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Improvement of scientific and methodological bases for forecasting the development of low -permeable formations based on a comparative analysis of guar and polyacrylamide hydraulic fracturing systems in horizontal wells

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Abstract. *The article deals with the issues of geomechanical modeling of hydraulic fracturing cracks using liquids based on guar gel and polyacrylamide. A comparative analysis of the influence of the rheological properties of these fluids on the formation of crack conductivity and filtration damage to the bottom-hole zone of the formation is carried out. Special attention is paid to modeling the interaction of reagents with reservoir rock and predicting changes in permeability in the crack zone. It was found that polyacrylamide systems demonstrate an advantage in minimizing residual crack damage due to the ability to completely destroy the molecular structure. Geomechanical modeling confirms a more uniform distribution of propane in the crack when using polyacrylamide fluids due to optimized rheological characteristics. Practical recommendations for choosing the type of fracturing fluid depending on the geomechanical properties of the rocks of the target formation are proposed. The results of the study allow us to optimize the parameters of hydraulic fracturing in low-permeable reservoirs to increase oil recovery.*

Keywords. hydraulic fracturing · fractures · horizontal wells · low-permeability reservoir · filtration · oil · geomechanical modeling · guar gel · polyacrylamide · rheological properties.

Mathematics Subject Classification (2010): 76A05, 76S05

1 Introduction

In the conditions of depletion of traditional hydrocarbon reserves with high filtration and capacity properties, the development of hard-to-recover reserves is becoming a strategic direction for the development of the oil and gas industry. A significant part of which is concentrated in low-permeable reservoirs, the development of which by traditional methods is unprofitable or ineffective [2].

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The key technology that has provided an economic effect in the development of such facilities is the joint use of horizontal well drilling and multi-stage hydraulic fracturing. A horizontal wellbore significantly increases the area of contact with the reservoir, and MGRP creates a branched network of highly conductive cracks that connect remote zones of a low-permeable reservoir with the wellbore, improving the mobility and speed of fluid movement to the well. The most important element of MGRP technology is the use of fracturing fluids with high rheological properties, which are necessary for opening and splitting cracks with propane. Historically and still widely used liquids based on guar gel and its derivatives, providing the required viscosity and ability to hold propane in suspension. However, the main problem of such systems is the residual damage in the bottom-hole zone of the formation and the crack itself, which can significantly reduce the effective conductivity, and therefore the flow rates of wells [8]. As an alternative, liquids based on synthetic polymers, such as polyacrylamide, which are characterized by the ability to create ”clean” or ”smart” systems, have recently been actively introduced [6, 9, 10, 13]. These systems are either easily and completely destroyed, or have a rheology sufficient to transport proppant at high shear rates in the crack, but significantly reduced in the low-permeable formation matrix, minimizing filtration damage. Comparative analysis of the effectiveness of using traditional guar and promising polyacrylamide systems for the conditions of specific low-permeability objects is an urgent scientific and practical task.

However, designing and predicting the effectiveness of such complex systems involves a number of scientific and technical problems, for example, the complexity of predicting the geometry and conductivity of multiple fractures, their interaction with each other and with natural fracturing, nonlinear filtration processes in the reservoir, as well as significant spatial heterogeneity of reservoir properties. Existing methods for predicting technological indicators often have either insufficient accuracy (analytical models) or high computational cost (numerical models). This makes it important to develop and improve techniques that allow us to assess the potential of horizontal wells with MGRP in low-permeable reservoirs at various design stages with acceptable accuracy and reliability.

Issues related to fluid migration to horizontal wells and fractures formed during hydraulic fracturing are widely covered in the works of S. A. Khristianovich, Yu. P. Zheltov, V. Sh. Shagapov, R. D. Kanevskaya, V. I. Astafiev, L. F. Kemp, and others [7-9]. However, the problem of complex forecasting, which takes into account the entire chain from hydraulic fracturing parameters to long-term development indicators, remains insufficiently solved, especially in relation to the specific conditions of specific fields [3 - 5]. Therefore, justification of the development of new technologies, new methods, as well as the symbiosis of technologies and techniques for developing low-permeable reservoirs is an urgent task for the oil industry.

2 Comparative Characteristics of Guar- and Polyacrylamide-Based Fracturing Fluids

To build a geomechanical model and then perform an analytical comparison of technological indicators, the wells were divided into two groups depending on the applied fracturing fluid:

1 wells using guar gum-based fluids;
2 wells using polyacrylamide.

The selection of two groups allows us to conduct a comparative analysis of the effectiveness of various polymer systems under similar geological and physical conditions. The results of systematization of the initial data are presented in Table 1.

The above parameters are basic for geomechanical modeling and subsequent analytical comparison of the operation of wells with hydraulic fracturing based on guar gum and PAA.

The object of research is an oil field with a predominantly clay-sand reservoir and a low-permeable oil-saturated horizon of the Achimov formation.

The studied wells are characterized by an average length of the horizontal part of the trunk, equal to 1200 m. The diameter of the used shank is 114 mm.

Table 2.1. Comparative table of averaged parameters of two groups of wells

Indicator	Wells with hydraulic fracturing based on guar	Wells with hydraulic fracturing based on PAA
Number of wells, pcs	11	2
Average number of hydraulic fracturing stages, pcs	8	8
Average reservoir pressure, MPa	286	280
Average reservoir temperature, °C	89	90
Saturation pressure, MPa	105	101
Total reservoir thickness, m	50.1	51.5
Average effective reservoir thickness, m	35.2	35
Average permeability, mD	1.1	1.1
Average porosity, %	13	13
Average volume of injected liquid per well, m3	351	316
Average mass of proppant per well, t	90	75
Average polymer concentration, kg /m^3	4.0	6.0

Actual well wiring is shown in Fig. 2.1.

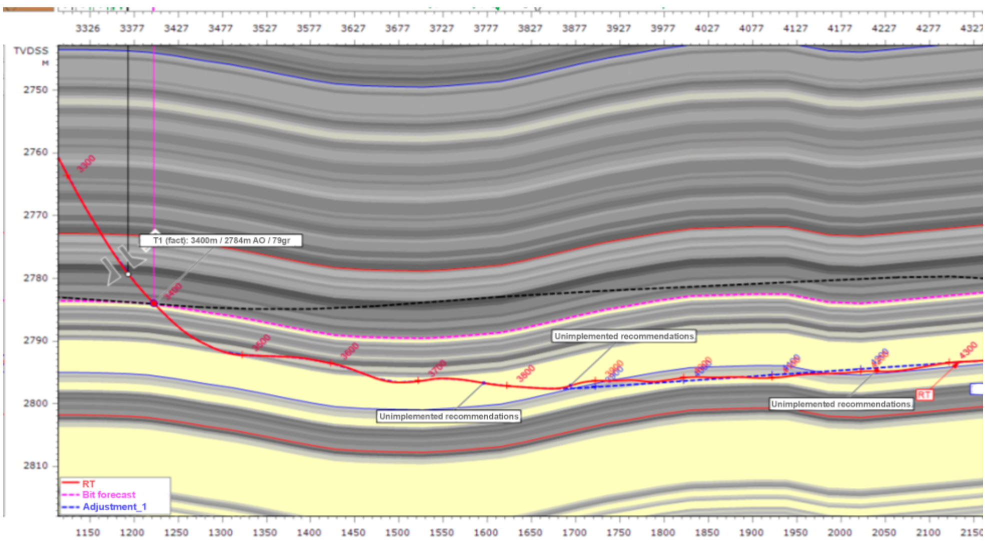

Fig. 2.1. Actual well wiring

To perform hydraulic fracturing, MGRP sliding couplings are lowered into the wells, allowing for targeted hydraulic fracturing in the reservoir interval. In order to separate the intervals between the couplings, we use round-column swell packers, the purpose of which is to separate the zones of injection intervals.

To analyze the effectiveness of hydraulic fracturing in wells of the Achimov formation using a differential approach to the formulation of fracturing fluids, it is advisable to identify key parameters for both guar gum-based fluids and PAA-based fluids.

3 Methodology of Geomechanical Modeling of Hydraulic Fracturing

Polyacrylamide-based fluids are partially hydrolyzed with polymers and copolymers based on acrylamide and its derivatives. This group of polymers has a high rate of hydration, even at low temperatures (from 10 °C). The resulting gel exhibits the properties of a non-Newtonian liquid without the addition of additional chemical reagents, provides efficient transport of proppant (proppant) at standard hydraulic fracturing injection rates (from 2 to 6 m^3), and can exhibit the ability to hold the proppant in a suspended state. This group of polymers does not include low-molecular polymers and copolymers based on acrylamide and its derivatives, which are used as viscosity reducers in the production of high-flow hydraulic fracturing (with an injection speed of more than 10 m^3).

A distinctive feature of PAA in comparison with guar gum is the creation of "cleaner" cracks. Thus, the results of testing the residual conductivity of a medium propane pack are shown in Fig. 3.1. It is necessary to compare the values for cross-linked gel and BBSG (high-viscosity synthetic gelling agents, the second name of polyacrylamides). The result of the study is ˜ 50% of the standard cross-linked systems based on guar gum.

Guar gum is a natural high-molecular polysaccharide obtained from the seeds of the legume Cyamopsis tetragonoloba. Due to its high molecular weight and hydration properties, guar forms viscous colloidal solutions even at low concentrations. Liquids based on guar, can reach a significant viscosity. Depending on the concentration and shear rate - from 50 to 500 MPa·s at 100 s^{-1}; for cross-linking (crosslinking) - up to 1000-1500 MPa·s. They have a high degree of proppant retention in the suspended state.

They are based on mechanisms for modification (stitching). Guar solutions are cross-linked to increase their stability and load-bearing capacity. For example, Borane systems form mesh structures at pH 8-10 and are effective at temperatures up to 90-120 °C.

They are most sensitive to water quality. They are susceptible to bacterial infection, which can negatively affect the success of their work.

A comparative analysis of the quantitative parameters of the hydraulic fracturing fluids under consideration shows that guar gum based fluids provide significantly higher viscosity (50-500 MPa·s at 100 s^{-1}, with the possibility of reaching 1000 MPa·s when cross-linking) compared to polyacrylamide (20-150 MPa·s), which provides a greater load-bearing capacity.

At the same time, polyacrylamide shows the best performance in conditions of high temperatures (up to 170 °C versus 140-160 °C for guar) and high salinity of reservoir waters, where viscosity losses do not exceed 15%, while for guar they can reach 50 %.

A significant difference is the nature of degradation: guar is destroyed within 0.5-2 hours under the action of enzymatic breakers and leaves up to 200 mg/l of solid residues that can reduce the permeability of the formation. PAA requires more aggressive oxidizing agents and a time of 2-6 hours for destruction, but the residual deposits are much lower (<50 mg / l).

Therefore, guar gum is preferred for operations where maximum load-bearing capacity and control of proppant transport is required. It is advisable to use PAA in conditions of high temperatures and mineralization, as well as, if necessary, to minimize residual damage to the formation, which is most suitable for performing work on the Achimov formation, due to the extremely low permeability of the formation.

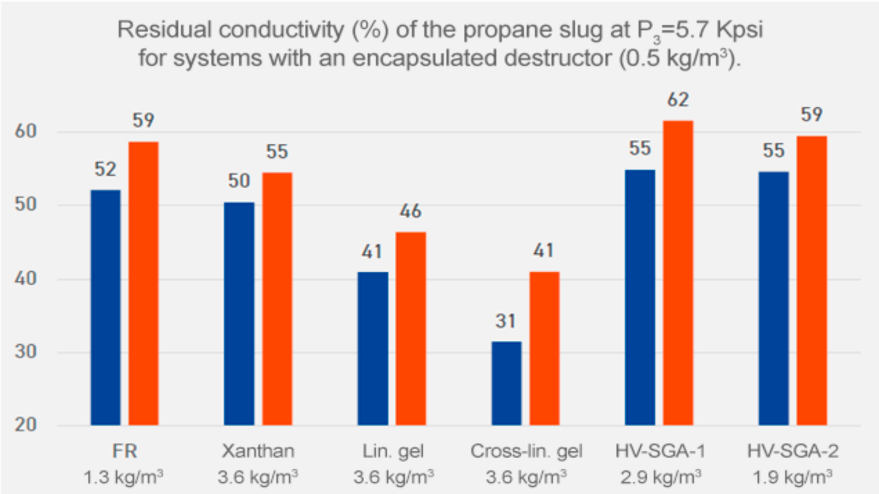

Fig. 3.1 Residual conductivity of the propane pack for different fluid systems

4 Simulation Results and Analysis of Fracture Geometry

Geomechanical modeling was performed to analyze the effectiveness of hydraulic fracturing in horizontal wells. In order to perform an analysis of the effectiveness of the operation performed, 2 types of fluids were used in the simulation: PAA and guar.

Modeling of the hydraulic fracturing process is performed by solving a system of equations that include:

The formation mechanical equilibrium equation:

$$\sigma_v > \sigma_H > \sigma_h > P_{frac} > \sigma_{min} \tag{4.1}$$

where σ_v is the vertical stress, σ_H is the maximum horizontal stress, σh is the minimum horizontal stress, and P_{frac} is the crack pressure.

The condition for crack opening is that the fluid pressure exceeds the minimum stress.

Elasticity equation for calculating the crack width:

$$w\left(x\right) = \frac{4\left(1 - \nu 2\right)}{\pi E} \int_{-L}^{L} \frac{p\left(\xi\right)}{x - \ \xi} d\xi \tag{4.2}$$

where $w(x)$- crack width at the point$x$, ν-Poisson's ratio, E- Young's modulus, $p(\xi)$- pressure along the crack.

Fluid filtration equation (Darcy's Law):

$$q = -\frac{k}{\mu L} \Delta P \tag{4.3}$$

where q is the filtration rate, k is the reservoir permeability, μ is the liquid viscosity, Δ P is the pressure gradient, and L is the length of the sample under study.

Equation of conservation of mass of liquid and propane:

$$Q_{inj} = Q_{frac} + Q_{filtr} \tag{4.4}$$

where Q_{inj} is the total volume of the injected liquid, Q_{frac} is the volume used to open the crack, Q_{filtr} and is filtration into the reservoir (losses).

To perform the simulation, inclinometry of newly drilled wells was taken. A schematic representation of the well profile is shown in Fig. 4.1.

In order to determine the optimal crack geometry, 75-ton and 90-ton injection simulations were performed for liquids based on polyacrylamide and guar gum, respectively. The difference in injection volumes is due to the fact that hydraulic fracturing using polyacrylamide achieves a large half-crack length compared to guar liquid. This difference is explained by the less pronounced pseudoplastic properties of polyacrylamide and the predominance of its viscoelastic characteristics.

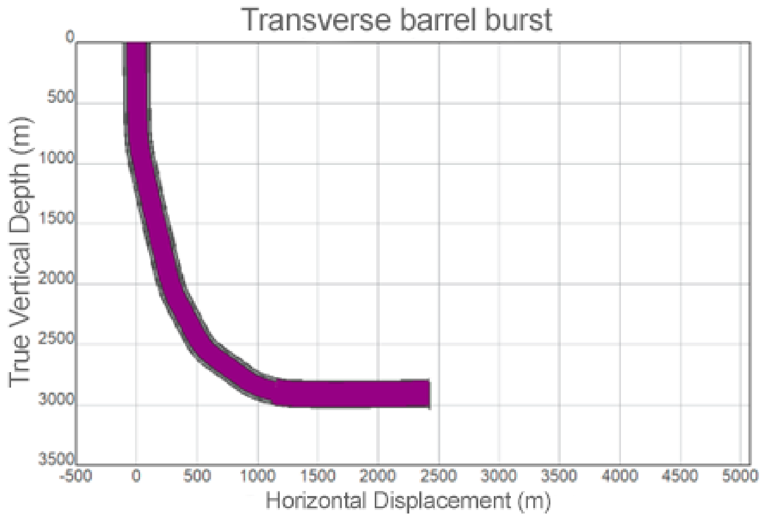

Fig. 4.1 Well profile X

The schedule of hydraulic fracturing before the main injection stage included the stages of information injection: substitution and mini-hydraulic fracturing. Carrying out these operations is mandatory, since it is necessary to replace drilling and process fluids remaining after the construction of the well with fracturing fluids. This ensures correct interpretation of geological conditions. Mini-hydraulic fracturing is performed for the purpose of injecting a test proppant pack, checking the quality of the hydrodynamic coupling of the well-formation system, and also for evaluating the passage of proppant through the hydraulic fracturing couplings.

Correct assignment of initial geomechanical parameters is a key condition for constructing a reliable hydraulic fracturing model [11]. Gamma-ray logging data were used to determine the elastic characteristics of the rock mass. The values of the Young's modulus, which determines the rock stiffness and has a direct effect on the crack opening value, were taken based on the results of core tests performed for the drilling area under consideration. The same principle was used to determine the values of the Poisson's ratio, which reflects the deformation properties of the rock.

The stress gradient, as well as the magnitude of the active mountain stresses, are calculated based on the interpretation of gamma-ray logging data using mathematical dependencies used inthe geomechanical simulator.

An important factor for modeling hydraulic fracturing processes is the convergence of efficiency and net pressure with statistical data for a given well area. An efficiency of 55% and a net pressure of 70 atm were assumed.

In order to correctly define the properties of hydraulic fracturing fluids, laboratory testing of guar-based fluids with a load of 4.0 kg/^{m3} and PAA fluids of 6.0 kg/^{m3}was performed.Coefficients n and k were determined for two types of fluids. The consistency index k physically reflects the viscosity of the fluid at a certain shear rate. The flow index n determines how the viscosity of the fluid changes when the shear rate changes.

The obtained values serve as initial parameters for mathematical modeling of the hydraulic fracturing process and allow us to correctly take into account the rheological features of working fluids when predicting crack opening.

The results of the simulation are reflected in a graphical representation in the form of a crack contour with an indication of the main geometric parameters in Fig. 4.2 and 4.3.

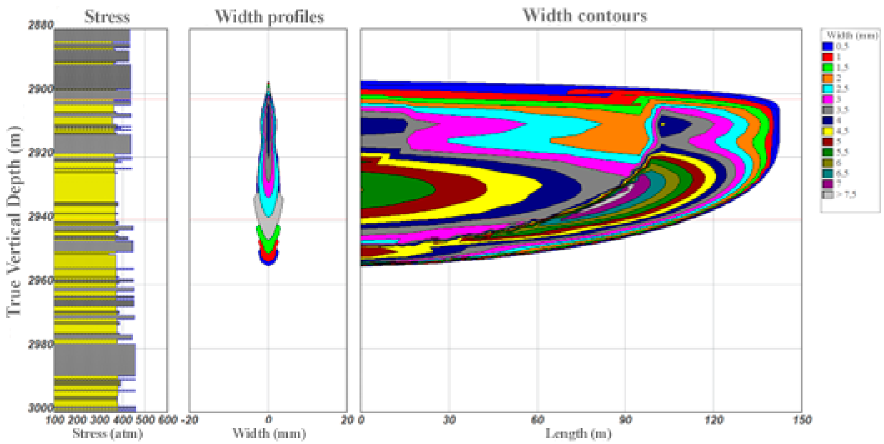

Fig. 4.2 PAA crack geometry

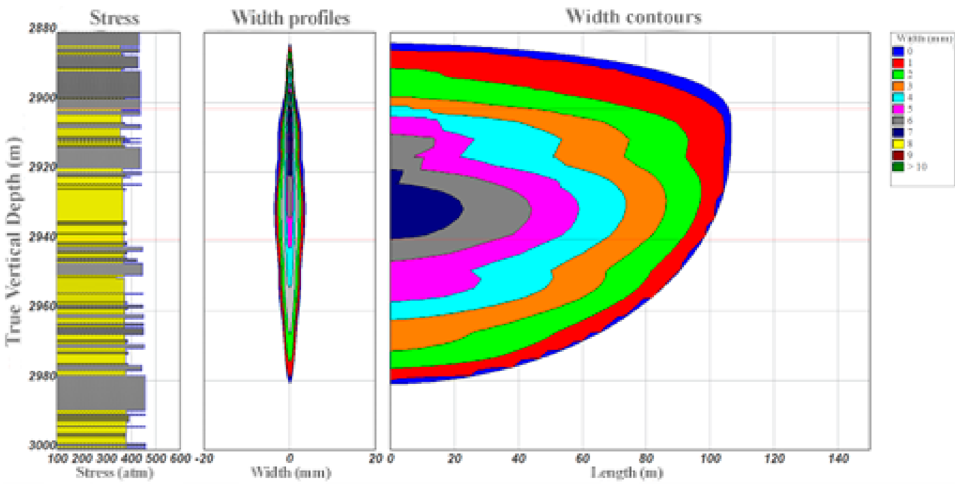

Fig. 4.3 Guar crack geometry

Analysis of the graphs of changes in the geometric parameters of the crack obtained during the simulation of the hydraulic fracturing process allows us to conclude that the rheological properties of the liquid significantly affect the formation of cracks. For a polyacrylamide-based liquid, the crack length increases by about 40% compared to a guar base. This observation indicates a significant role of viscoelastic characteristics of PAA in the processes of crack propagation and opening, which should be taken into account when designing hydraulic fracturing parameters.

Simulated hydraulic fracturing injection graphs are shown in Fig. 4.4 and 4.5.

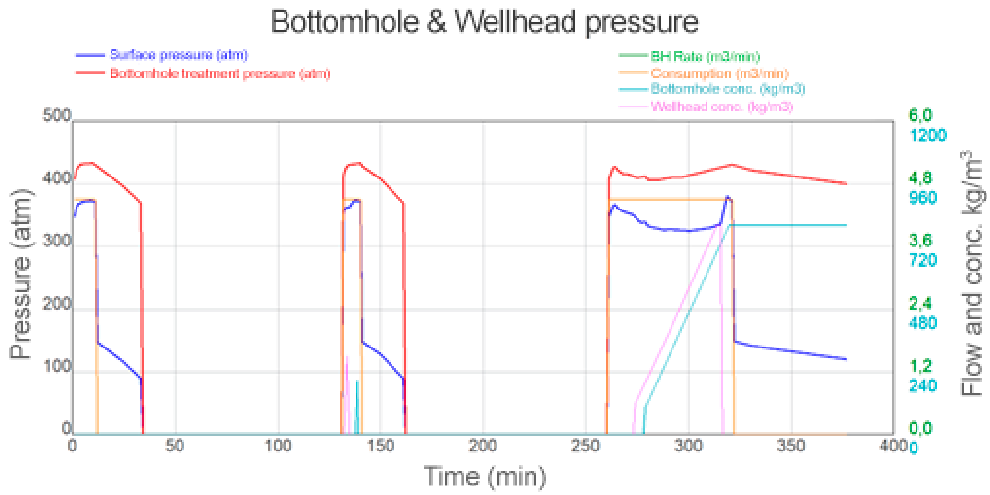

Fig. 4.4 PAA upload schedule

Analysis of injection wellhead pressure data shows a slight increase in pressure when using a polyacrylamide-based fluid. Thus, the wellhead pressure during the injection of PAA exceeds the parameters of guar liquids by about 10%. This difference is explained by the different nature of the working fluids: PAA is characterized by pronounced viscoelastic properties, which leads to increased flow resistance under the same hydrodynamic conditions.

Additionally, when using PAA, a larger flow rate of liquid is required, due to the need to form a crack of sufficient width to accommodatethe proppant of the planned fraction 16/20. Viscoelastic characteristics of PAA contribute to an increase in crack opening along the length and width, which directly affects the wellhead pressure and fluid flow. These results emphasize the need to take into account the rheological properties of the working fluid when designing hydraulic fracturing parameters and predicting the efficiency of proppant distribution in the crack [14].

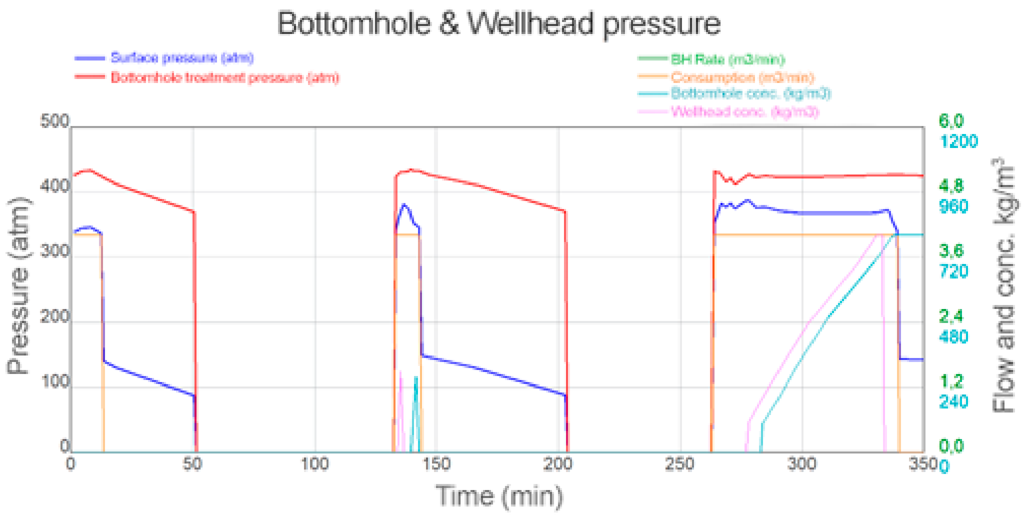

Fig. 4.5 Guar upload schedule

Summary data of the simulation results are shown in Table 4.1.

Thus, the simulation of hydraulic fracturing in a single well was performed using two different working fluids. Modeling was performed for various tonnages, in order to create optimal geometry and save money.

Analysis of the simulation results presented in Table 4.1 allowed us to draw the following conclusions:

1) with a 17% reduction in tonnage during hydraulic fracturing using polyacrylamide compared to guar gum, an increase in the half-length of the fixed crack is observed by 33 %. This indicator has a significant impact on the coverage of the drained area and, as a result, on the efficiency of well production. According to the principles of" Unified Hydraulic Fracturing Design " by Michael Economidis, in low-permeable formations, the greatest contribution to development is made by the half-length of the crack;

2) the hydraulic height of the crack created during the injection of PAA is 40% lower compared to the use of guar liquid. This fact demonstrates the importance of using polyacrylamide at sites where it is critical to prevent breakthroughs in aquifers. At the same time, the fixed crack height practically does not change;

3) the use of guar gum contributes to the formation of wider cracks both at the trunk and in the productive zone. The obtained result confirms that PAA mainly contributes to the formation of longer cracks, which is consistent with its viscoelastic properties.

4) the results obtained for calculating the dimensionless crack conductivity are 40% less than the results obtained for guar. According to the principles of "Unified Hydraulic Fracturing Design" by Michael Economidis, this fact has a positive effect on the dimensionless well productivity index Jd. According to Economidis,". As can be seen from Fig. 4.6, for any values of the number of dimensionless proppant N_p, the maximum productivity index is achieved with a strictly defined dimensionless crack conductivity. Since the given proppant number represents a fixed volume of proppant reaching the productive horizon, the best compromise between length and width is achieved with a dimensionless crack conductivity located near the peak of individual curves".

Achimov deposits are characterized by low permeability and complex clay-siltstone composition. In such conditions, the ability of the working fluid to create extended cracks to ensure drainage of the reservoir, as well as to leave minimal damage to the formation by polymer residues, is critical.

Table 4.1 Summary results of the conducted simulation

Parameter	PAA	GUAR parameter	Percentage of change in PAA/Guar
parameters Injection tonnage, tn	75	90	-17%
Volume of injected mixture, m3	358.55	396.32	-10%
Injected fluid volume, m3	332.47	363.03	-8%
Fluid loss volume, m3	201.53	146.64	37%
Burst fluid efficiency, %	0.43792	0.63	-30%
Net burst pressure, atm	48.769	23.423	108%
Maksim. crack width in the perforation zone, mm	11,972	15,633	-23%
Average hydraulic crack width, mm	8,6124	11,398	-24%
Crack length-created, m	142.4	107.33	33%
Crack length-fixed, m	141.56	106.46	33%
Crack height-average, m	47,701	78,42	-39%
Fixed height (product. zone) - average, m	36,529	37,249	-2%
Fixed width (well) - average, mm	4,9688	6,8251	-27%
fixed width (product. zone) - average, mm	3,658	4,1159	-11%
Concentration / Area (Frac) – Average value per EOJ, kg/m^2	5,427	5.32	2%
Concentration/area (product. zone) – Average value at closing, kg / m^2	6,398	7,1033	-10%
Crack conductivity (product. zone) – Average value. at the close, mD·m	1027.5	1258.9	-18%
Unadjusted. crack conductivity (product. zone),	6.0484	9.8538	-39%
beta, $atm\text{-}c^2/g$	0	0	-
Total filtration coefficient, Darcy	277.9	272.08	2%

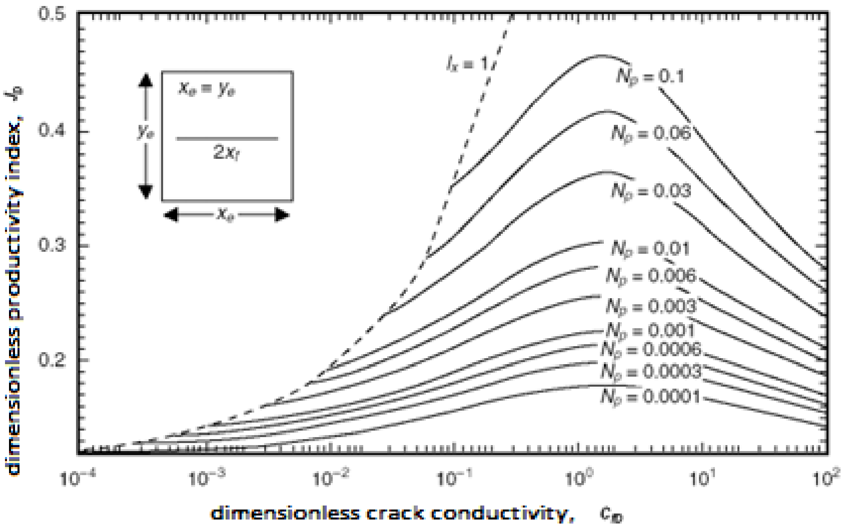

Fig. 4.6 Dimensionless productivity index as a function of dimensionless crack conductivity

5 Conclusions

The conducted study confirms that the type of fracturing fluid has a decisive influence on fracture geometry, conductivity, and overall hydraulic fracturing efficiency in low-permeability reservoirs.

Polyacrylamide-based fracturing fluids enable the creation of longer fractures with reduced height growth, which is particularly advantageous for reservoirs with a high risk of water breakthrough and extremely low permeability.

Although guar-based fluids provide higher fracture width and conductivity, their application is associated with increased residual damage due to incomplete polymer degradation.

The dimensionless fracture conductivity obtained for PAA systems is closer to the optimal values required to maximize the well productivity index according to the Unified Hydraulic Fracturing Design methodology.

For Achimov-type deposits and similar low-permeability formations, polyacrylamide-based fluids can be considered a preferable solution, allowing optimization of hydraulic fracturing parameters, reduction of formation damage, and improvement of oil recovery efficiency.

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