Journal of Geotechnology and Energy | vol. 38 | no. 2 | 2021 | pp. 15–24

https://doi.org/10.7494/jge.2021.38.2.15

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ELEMENTS OF RESERVOIR SIMULATION FOR TIGHT GAS RESERVOIRS WITH WATER INFLUX

Date of submission:
28.06.2021

Date of acceptance:
29.06.2021

Date of publication:
31.08.2021

https://journals.agh.edu.pl/jge

Abstract: At present, gas obtained from unconventional deposits plays an important role in the global economy as an energy factor. The simulation of the exploitation of this type of deposits is very complex and requires an individual approach for each case, which is extremely inspiring and interesting, therefore this article attempts to deal with the problem of modeling the extraction of natural gas from tight unconventional deposits. Extraction of tight gas requires the use of measures that stimulate this process and requires an unusual approach both at the stage of deposit recognition, its drilling and exploitation. Using computer programs, more and more accurate models are developed taking into account almost all known processes occurring in the deposits during exploitation, which significantly influences the better selection of parameters of wells and operations that intensify the production, and thus improves the results of exploitation.

Keywords: tight gas, reservoir simulation, water influx, hydraulic fracturing

1. Introduction

Crude oil and natural gas are energy resources of tremendous economic and political importance, both for highly developed and poor countries, which have these raw materials in quantities that allow them to create a market, as well as for countries that do not have hydrocarbon resources or have small amounts at their disposal. Therefore, over time, new gas deposits are sought in structures that were previously not of interest. Both during the exploration and their subsequent exploitation, there are problems that must be defined and solved. Therefore, over the years, the following deposits have been distinguished, i.e. the natural accumulation of hydrocarbons in the rocks as: conventional, i.e. those that can be exploited through boreholes without additional technical and technological treatments aimed at intensifying extraction, and unconventional ones – requiring specialized treatments and an individual approach, without obtaining the raw material would be insignificant, and thus unprofitable [1].

Among the terms that have emerged in connection with the search for gas in unconventional structures is the term “closed gas”. The term is commonly used to refer to structures with low permeability in which natural gas is trapped. In the 1970s, the concept of tight gas was defined and standardized by the government in the United States. The US Natural Gas Policy Act (NGPA, Public Law 95–621) of 1978 classifies tight gas fields as structures with a permeability of less than 0.1 mD. This definition, according to the sources, was a political definition and was used to determine which wells would receive federal and/or state tax credits for gas production. Today, this definition is a function of many physical and economic factors. Another definition of tight natural gas deposits, which is considered the best at present, is the definition of gas tight in a rock structure, and its extraction is not possible on an economically justified level without performing intensification procedures, such as e.g. hydraulic fracturing. Additionally, it is justified to make horizontal holes, including branched wells [2].

In order to properly classify a newly discovered natural gas deposit, it is necessary to characterize the deposit parameters. Important geological parameters that should be investigated and determined for the stratigraphic unit in question include: the spatial arrangement of the deposit, the type of genetic facies, textural maturity, mineralogy, diagenetic processes, dimensions of the structure and the occurrence of natural fractures in the rock. One of the most difficult parameters to evaluate for a tight gas field is the size and shape of the drainage zone. These types of structures show constant pressure disturbances even after long periods of operation (months or even years). When the drainage zone takes an oblong shape, it may indicate the presence of natural fractures in the rock or the presence of hydraulic fractures during the treatment. The drainage zone in this type of deposit largely depends on the number of drilled holes and the number, method and quality of fracturing treatments. The pressure and temperature rise are abnormally high due to the considerable depth of the gas-bearing layers. Other important parameters strongly related to the petrophysical description of the deposit are: rock porosity and permeability. From the point of view of tight gas deposits, it is important that the pore space distribution in the deposit rock is largely regular, and the porosity in this type of sandstone usually ranges from 2% to 12% [3]. Pores are usually poorly connected, which is caused by numerous diagenetic processes generating, for example, an increase in quartz, which in turn significantly impedes gas exploitation, as well as easy gas flow to the borehole. For this reason, the permeability of these rocks also reaches low values, which causes a rapid drop in extraction during exploitation. Natural cracks in the rock structure are a positive aspect that enables the exploitation of tight gas. Moreover, rocks forming tight gas deposits are usually thicker (in the order of several hundred meters) than those of conventional deposits.

Saturation of the deposit rock with bound water is another important parameter in the process of identifying and modeling hydrocarbon extraction from a tight gas deposit. There are several problems with the analysis of this parameter. In the first place, bound water saturation in rocks of this type is usually quite high, although it can vary depending on the type of rock, and is also irreducible [4]. Sandstones, classified as conventional formation rocks, exhibit an irreducible bound water saturation of between 15% and 20%. Compact gas-bearing sandstones have higher water saturation values – approx. 40%, and thus also a higher capillary pressure. On the other hand, for example, shale and siltstones show the highest irreducible water saturation – over 60% and thus high capillary pressure. Compact gas-bearing sandstones, despite high water saturation, often still accumulate gas that is “free” of water. This property plays a particularly important role when the gas-saturated part of the bed is accompanied by a water-saturated zone. Depending on the size of this zone, the amount of water saturation of the deposit rock, the wettability of the rock surface with water, the surface tension at the phase boundary, as well as the amount of hydraulic resistance of water flow in the analyzed porous medium, the inflow of water to the deposit poses a potential threat to the mining process. This zone may occupy most of the deposit, leading to the movement of water in the direction of the borehole, resulting in the formation of, for example, a water cone. In order to avoid or limit the consequences associated with this unfavorable phenomenon, reservoir engineering is to determine the maximum efficiency for which gas is exploited without water (the fluid flow towards the well is single-phase) [4].

2. Method section

To create the base simulation model, the author used the CMG GEM (GEM – Generalized Equation of State Model) software – a compositional simulator (in the academic version) operating on the basis of an adaptive implicit scheme developed by Thomas and Thuranau and Collins et al.

The construction of the batch file began with the determination of the area of an exemplary deposit. At this stage, the author did not have data from the real deposit. The assumed area of the deposit is a 1500 m × 1500 m saturated with high-methane gas. The assumed thickness of the structure saturated with gas is 40 m, and the zone saturated with the underlying water has a thickness of 30 m. It was assumed that the structure was homogeneous. The assumed depth of the top of the deposit is 4500 m, and the depth of the aquifer is 4540 m. The temperature of the deposit was set at 60°C, while the initial pressure was set at 50 MPa. This pressure is 10% higher than the hydrostatic pressure, which is a phenomenon characteristic of tight gas deposits (anomalously high reservoir pressure) [3]. One of the initial elements defined in the batch file creation phase in Builder is to define the dimensions of the block grid for the subsequent calculation process. The correct selection of the mesh is an extremely important element, as it determines to a large extent not only the accuracy of the results, but also the possibility of creating calculation variants. Considering the time-consuming nature of the simulation, the number of blocks should be minimized (the CMG GEM academic license, which was used to carry out this part of the work, allows to create a maximum of 1000 blocks), which in turn maximizes their dimensions to meet the initial assumption of the dimensions of the deposit. On the other hand, smaller block dimensions give more accurate calculation results, which is of particular importance when analyzing, for example, hydraulic fracturing of boreholes and determining the impact of deposit water activity on the course of exploitation. Therefore, in the base model, the dimensions of blocks in the X-Y plane were assumed to be 50×50 m. The vertical dimensions of the blocks were varied so that the smallest dimensions were closest to the gas-water contour, which will allow for more accurate results regarding the amount of water flowing into the deposit from the aquifer during the simulation. Such assumptions led to the separation of 7 layers in the model (Tab. 1). The model uses a Corner Point mesh. Keeping the area of the modeled deposit area assumed at the beginning, the number of blocks in each direction is arranged as follows: in the x-axis direction – 30, in the y-axis direction – 30, in the z-axis direction – 7, blocks equal to 6300. For the entire model, a constant value of porosity equal to 6% and the horizontal permeability – 0.05 mD, while the vertical permeability was adopted at the level of 10% of the horizontal permeability.

Table 1. Comparison of the thickness values of individual layers of the simulation model

Layer	Volume [m]
1	15
2	10
3	10
4	5
5	5
6	10
7	15

Another section defined in the process of creating the simulation model is determining the parameters of the reservoir fluid. A simplified gas-water model was adopted. The values of individual parameters are collected in Table 2, while the remaining ones needed calculations that were generated using correlations that are part of the software used.

Table 2. List of values of PVT model parameters

Parameter	Value	Unit
Temperature	60	[°C]
Gas den sity	0.697	[kg/m^3]
Water density	1075	[kg/m^3]
Water volume coefficient in relation to initial pressure	1.02395	[–]
Water compressibility ratio	$4.62 \cdot 10^{-7}$	[1/kPa]
Pressure at standard conditions	101.325	[Kpa]
Water viscosity	0.421	[cP]

An important part of the model is the preparation of phase permeability plots. In this case, they were created based on the two-phase gas-water correlation in moderately wettable sandstone with interfacing. The assumed values of characteristic points are presented in the diagrams Figure 1.

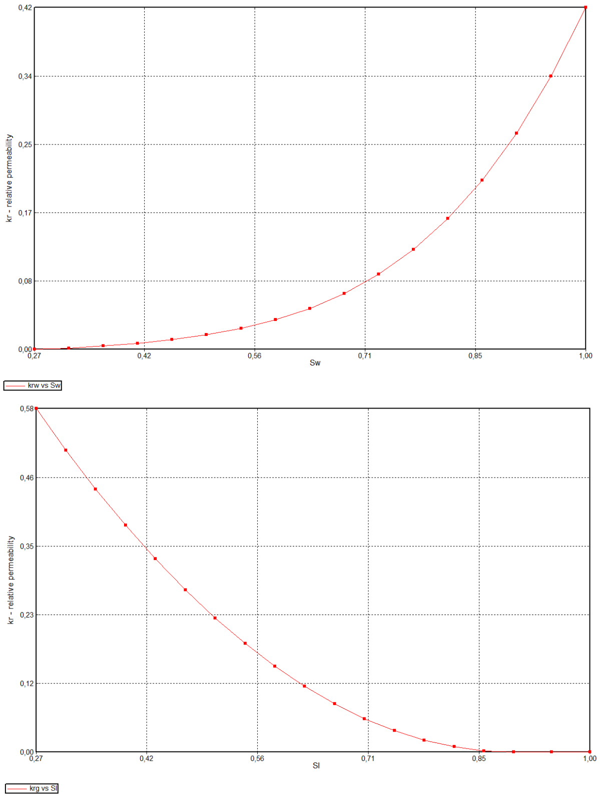

Fig. 1. Relative permeability curves as a function of fluid saturation

For all variants, it was assumed for comparison that the gas would be operated with a maximum initial expenditure of 150,000 nm^3/day. The operating time was assumed to be 30 years, with a time step of one year.

3. Results

The created base model was used to generate various exploitation variants. In the calculations, the author analyzed the following variants: mining with a vertical, horizontal well (and within these variants, the impact of the location of the well in the deposit and the available volume of the deposit were analyzed), as well as mining with a hydraulically fractured vertical well and a horizontal well-fractured well. In the variants with the use of the fracturing treatment, not only the impact of the location of the borehole or the available thickness was examined, as in the case of without the use of fracturing, but also the impact of individual fracturing parameters on the operation process, as well as the impact of the initial size of the drilling expenditure on gas and water production over time.

For the assumed variants, a simulation of the course of reservoir fluid extraction was carried out in order to compare the effectiveness of the operation of a vertical and horizontal well, to evaluate the effectiveness of the hydraulic fracturing treatment, as well as to analyze the impact of well parameters such as: well depth, deposit thickness made available by the well, as well as fracturing parameters such as such as the fracture permeability, the length of the fracture wing (impact range) or the number of fractures made in the case of horizontal wells On the basis of the simulations, the most interesting aspect was the influence of hydraulic fracturing parameters on the exploitation process, therefore the results obtained for this variant will be presented in the further part of the article.

3.1. Horizontally drilled horizontal wells

For a horizontal well fractured several times, the impact of changes in the length of the fracture wing, permeability and the number of fractures in the horizontal section on the mining process was analyzed. The calculations assume the length of the fissure wing (for x: 50; 100; 150; 200; 250 m) and the permeability (k: 1; 5; 10; 20; 50 D), but also the number of gaps: 5; 8; 10; 12. The following parameter values were adopted in the reference model: number of gaps equal to 10, wing length x_{ref} equal to 150 m and permeability k_{ref} 5 D.

In order to improve the quality of the calculation results, the author adapted the block grid. The dimensions of the blocks 25×25 m were assumed closest to the well, and as they moved away from the well, the dimensions were doubled, resulting in a deposit area of 1100×2800 m, which gives the number of blocks equal to 6.426. Simulating only one wing of the slot. Such a procedure allows to obtain a larger impact zone of the well and more accurate simulation results, and due to the symmetry running along the horizontal section of the well, which is 1000 m, the obtained results of the quantity of extracted formation fluids can be multiplied by two, obtaining the same results as for the operation of both wings Figure 2.

The first analyzed parameter was the distribution of hydraulic fractures in the stimulated zone. On the basis of the analyzed variant results, it was found that the number of hydraulic fractures made should be selected in such a way as to ensure effective drainage of the stimulated zone, while avoiding overlapping zones of adjacent fractures. Planning too many fractures in close proximity causes the parameters of the fracturing treatment to deteriorate.

Figure 3 presents the profiles of efficiency and total gas extraction for the proposed variants, while Figure 4 presents changes in water extraction depending on the variant. Based on the charts and results presented in Table 3, the following relationship was observed: with the increase in the density of hydraulic fractures, the production of natural gas and water increases, and the increase is greater for water. In the case with the smallest number of fractures, gas production is 7.2% lower than in the reference variant (10 fractures), while for water it is 31.41% lower. For the variant with the largest number of fractures, gas production increased by only 2.92%, and water by as much as 47.01%. As can be seen from diagram Figure 3, the impact of the arrangement of the fractures is of key importance on the production of gas in the initial stage of exploitation, then the greatest differences in expenditure are observed, moreover, the greater the number of fractures, the longer the production remains with the given initial expenditure. However these differences then fade away. The opposite is true, however, in the case of extracted water, in the first years of exploitation the amount of extracted water is similar in each variant, and the greatest differences are observed in the last year of extraction.

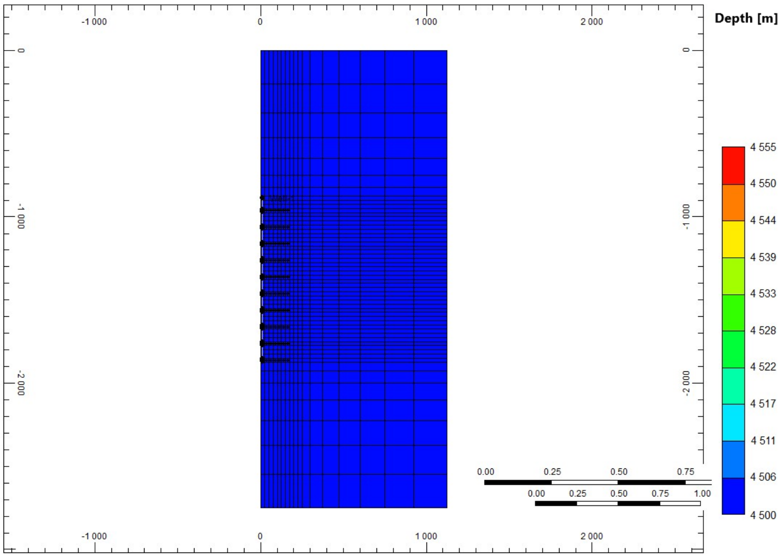

Fig. 2. Location of the horizontal well along with hydraulic fracturing in the model – reference model

Table 3. Summary of the results of the analysis of the influence of the number and distribution of hydraulic fractures on the course of exploitation

Number of hydraulic fractures	Total gas extraction $[10^6\ m^3]$	Difference in extraction relative to reference values [%]	Total water extraction $[10^3\ m^3]$	Difference in extraction relative to the reference value [%]
5	1973.44	−7.20	31.27	−31.41
8	2093.2	− 1.57	44.6	−2.16
10	**2126.6**	–	**45.58**	–
12	2188.6	2.92	67.01	47.01

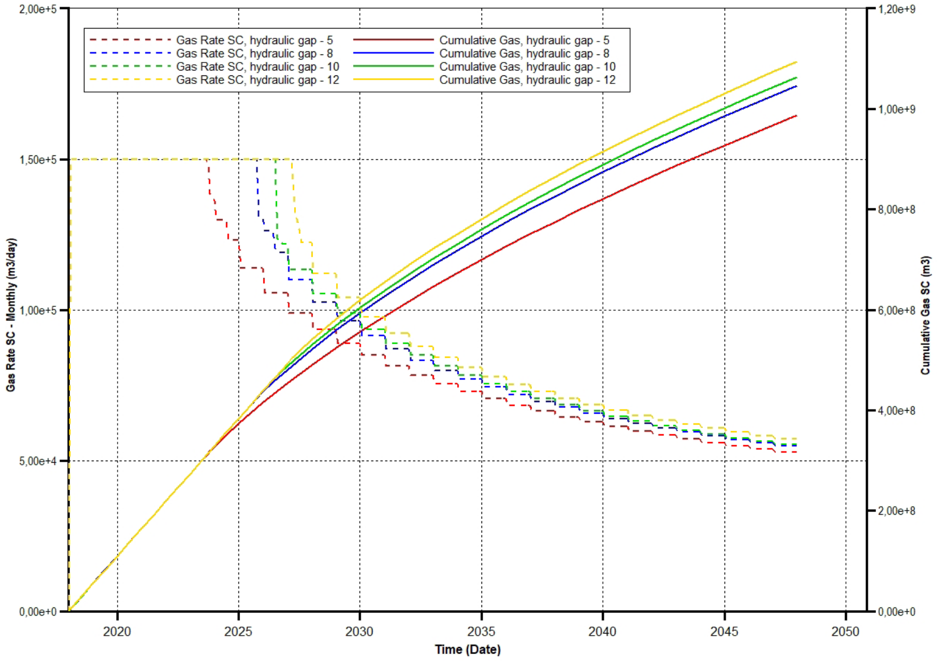

Fig. 3. Profiles of efficiency and total gas production depending on the number of hydraulic fractures (green – base value)

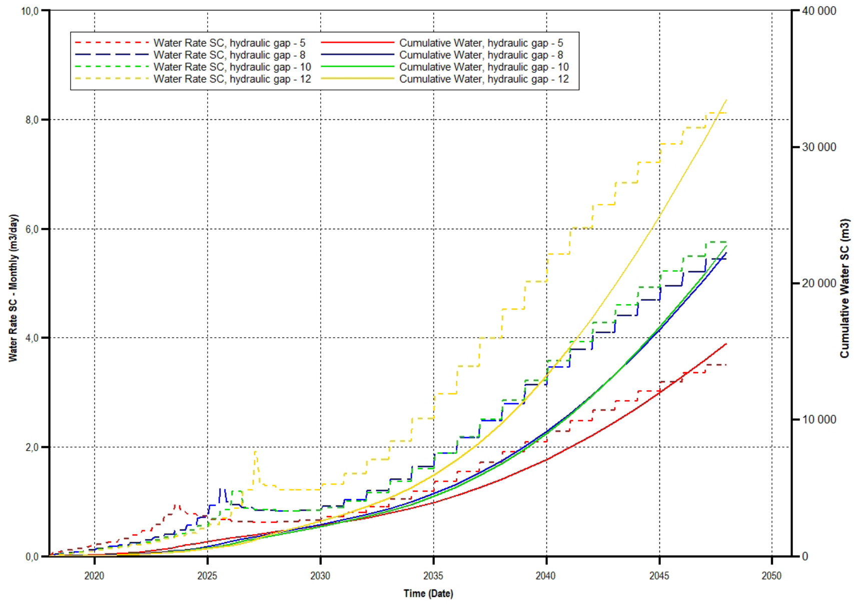

Fig. 4. Performance and total water extraction profiles depending on the number of hydraulic fractures (green – base value)

Another important parameter influencing the efficiency of hydraulic fracturing is the range of impact of this treatment. As part of this analysis, five fissure wing lengths were examined. The assumed range in this case was between 50 and 250 m with a step of 50 m. The simulation results are summarized in Table 4 and in the graphs Figures 5 and 6 on the basis of which it was found that the production of gas and water from the deposit increases with the increase of the wing length. The longer the range of the slot wing, the longer the initially assumed gas flow is maintained. The differences in the flow of gas and water over time depending on the variant are similar to the arrangement of the slots in the well.

Table 4. Summary of results of the analysis of the impact of the range of hydraulic fractures on operation

Range of the hydraulic gap wing x_{hf} [m]	Total gas extraction [10^6 m^3]	Difference in extraction relative to reference values [%]	Total water extraction [10^3 m^3]	Difference in extraction relative to reference values [%]
50	1823.16	–14.27	41.53	–8.89
100	1987.78	–6.53	49.18	7.90
150	**2126.6**	–	**45.58**	–
200	2251.6	5.88	39.33	–13.72
250	2380.6	11.94	33.78	–25.90

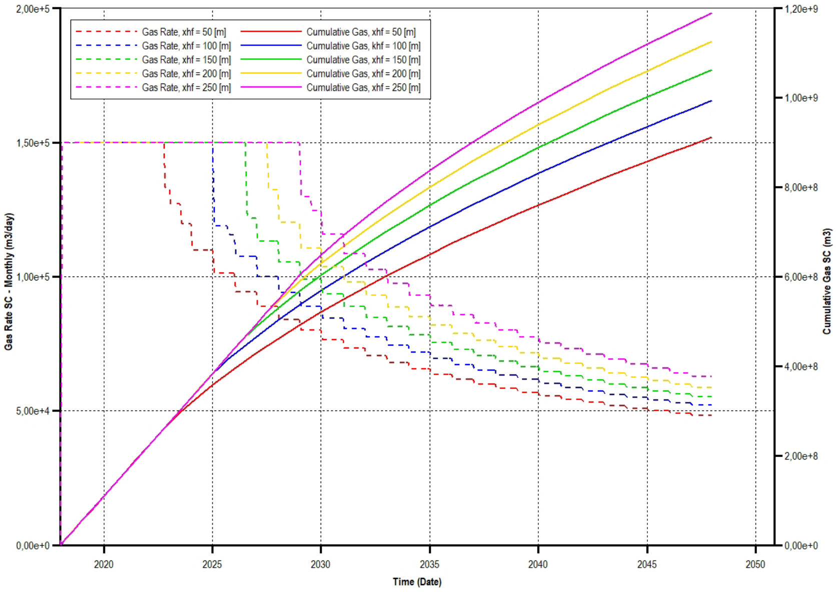

Fig. 5. Profiles of efficiency and total gas extraction depending on the range of hydraulic fractures in the range of 50–250 m (green – base value)

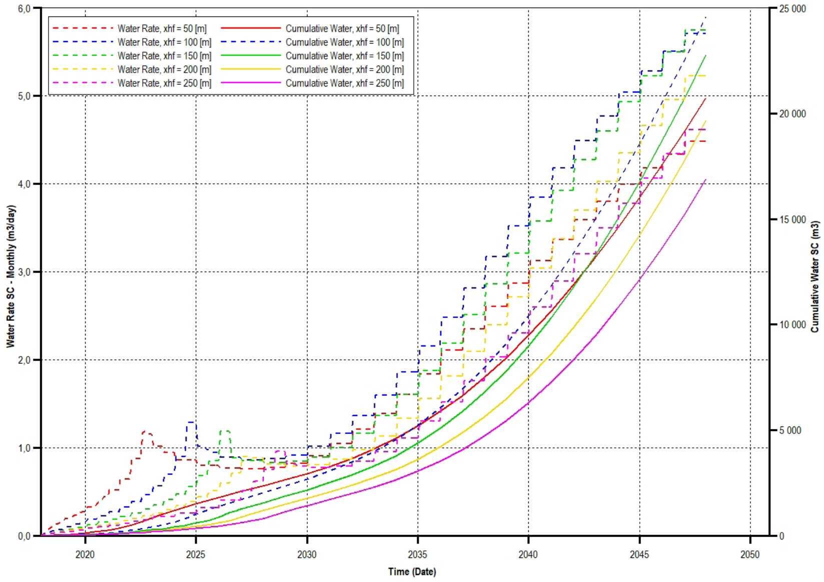

Fig. 6. Performance and total water extraction profiles depending on the range of hydraulic fractures in the range of 50–250 m (green – base value)

Analyzing the impact of hydraulic fracture permeability on the work efficiency of the well on basis of the obtained simulation results collected in Figures 7 and 8 as well as in Table 5, it can be concluded that it is much smaller than in the case of changes in the length of the fracture wing. There is a slight increase in gas extraction of, only 8.02%, with the fracture permeability of 50 D. However, it plays a significant role in the amount of water extracted. For the same case, an increase in water extraction by 142.57% compared to the reference variant was observed. The best fluid-conducting capacity of hydraulic fractures is generated at the beginning of the service life, then the gas and water supply is the most intense, so at this time the fractures with the highest permeability will be able to deliver fluid to the well with sufficient capacity, but at a later time the difference between reservoir rock permeability and the hydraulic fracture permeability is so great that even fractures with weaker permeability will be able to deliver fluid to the wellbore with a sufficient flow. Therefore, the design of fractures with high permeability is unjustified in the context of the entire operation.

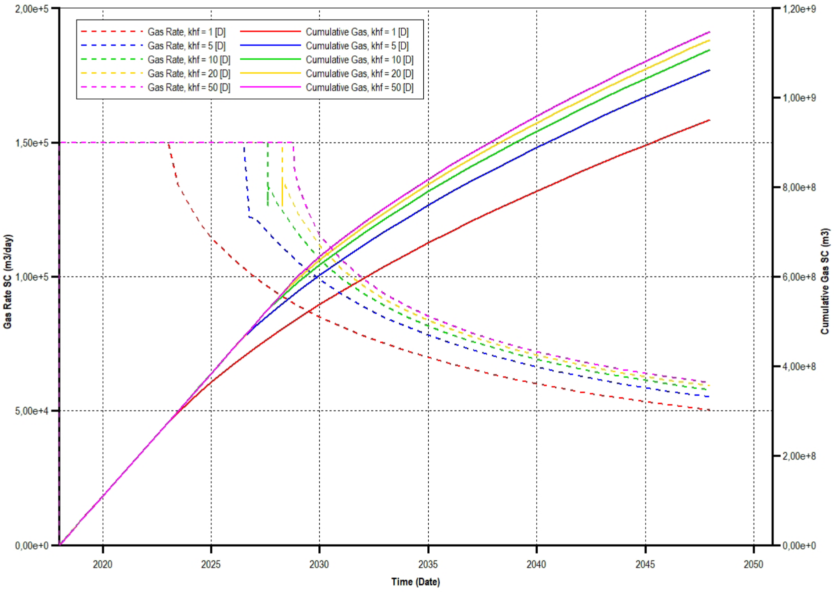

Fig. 7. Performance and total gas extraction profiles depending on the permeability of hydraulic fractures in the range of 1–50 D (blue – base value)

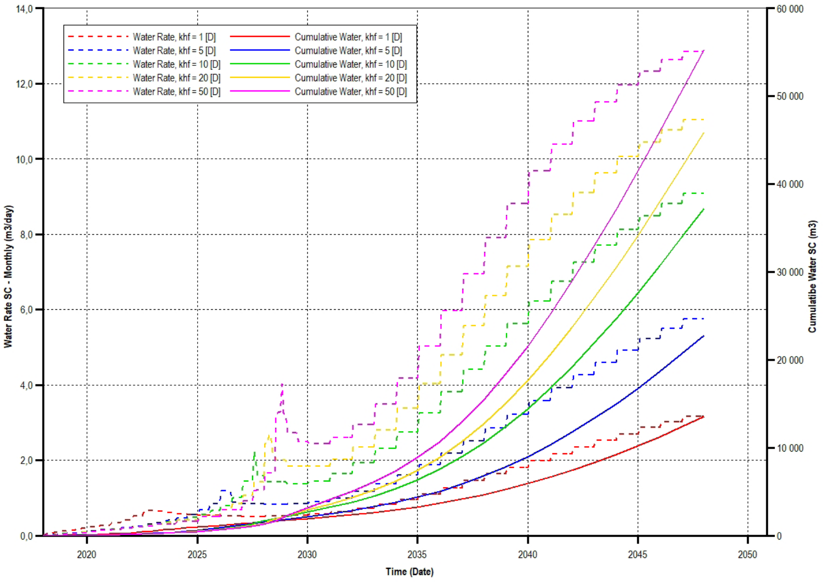

Fig. 8. Performance profiles and total water extraction depending on the permeability of hydraulic fractures in the range of 1–50 D (blue – base value)

Table 5. Summary of the results of the impact of the hydraulic gap permeability on operation

Permeability of hydraulic fractures k_{hf} [D]	Total gas extraction [10^6 m^3]	Difference in extraction relative to reference values [%]	Total water extraction [10^3 m^3]	Difference in extraction relative to reference values [%]
1	1901.02	−10.61	27.05	−40.66
5	**2126.6**	–	**45.58**	–
10	2214.4	4.13	74.51	63.47
20	2260.4	6.29	91.84	101.48
50	2297.2	8.02	110.57	142.57

4. Discussion

The article presents a simulation model which is a numerical image of a fragment of an exemplary deposit with petrophysical parameters characteristic of a tight gas structure. The parameter values were adopted based on the collected literature. Additionally, the author defined the underlying layer in the base model. The author performed calculations for the variants mentioned in the article.

When designing a hydraulic fracturing treatment, basic parameters are selected such as: the range of the fracture wing, fracture permeability, and for a horizontal well, additionally the location of fractures on the horizontal section of the well. Therefore, the impact of changing individual parameters on the production was assessed. The analysis of the obtained results of the total gas production after 30 years of operation shows that the longer the fracture wing, the greater the production, but this relationship is true only up to a certain upper limit of the fracture length, different for different variants (depending on the location of the well in relation to the aquifer and the available thickness). This is due to a significant difference in the parameters of the zone covered by fracturing and the rest of the deposit, and the selection of better and better parameters of this treatment does not give the desired effects, because the gas flowing between the narrow fractures is not able to replenish the zone near the well so quickly. This leads to a sharp drop in pressure at the wellbore and, consequently, to cessation of operation until the pressure is rebuilt. The same is also true of gap permeability. The greater the permeability of the fracture, the more gas is able to flow into the well in a shorter time. However, the improvement of the gas flow conditions covers only the area of the fracture range and in the case of the analysis of this parameter, the rapid pressure drop, which was also observed in the fracture wing length analysis, is even more visible with the increase in fracture permeability. In some embodiments, this led to such a large pressure difference between the bed and the zone around the wellbore that operation was only possible for a few days. The relationship is also true for the number of slots in a horizontal well, but in this case, when selecting an appropriate variant, the interaction of individual slots should be taken into account. If the gaps are located too close to each other, the effects of this treatment overlap. Such a solution has the opposite effect, leading to a deterioration of the operating results. In addition, the implementation of each additional gap generates a greater cost of the entire procedure.

Another aspect considered in the article was the amount of water flowing into the well. As for gas, the volume of water extraction is influenced by individual fracking parameters. The selection of appropriate fracking parameters and the location of the well in the reservoir can be the basis for limiting water extraction from the reservoir and preventing the formation of water cones.

5. Conclusion

To sum up, the specificity of tight gas deposits requires an individual approach to each newly discovered deposit at the stage of its modeling. The use of mining intensification procedures significantly complicates this process, however, it is necessary to obtain satisfactory results, as evidenced by both industrial practice and the obtained research results. Observing the behavior of the constructed deposit model when a horizontal well is operated with a fracturing treatment performed, it can be concluded that the most effective operation is a well with average parameters such as those adopted in the reference model, providing a small deposit area that will be exhausted as much as possible. At the same time, an appropriate network of wells should be created, which will have a slight interaction with each other, thanks to which effective gas extraction from the deposit will be achieved.

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