

Research article

Simulation of water coning phenomenon and effective factors on it using ECLIPSE simulator

Ali Rahmani¹, Mojtaba Rahimi^{1,2*}, Yahya Sanjoory¹

¹ Department of Petroleum Engineering, Kho.C., Islamic Azad University, Khomeinishahr, Iran

² Stone Research Center, Kho.C., Islamic Azad University, Khomeinishahr, Iran

mrahimi@iau.ac.ir; rahimi2726@gmail.com

(Manuscript Received --- 31 Dec. 2023; Revised --- 09 Apr. 2024; Accepted --- 12 May 2024)

Abstract

One of the major and important problems in the production of oil and gas from reservoirs is unwanted water production. Fluids tend to flow through highly permeable areas. The problem of water production is very acute, especially in reservoirs with active aquifers. Furthermore, this problem in oil wells not only increases the cost of separating water from oil and the cost of repairing and maintaining surface equipment but also causes oil production to stop in much worse cases. Due to the current conditions of some oil production wells, the problem of water production will increase in the future. Therefore, studying the factors effective on water coning and finding ways to manage and control it is one of the main objectives of this research. In this regard, by simulating an oil reservoir located in the south of Iran that has a water production problem, the field model is simulated with the help of reservoir simulation software, ECLIPSE. First, the phenomenon of water coning and its effective factors in the oil reservoir are investigated, and then, to better investigate the factors affecting the coning phenomenon, sensitivity analysis is performed on various parameters. The following results were obtained according to the simulation: 1) As the density of oil increases, the phenomenon of water coning occurs faster, 2) Increasing the thickness of the oil permeable zone is an important factor in preventing the occurrence of the phenomenon of coning, 3) With the increase of oil production flow rate, the time of occurrence of water coning phenomenon decreases, 4) The time of occurrence of this phenomenon strongly depends on the vertical permeability of the reservoir, and 5) In presence of a fracture, the probability of rapid occurrence of the coning phenomenon is much greater.

Keywords: Reservoir simulation, Water coning, Water production, ECLIPSE

1- Introduction

In most oil and gas reservoirs, as the production continues, the water and gas existing in the aquifer and the gas cap move towards the wellbore in the shape of a cone because of the disruption of the balance between gravitational, capillary, and viscous forces. As a result of this, water and gas will simultaneously be

produced with the oil. Water production is one of the chief problems in the production of oil and gas from reservoirs. Fluids have a high tendency to flow through areas that have high permeability. The existence of these areas is completely common due to the natural heterogeneity of reservoirs, which also plays a key role in water coning (Fig. 1) [1-3].

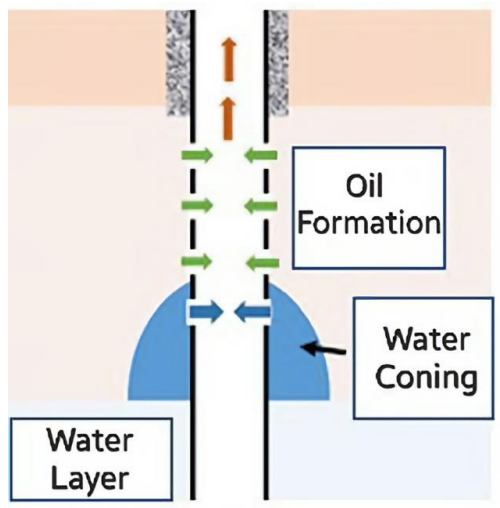


Fig. 1 A sketch of the water coning phenomenon in an oil reservoir [1].

As can be observed in Figs. 1 and 2, the coning phenomenon in oil and gas reservoirs mostly occurs by water and gas cap drive; water and gas enter the wellbore from the bottom and top sections of the perforated area, causing problems in the well, the reservoir, and the wellhead facilities. If a well faces this problem, its production will be impacted and production costs will rise; and the useful life and the production of the well will decrease [4]. What causes the coning phenomenon is the additional pressure gradient that exists in the wellbore. This additional pressure gradient can be the result of producing flow rates higher than the critical flow rate, leading to a rise in oil-water contact (OWC) level and a decline in gas-oil contact (GOC) level towards the perforated area. A potent aquifer and high vertical permeability can also further contribute to the coning phenomenon [5].

Coning is one of the most common problems in hydrocarbon production from reservoirs of Iran, particularly fractured reservoirs. The negative effects of this problem can be countered via several methods, such as the reduction of

production flow rate, relocation of production interval, well shut off, drilling horizontal wells, dual well completion, and using polymer gels [6-8].

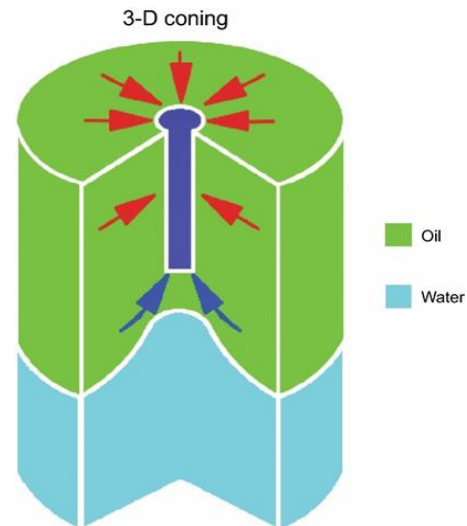


Fig. 2 A 3D sketch of the water coning phenomenon [1].

The water produced as a result of coning contains chemicals and metallic compounds. It is of extreme salinity and is also polluted with petroleum chemicals which have detrimental impacts on the environment. The results of the relevant studies show that this wastewater is a main threat to the environment in the area, leading to seawater pollution, soil pollution, and further aftermaths. To control and abolish the destructive impacts of the activities of the petroleum industry and wastewater production in the area, it is essential to apply environmental considerations to the processes, purchase or design efficient equipment, utilize thermal methods, use foam injection procedures to ward off wastewater, use water injection procedures to increase pressure, and overall launch projects aiming to repair damages and cleanse the environment [9].

In this research, we endeavor to analyze the effective methods suggested to stop

water production from oil reservoirs in case of water coning occurrence; and to minimize the negative outcomes of this problem by presenting solutions and applying managerial means. ECLIPSE reservoir simulator software is adopted to model a field by simulating an oil reservoir experiencing a water production problem. First, the water coning phenomenon and the factors affecting it in the oil reservoir are analyzed. Next, to better investigate the factors impacting the coning phenomenon, sensitivity analysis is carried out on various parameters. The main objective of this research is to present applicable solutions based on simulational studies that take into account the type of reservoirs (conventional or fractured) and the location of water coning occurrence. Considering the sophisticated nature of fractured reservoirs, for the first time in Iran, this study meticulously and thoroughly investigates conventional and fractured reservoirs and demonstrates the effect of the coning phenomenon on the production from these reservoirs.

2- Reservoir simulation and computational details

The simulator software for oil reservoirs, known as ECLIPSE, which is developed by the Schlumberger company, is utilized for simulations and modeling of a reservoir that is adjoined by an aquifer and (because of the water coning phenomenon) is facing the challenge of water production. ECLIPSE is considered one of the most recognized and credible software in the field of oil and gas reservoir simulation worldwide. This simulator is a complete and comprehensive software for simulating diverse types of reservoirs regardless of their structural or geological sophistication and type of fluid. Considering its extensive

and diverse capabilities compared to other similar softwares, the applications of the ECLIPSE simulator are extensively increasing in such a way that it can be claimed that this software has been established as a universal standard. This simulator software consists of several modules; the two main modules are briefly explained in the following. The ECLIPSE 100 module of the software is the simulator of black oil in reservoirs. In this module, the default assumption is that oil, solution gas, and water are the reservoir's fluids, and the oil in the reservoir and solution gas are miscible in all ratios. In addition to having the features and capabilities of the ECLIPSE 100 module, the ECLIPSE 300 module of the software can utilize equations of state and pressure-dependent equilibrium ratios to solve the relevant problems. In this research, a reservoir of a field located in the southwest of Iran in the Dezful depression is simulated using the ECLIPSE software. The simulated dimensions of the aforementioned reservoir are a length of 22.99 miles and a width of 9.2 miles. The reservoir consists of five layers, among which only the first, second, and third layers are in the oil-bearing area of the reservoir according to OWC (at a depth of 8793 feet below sea level).

The reservoir has an area of 134326.5 acres and is located at a depth of 7401.6 feet below the sea level with the initial oil-water contact at the depth of 8793 feet below the sea level. The amount of oil in place exceeds 3.5 billion barrels; the producing layers are numbers 1, 2, and 3 and the average thickness of the oil column is 446.2 feet. The mean density of all layers is 165.4 lb/ft³, and the average matrix porosity and horizontal permeability of all layers are 10% and 1 md. The reservoir rock is oil-wet.

The reservoir's initial pressure at a depth of 8250 ft is 3458 psi, and its temperature at GOC depth is 212°F. Bubble point pressure and solution gas-oil ratio (R_s) vary between 2646 and 6014 psi and 0.43 and 0.76, respectively. Based on the reports, the average gas-oil ratio (GOR) of producing wells in the initial years of production was 0.7 Mscf/stb, and the oil has a density of 34.3 lb/ft³ and an API of 30. Detailed supplementary information on the reservoir is presented in Tables 1-3. In the base pressure of 3900 psi, the compression ratio (CR) was given the values of 3200×10^{-5} and 2200×10^{-5} psi⁻¹ for consolidated and unconsolidated limestones, respectively.

Table 1: The porosity and permeability of layers in the simulated reservoir.

Layer	1	2	3	4	5
Thickness (ft)	250	250	300	300	700
Porosity (fraction)	0.1	0.1	0.1	0.1	0.07
Permeability (md)	1	1	1	1	1

Table 2: Relative permeabilities and capillary pressures of oil versus oil saturation in the simulated reservoir.

P_c	K_{ro}	S_o (%)
0.220	0.00	0.00
N/A	0.001	0.01
0.50	0.005	0.012
0.75	0.05	0.016
1.00	0.05	0.033
N/A	0.10	0.061
1.400	N/A	0.10
2.400	0.30	0.146
N/A	0.50	0.20
N/A	0.70	0.245
3.200	0.9	0.3

Table 3: Relative permeabilities and capillary pressures of water versus water saturation in the simulated reservoir.

P_c (psi)	K_{rw}	S_w (%)
4	0.0	0.3
2.95	0.02	0.5
0.85	0.2	0.7
0.0	1	1

In constructing the dynamic model of the reservoir, the ECLIPSE 100 module was used to simulate the three-phase model. To simulate the reservoir in the field, the reservoir was divided into numerous blocks, among which a block with the dimensions of $15 \times 15 \times 5$ was selected for the simulation process and intended studies.

In the defined reservoir, there exist nine production wells with a flow rate of 1,000 bbl/day. A 3D sketch of the reservoir model and the location and arrangement of wells is demonstrated in Fig. 3.

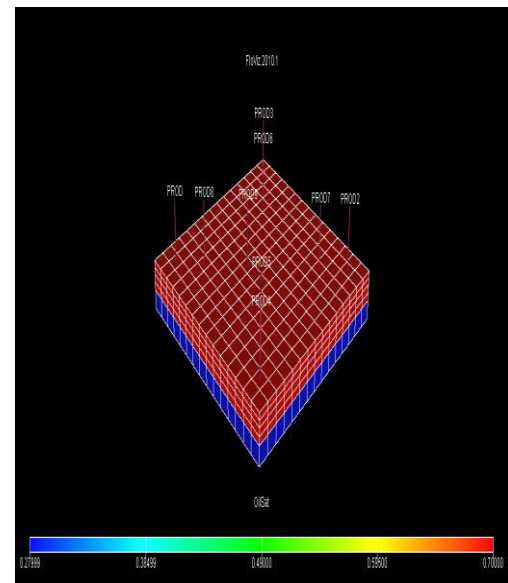


Fig. 3 A 3D sketch of the simulated reservoir and wells.

Via further modeling, the way water coning occurs was depicted through a graph for water production versus time in the simulated reservoir (Fig. 4). Based on the results, 160,000 barrels of water are produced after 5,000 days of production. Understanding and analyzing the factors contributing to water coning play a critical role in reaching a concise insight into alleviating this condition. Furthermore, the most influential parameters in the occurrence of the water coning phenomenon are analyzed in this study. These parameters include: 1) the density of oil, 2) the presence of fractures in the reservoir, 3) the amount of production flow rate, and 4) the ratio of vertical permeability to horizontal permeability. These parameters are comprehensively scrutinized in the following section.

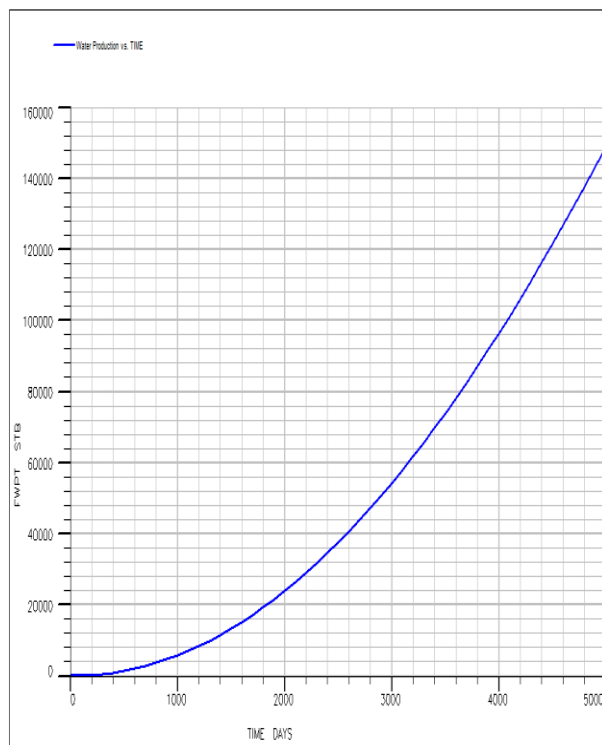


Fig. 4 Water production in the simulated reservoir versus time.

3- Results and analytical discussions

The effects of the density of oil, the presence of fractures in the reservoir, the

amount of production flow rate, and the vertical-to-horizontal permeability ratio, which are crucial factors in the water coning phenomenon, are investigated in the following. In the end, sensitivity analyses are carried out on the number of grid blocks and fracture length.

3-1 The density of oil

To perform sensitivity analyses on the oil density as an effective parameter, three types of oils with densities of 15, 34, and 45 lb/ft³ were applied to the simulated model. The results of this process are presented in Fig. 5. Analyzing the results reveals that increases in oil density lead to proportionate decreases in the pace of oil production compared to water, which speeds up the water coning phenomenon. Thus, according to the results obtained from the simulation, the low density of the oil in the reservoir is an advantage when water coning is of concern.

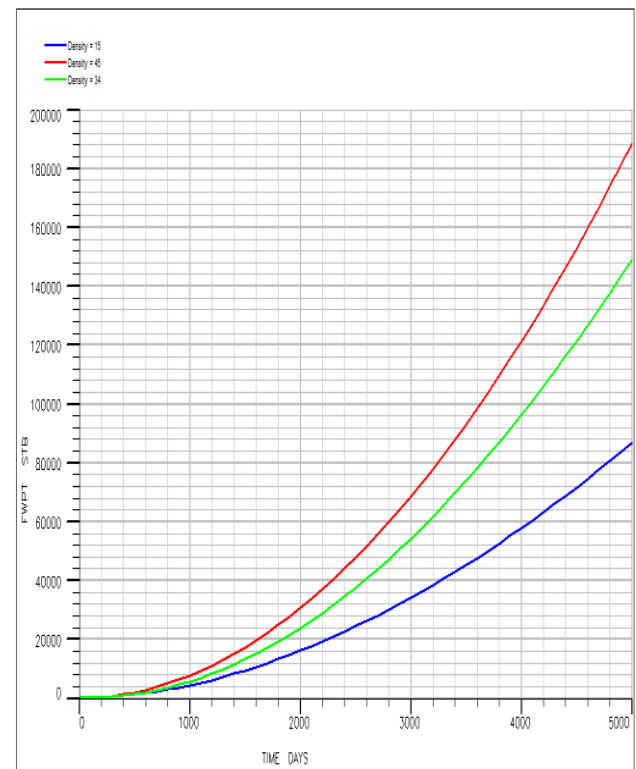


Fig. 5 The effect of oil density on water coning in the simulated reservoir.

3-2 The presence of fractures in the reservoir

To model the impact of fractures on water coning, a reservoir with dual porosity was assessed. To do so, the number of layers for simulating the coordinates of fractures was doubled, and the dimensions of the reservoir were defined to be $15 \times 15 \times 10$. Permeabilities of the simulated fractures according to the petrology of the present layers and the extent of fractures are provided in Table 4.

Table 4: Permeabilities of the simulated fractures.

Layer	1	2	3	4	5
K_x = K_y (md)	2000	2000	1000	1000	100
K_z (md)	500	2000	500	500	5

When the reservoir is fractured, the possibility of the coning phenomenon is considerably higher. Based on the simulation results (Fig. 6), in the presence of fractures, water production drastically surges and reaches approximately 45 million barrels after 5,000 days of production. Therefore, it can be concluded that practicing caution and controlling the production flow rate is a crucial measure. Fig. 7 illustrates a view of the formed water cone in the simulated reservoir.

3-3 The amount of the production flow rate

Production flow rate of oil is a significant and influential factor in water coning and the volume of water production in wells. To perform sensitivity analyses on the amount of oil production rate, several flow rates were separately tested. The tested flow rates varied between 300 to 1,000 bbl/day.

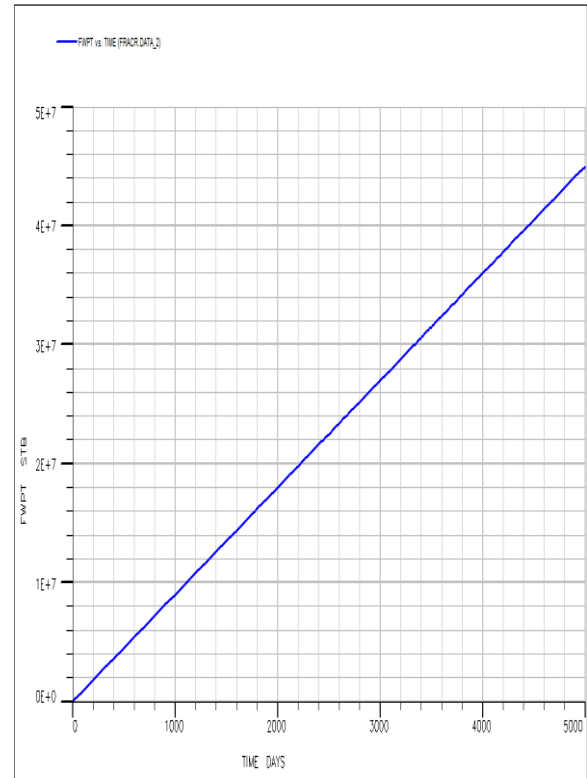


Fig. 6 The effect of the presence of fractures on water coning in the simulated reservoir.

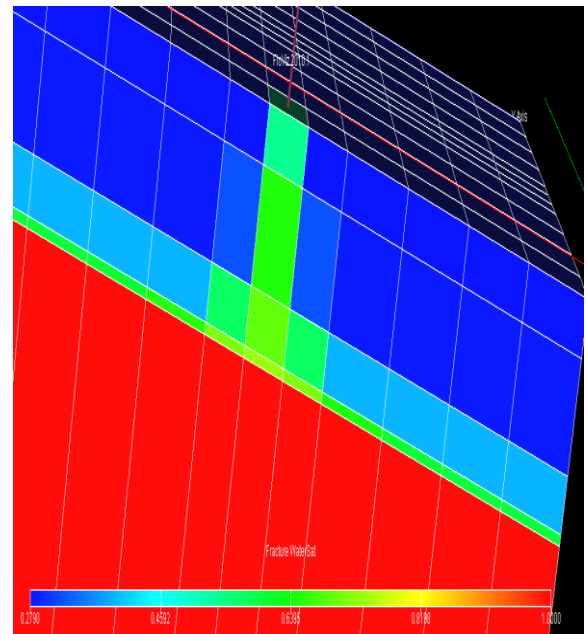


Fig. 7 A sketch of the formed cone of water in the simulated reservoir.

Fig. 8 suggests that production with low flow rates drastically decreases the water produced by coning. However, production with high flow rates strikingly increases water coning and water production. It is

also noticed that for a 5,000-day period, while the water production is 10,000 barrels for the oil production flow rate of 300 bbl/day, it soars to 160,000 barrels for the oil production flow rate of 1,000 bbl/day.

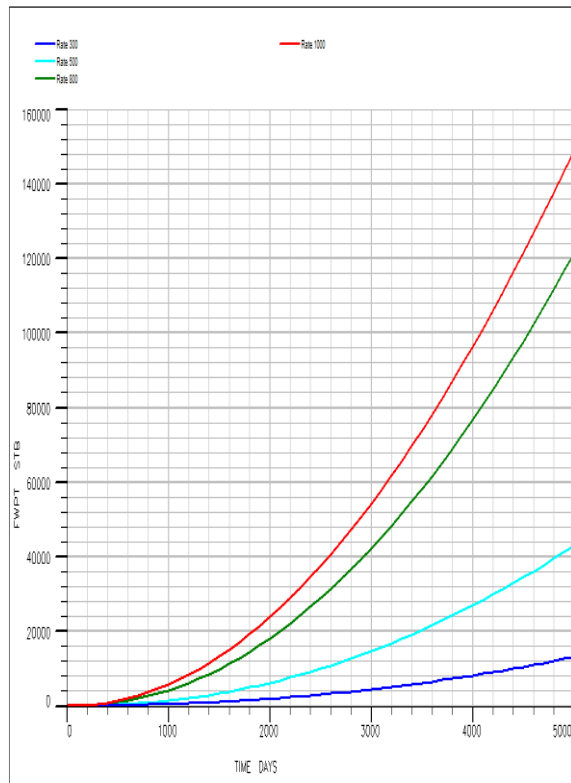


Fig. 8 Effect of the production flow rate of oil on water coning in the simulated reservoir.

3-4 Vertical to horizontal permeability ratio

Simulations were carried out under three different vertical to horizontal permeability ratios, and the results are presented in Fig. 9. With an increase in vertical permeability of the reservoir from 1 md to 2 md (the red graph), water production rises as well. This tendency is also observed in a further increase in vertical permeability to 3 md (the blue graph), and more water is produced. These findings demonstrate that the amount and time of water production by coning are highly dependent on the vertical permeability of the reservoir. This seems logical since water is generally drawn to the drilling area from underlying

lower layers; and the higher the permeability of this path, the faster water is drawn to upper layers and wellbore.

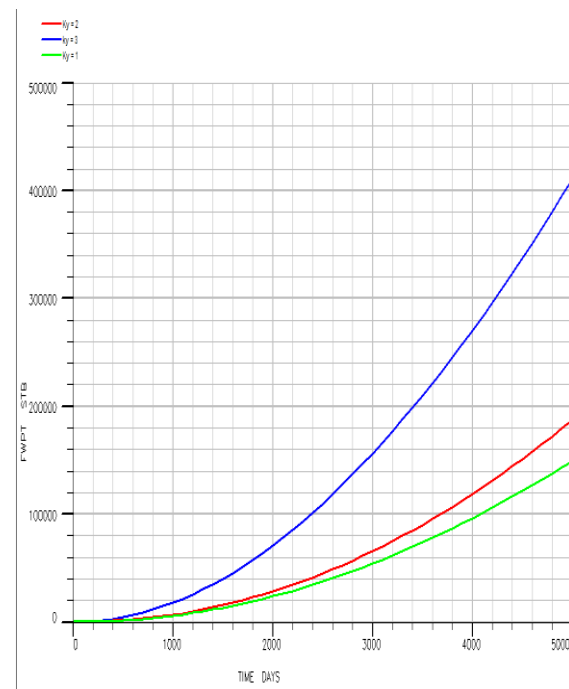


Fig. 9 Effect of permeability of oil-bearing layers on the water coning in the simulated reservoir.

3-5 Number of grid blocks

Considering three different numbers for the total number of grid blocks (namely 1125, 3125, and 500) and assuming the same reservoir size and reservoir properties for these three cases, it is observed from Fig. 10 that the smaller the number of grid blocks, the smaller the cumulative produced water. This means that the smaller the size of the grid blocks, the larger the cumulative produced water. A future optimization study is required to determine the optimum size for the grid blocks by considering the trade-off between the simulation accuracy and reasonable computation time.

3-6 Fracture length

Sensitivity analysis on the fracture length in the z-axis direction for three lengths of 3, 15, and 100 ft demonstrates that the producing layer with a 3-ft fracture has the

least water production and that with a 100-ft fracture has the highest water production (Fig. 11). This suggests that water production will substantially decrease with the decrease in the fracture length.

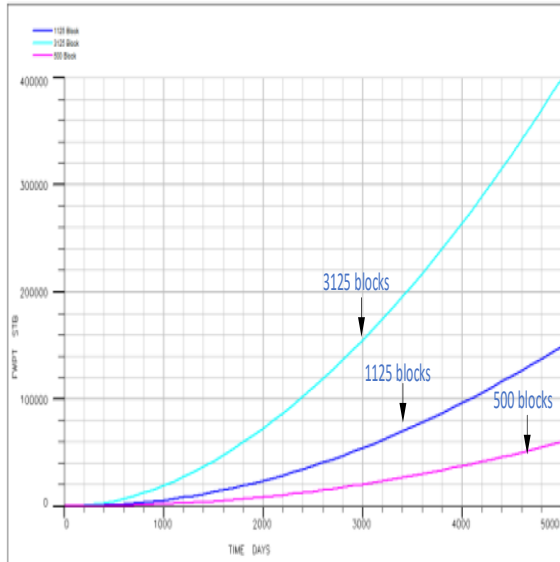


Fig. 10 Sensitivity analysis on the number/size of grid blocks

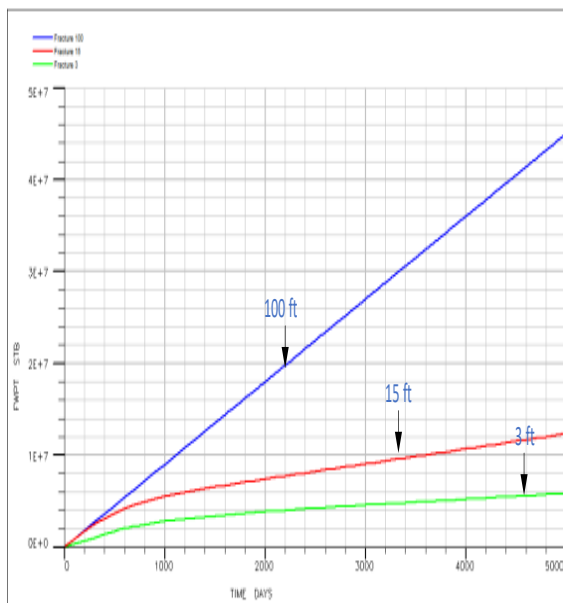


Fig. 11 Sensitivity analysis on the fracture length

4- Conclusion

In this simulational study, a reservoir experiencing a water production problem was simulated via the ECLIPSE simulator software. At first, the water coning occurrence and factors affecting it in oil

reservoirs were assessed. Subsequently, to gain a more accurate understanding of the significance of each factor, sensitivity analyses were performed on them. The following conclusions were made:

- Higher densities of oil result in lower oil speeds for production compared to water speeds; thus, water coning occurs faster. Therefore, in terms of water coning, lower oil densities are advantageous as they lessen the intensity of coning.
- The possibility of water coning occurrence is significantly higher if the reservoir is fractured. Hence, controlling the production flow rate is vital in these reservoirs.
- Increasing the oil production flow rate accelerates water coning occurrence, so the water production increases.
- The amount and time of water coning are highly controlled by the vertical-to-horizontal permeability ratio of the reservoir. The time of water coning is delayed by a decrease in the vertical-to-horizontal permeability ratio, causing a reduction in the amount of water coning.

References

- [1] Zewain, I., & Elgibaly, A. (2020). Production Optimization of Water Coning Wells Using Numerical Simulation and Neural Network Modeling. *Petroleum & Coal*, 62(3).
- [2] Kuo, M. C. T., & DesBrisay, C. L. (1983, October). A simplified method for water coning predictions. In *SPE Annual Technical Conference and Exhibition* (pp. SPE-12067). SPE.
- [3] Jin, L., Wojtanowicz, A. K., & Hughes, R. G. (2010). An analytical model for water coning control installation in reservoir with bottomwater. *Journal of Canadian Petroleum Technology*, 49(05), 65-70.
- [4] Høyland, L. A., Papatzacos, P., & Skjaeveland, S. M. (1989). Critical rate for water coning: correlation and analytical solution. *SPE Reservoir Engineering*, 4(04), 495-502.

-
- [5] Ahmadi, M. A., Ebadi, M., & Hosseini, S. M. (2014). Prediction breakthrough time of water coning in the fractured reservoirs by implementing low parameter support vector machine approach. *Fuel*, 117, 579-589.
- [6] Wong, D. L. Y., Doster, F., Geiger, S., Francot, E., & Gouth, F. (2019, June). Investigation of water coning phenomena in a fractured reservoir using the embedded discrete fracture model (EDFM). In *81st EAGE Conference and Exhibition 2019* (Vol. 2019, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.
- [7] Safari, M., Ameri, M. J., Gholami, R., & Rahimi, A. (2021). Water coning control concurrently with permeability estimation using Ensemble Kalman Filter associated boundary control approach. *Journal of Petroleum Science and Engineering*, 203, 108590.
- [8] Okon, A., Appah, D., & Akpabio, J. (2017). Water coning prediction review and control: developing an integrated approach. *Journal of Scientific Research and Reports*, 14(4), 1-24.
- [9] Onwukwe, S. I. (2015). Techniques of Controlling Water Coning in Oil Reservoirs. *Advanced Reservoir Petroleum Technology*, 1(1), 8-16.