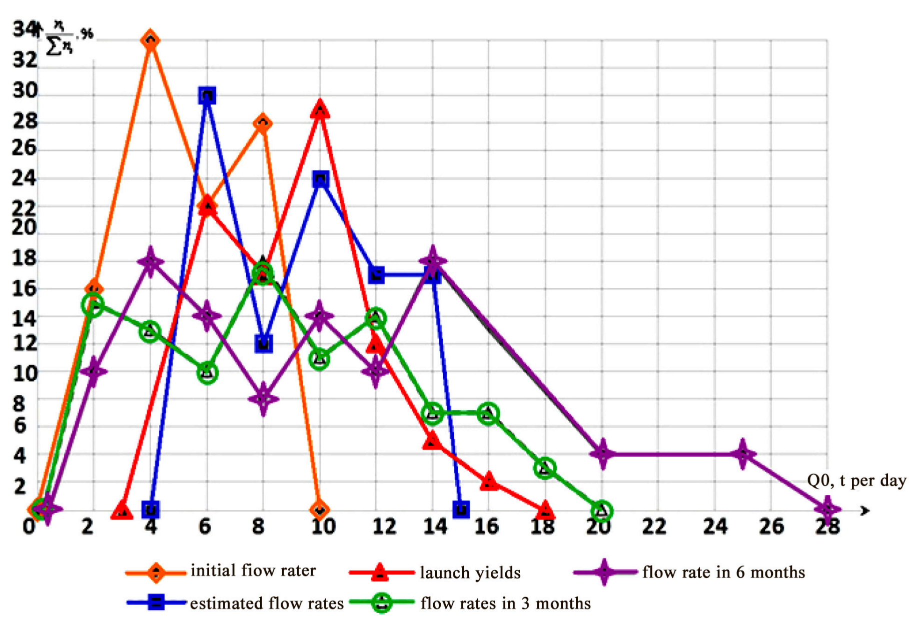
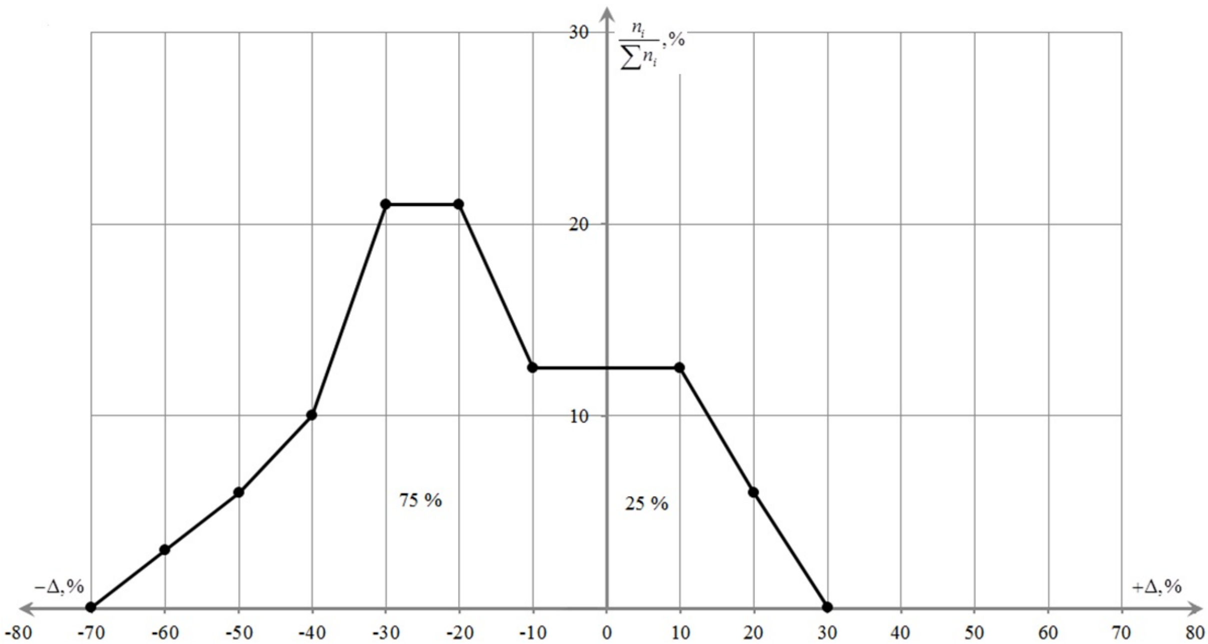


Fig. 12. The graphs of the distribution of the oil production rates of wells after the multistage hydraulic fracturing of the AC-12-3 formation

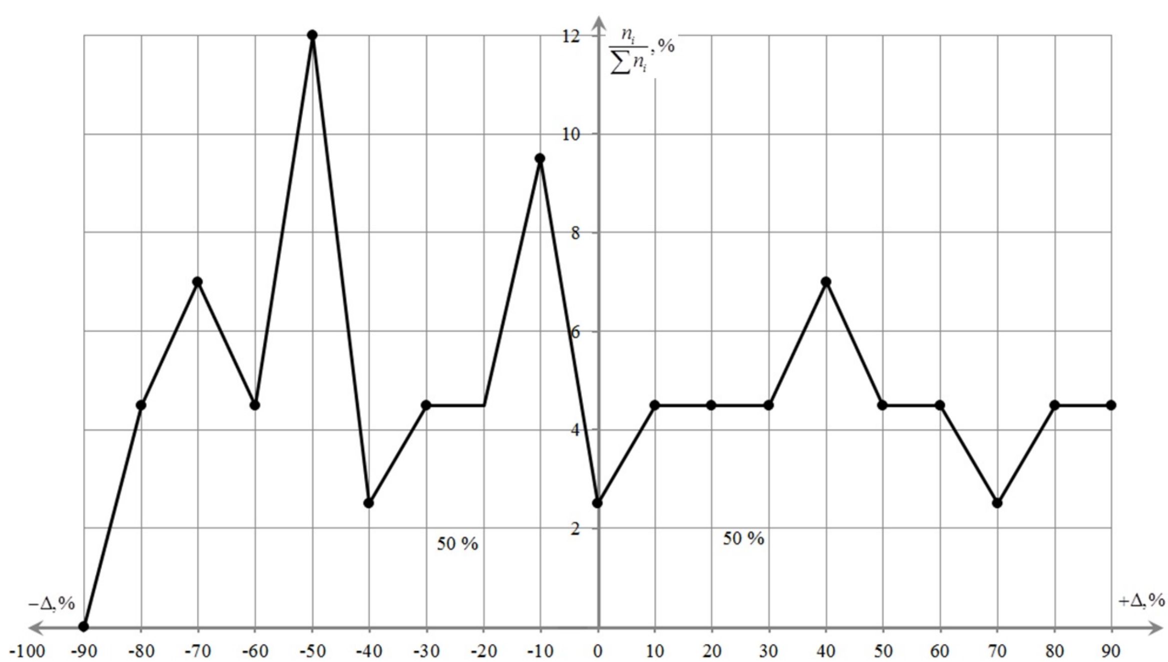
However, after the first 3 months and then after the 6 months, the real flow rates began to differ significantly from the estimates. Moreover, these differences reflected both a direction towards decreasing flow rates, compared with the estimated data, and a tendency towards their increase. This behaviour was due to an error in the produced calculations that did not take into account the water content of the produced output in the first case and its decline in the second instance. However, it is necessary to find out whether the aforementioned shortcoming in the estimates calculation was a system error or just occasional. Let us consider the graphs that reflect the distribution of the real deviation from the projected production rates.

The relevant graphs are given in Fig. 13. They show that the projections concerning vertical and directional types of drilling were justified in 15 % of cases, after sidetrack drilling – in 25 % of cases, and in 50 % of cases after applying the multistage hydraulic fracturing technique.

If petroleum production is intensified by the multistage HF technique, there is an inevitable gradual reduction of the current flow rate over time due to the depletion of the reserves within the yield contour of a particular well. It is expedient to study the dependence of the real flow differences in the oil production rates decline and the water content.



a



b

Fig. 13. The graphs of the distribution of the real flow deviations from the projected production rates: *a* — shows the output after sidetrack drilling; *b* — reflects the output after hydraulic fracturing

Consequently, the analysis of the relationship between a likely positive projection of oil production increase and water content decrease has also produced additional quantitative criteria for determining the best properties of the resulting cracks. They ensure the necessary technological effectiveness of the HF method of enhanced oil recovery used in accordance with the estimates.

6. Conclusion

1. The productive horizon AC-12-3 has a complex geological and physical structure and low reservoir properties, which greatly complicates its development but facilitates active formation of its hard-to-recover deposits.

2. The use of the technology to enhanced oil recovery from the horizon BC-8-1 on the basis of a single-stage hydraulic fracturing has shown its effectiveness for quite a limited time not exceeding 3–4 years.

3. The use of the multistage HF technology on the horizon AC-12-3 showed its higher efficiency compared to the single-stage HF technology. However, the corroboration of the positive prognostic indicators of its use did not exceed 50 %.

4. The results of the probabilistic and statistical analysis of the commercial application of the multistage hydraulic fracturing technology on the horizon AC-12-3 have helped specify the range of the main parameters of post-HF cracks such as their length, height, number, and the amount of injected proppant.

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