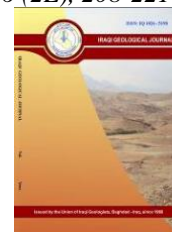




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Delaying Water Breakthrough Using Horizontal Wells in Khurmala Oilfield

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Abstract

Water coning presents a serious problem in many oil fields, in terms of reducing oil production rate and increasing production costs. As breakthrough time represents the time until coning occurs, it should be increased by studying the significant affecting parameters and proposing a method to control them. Since horizontal wells are known to have higher potentials than vertical wells, they are used worldwide to delay water coning among other purposes. In this study, four designed horizontal wells are proposed to replace a drilled vertical well in Khurmala oilfield in northern Iraq, and the effect of each on water breakthrough time is studied with four different production rates and six different permeability ratios. PERFORM software is used to model the wells, and calculate the expected breakthrough time for each well. It was found that the 1000-ft horizontal well, and longer wells, will delay water breakthrough time, in all cases. Also, higher permeability ratios increase the breakthrough time for longer wells, by up to 15.69 folds, except with the optimum production rate, and increasing production rate results in decreasing breakthrough time (t_{BT}) in all cases, where doubling the production rate may decrease t_{BT} by more than 73.5%. It is essential to determine the minimum horizontal well length required to delay water breakthrough time, compared to the vertical well, by considering both production rate and permeability ratio. The breakthrough time ratio, depending on the proposed to optimum production rate ratio, can be calculated using the developed correlation with an average error of 1.73%.

Keywords: Coning; Cresting; Water Breakthrough Time; Horizontal Well; Permeability Ratio

1. Introduction

Water coning is a serious problem in many oil fields (Shadizadeh and Ghorbani, 2001) as nearly 75% of the wells drilled around the world face that problem which is associated with oil production from reservoirs overlying aquifers (Alkhalissi, 2015), and it increases the production cost, decreases the efficiency of the depletion mechanism, and reduces the oil recovery (Garroucha et al., 2004), in addition to the environmental problems associated with high water cuts, i.e., water treatment and disposal (Menouar and Hakim, 1995; Alkhalissi, 2015), hence delaying water breakthrough is essential.

Several factors affect the time required for subsurface water to reach the well measured in days, i.e., water breakthrough time (t_{BT}), including: horizontal permeability, permeability ratio, oil density, reservoir thickness, pressure drawdown, flow rate, and -in a horizontal well- the productive interval length (Hatzignatiou and Mohamed, 1994; Omeke et al., 2010; Kozikhin et al., 2020). In addition to

these factors, porosity and vertical distance between the well and the water level should -also- be considered (Wang et al., 1993; Benamara and Tiab, 2001). The latter, i.e., oil-water contact is significantly important in the field's redevelopment plans in general (Alhusseini and Hamd-Allah, 2022) and can be determined at the level of water saturation of 100% (Al-Mozan and Al-Jawad, 2020).

The cone tendency decreases with more horizontal permeability, more porosity, more reservoir thickness, higher horizontal well length, higher fluids density difference, less oil viscosity, less oil production, and less vertical anisotropy ratio (Benamara and Tiab, 2001). Hence, reducing water coning in vertical wells or cresting in horizontal wells is possible through decreasing the production rate (Hatzignatiou and Mohamed, 1994), increasing the length of the lateral section of the horizontal well (Menouar and Huang, 1993), and selecting an optimum location for the well (Permadi, 1996).

In an oil reservoir with an aquifer, viscous and gravitational forces work on the interface of oil and water; the first is a result of fluid production while the latter is related to the fluid densities, and when viscous forces overcome gravitational ones, coning occurs (Ozkan and Raghavan, 1990; Permadi and Jayadi, 2010), consequently, one of the most important coning factors is pressure drawdown; because when the drawdown increases to more than the gravity pressure differential; which keeps the water below the oil column, water breakthrough occurs. The latter is generally called water coning in the case of vertical wells and water cresting in the case of horizontal wells (Permadi and Jayadi, 2010).

Since horizontal wells have lower drawdown pressures, they decrease water coning problems (Doan and Ali, 1995) compared to vertical wells which are more prone to coning (Wang et al., 1993; Hatzignatiou and Mohamed, 1994). In fact, modeling a horizontal well to be drilled instead of a vertical well showed that in addition to increasing both the oil production rate and recovery, the water coning risk would be reduced significantly (Wu et al., 1995).

Water coning does not only represent a significant problem in many Iraqi oil fields, such as those producing from Mishrif formation (Awadeesian et al., 2019), where new techniques are proposed and implemented to control water production; such as suggesting gas and water sink - assisted gravity drainage (G&DWS-AGD) in South Rumaila field (Al-Mudhafar et al., 2017), and using autonomous inflow control valve (AICD) for controlling water influx and reducing water cut in a field in southern Iraq (Razak et al., 2022), water coning represents -also- the most significant production problem in the Kurdistan region of Iraq (Ali et al., 2021).

The area of the current study is Khurmala dome in the northern section of the supergiant Kirkuk oil field. Khurmala is located about 80 km from Kirkuk and 35 km from Erbil, which is made of carbonate rock formed during the Late Paleocene to Early Eocene epoch (Assad et al., 2022). Bellen et al. were the first to describe Khurmala formation in 1959, in the Kirkuk-114 well where they found it to be around 185 m in thickness (Karim et al., 2018). Water coning represents a big problem in that field that has to be faced in noticeably short time. Converting the vertical wells into horizontal wells; which are wells drilled with a deviation -from the vertical axis- of more than 80° (Shedid and Zekri, 2001), can be a solution to the coning problem.

The number of horizontal wells drilled worldwide has increased in the last decades, to minimize coning among other purposes (Wang et al., 1993); as one of the advantages of horizontal wells over vertical wells is increasing water t_{BT} (Ozkan and Raghavan; 1990), and horizontal wells have proved their success in a number of giant oil fields in the Middle East, which led to the initiation of applying them in super giant oil fields in Iraq, considering the advantages of horizontal wells, especially in reducing water coning and producing with higher flow rates from low permeability formations (Khan et al., 2020).

The t_{BT} is larger in horizontal wells than in vertical wells, as the water and gas encroachment towards the well forms a crest rather than a cone, taking more time -for water- to enter the wellbore (Doan and Ali, 1995).

The objective of this study is to compare the water t_{BT} of a drilled vertical well and four different well length cases of a proposed horizontal well, with considering the essential factors affecting water coning and/or cresting, namely; horizontal well length, permeability ratio, and production rate, in addition to providing a general correlation to determine the t_{BT} for any flow rate depending on the optimum flow rate of the well and its calculated t_{BT} .

2. Materials and Methods

The vertical well (V1) is modeled using the reservoir, fluid, and vertical well data provided in Table 1, with applying Darcy method and Duns and Ros vertical lift performance correlation.

Table 1. Reservoir, fluid, and vertical well data

Parameter	Value	Unit
Oil Gravity	35	API
Gas Specific Gravity	0.878	fraction
Water Cut	0	%
Gas-Oil Ratio	394	Scf/STB
Reservoir Pressure	1232.8	Psig
Bubble Point Pressure	1200	Psig
Reservoir Temperature	120	°F
Horizontal Permeability	38.5	md
Porosity	25	%
Reservoir Pay Thickness	312	ft
Depth of Oil Water Contact	3363	ft
Connate Water Saturation (S_{wc})	0.129	fraction
Residual Oil Saturation (S_{or})	0.376	fraction
Relative Permeability of Oil at S_{wc}	0.645	fraction
Relative Permeability of Water at S_{or}	0.1725	fraction
Wellbore Radius	0.4479	ft
Measured Depth	3333	ft
Casing Depth	3054	ft
Tubing Depth	2461	ft
Tubing Inner Diameter	2.992	in
Drainage Radius	926	ft
Wellbore Radius	0.4479	ft

Four cases of a horizontal well; H1, H2, H3, and H4, are designed with lengths of 500, 1000, 1500, and 2000 ft respectively, as shown in Table 2, which includes also their drainage lengths which are calculated as the root of the mean of the drainage areas calculated using Equations 1 and 2 (Saavedra and Reyes, 2001) for each well after converting the unit from acres to ft^2 , and the horizontal wells' directional survey containing total vertical depth (TVD) and measured depth (MD). The latter is calculated based on the fact that most of the proposed horizontal well lengths are medium radius type with a turning radius (R) of 300 to 800 ft (Shedid and Zekri, 2001). A radius of 478 ft is selected, to go along a build up rate (BUR) of 12° , and a tangent angle (I) of 55° is chosen; since it is not recommended to drill with an angle higher than 60° (Ma et al., 2016), hence all horizontal wells will be designed with two build up sections, and a tangent section in between with length of 300 ft.

$$A_D = \frac{\pi ab}{43560} \quad (1)$$

$$A_D = \frac{2Lb + \pi b^2}{43560} \quad (2)$$

Where A_D is the drainage area (acre), a is half the major axis of the ellipsoidal drainage area (ft), b is the drainage radius of the vertical well (ft), and L is the horizontal well length (ft).

Table 2. Horizontal wells' data

Well	Horizontal Length (ft)	Drainage Length (ft)	MD (ft)	TVD (ft)
H1	500	1875	0	0
H2	1000	2084	2557	2557
H3	1500	2274	3015	2949
H4	2000	2449	3315	3121
			3607	3207
			3607+L	3207

The horizontal wells are modeled using Babu and Odeh method, and designed to be in the middle of the reservoir with applying the same vertical lift correlation used for the vertical well and reservoir and fluid data provided in Table 1. The directional survey data of these horizontal wells are provided in Table 2, while the same V1 wellbore radius, tubing and casing sizes are used for the four cases of the horizontal well. The horizontal wells' casing and tubing measured depths are 3557 and 3607 ft, respectively.

PERFORM software (version 7.53), which is an IHS software, is used to model the wells, and calculate their production rates and the expected water t_{BT} for each.

With including the saturation and relative permeability data tabulated in Table 1, the water t_{BT} is calculated for the vertical well and the four cases of the horizontal well. Six different permeability ratios (0.1, 0.2, 0.3, 0.5, 0.7, and 1.0) and four production rates (the optimum production rate, 1500 STB/Day, 2000 STB/Day, and 3000 STB/Day) are considered for each case. The effects of production rate, horizontal well length, and permeability ratio on both water t_{BT} and t_{BT} ratio are studied. The latter is calculated as the ratio of water t_{BT} when using a horizontal well to the t_{BT} when using the vertical well.

A correlation between the ratio of production rate to optimum production rate on one hand and the ratio of t_{BT} with the given production rate to the t_{BT} with the optimum production rate on the other hand, is developed to study the effect of changing the production rate from optimum on the change in water t_{BT} .

The error percentages of the correlation are calculated using Equation 3.

$$\text{Error Percentage} = \frac{|V_o - V_c|}{V_o} \times 100\% \quad (3)$$

Where V_o is the original value obtained from the software and V_c is the calculated value using the correlation.

3. Results

After simulating the vertical well and the different designed horizontal well cases, with various permeability ratios, the optimum production rates are recorded and plotted in Fig.1, while the corresponding drawdown pressures, to these different cases are plotted in Fig.2.

Horizontal wells (H1, H2, H3, and H4) have higher optimum production rates compared to that of the vertical well (V1), as shown in Fig.1, for most horizontal well lengths and permeability ratios, as expected because of the higher drainage area created by the horizontal well. The ratio of the horizontal well production rate to the vertical well production rate is less than one is only for lengths less than 650, 750, and 1000 ft with permeability ratios= 0.3, 0.2, and 0.1, respectively, as can be interpreted from Fig.1. These -generally- high production rates observed in the horizontal wells are accompanied with -generally- low drawdown pressures, as shown in Fig.2.

The higher pressure drops along the longer tubing in the horizontal wells (3607 ft) compared to the tubing length of the vertical well (2461 ft), and the relatively low horizontal lengths accompanied with low permeability ratios, both lead to the less than unity production rate ratio.

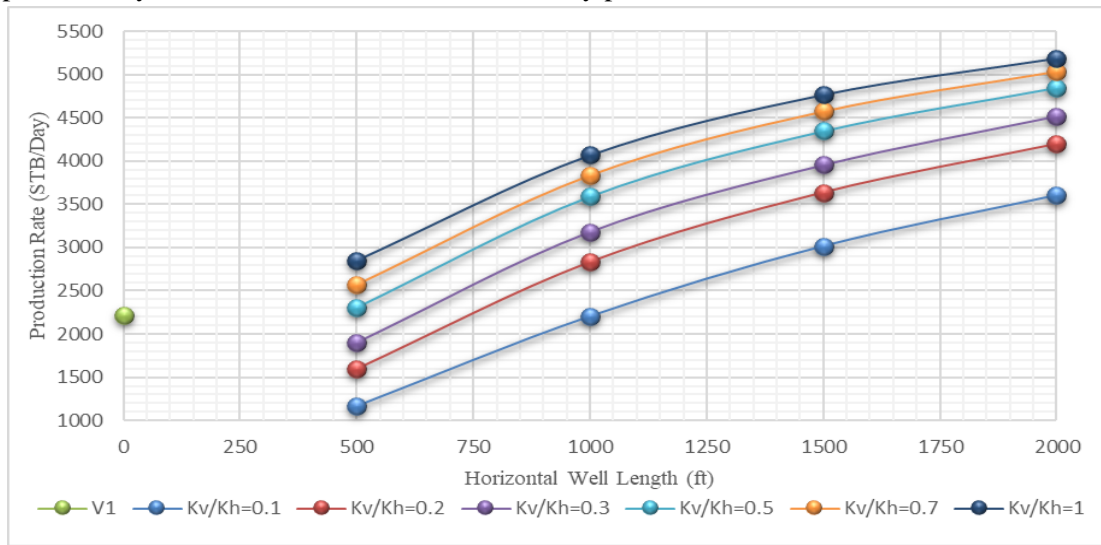


Fig.1. The Effect of horizontal well length on oil production rate

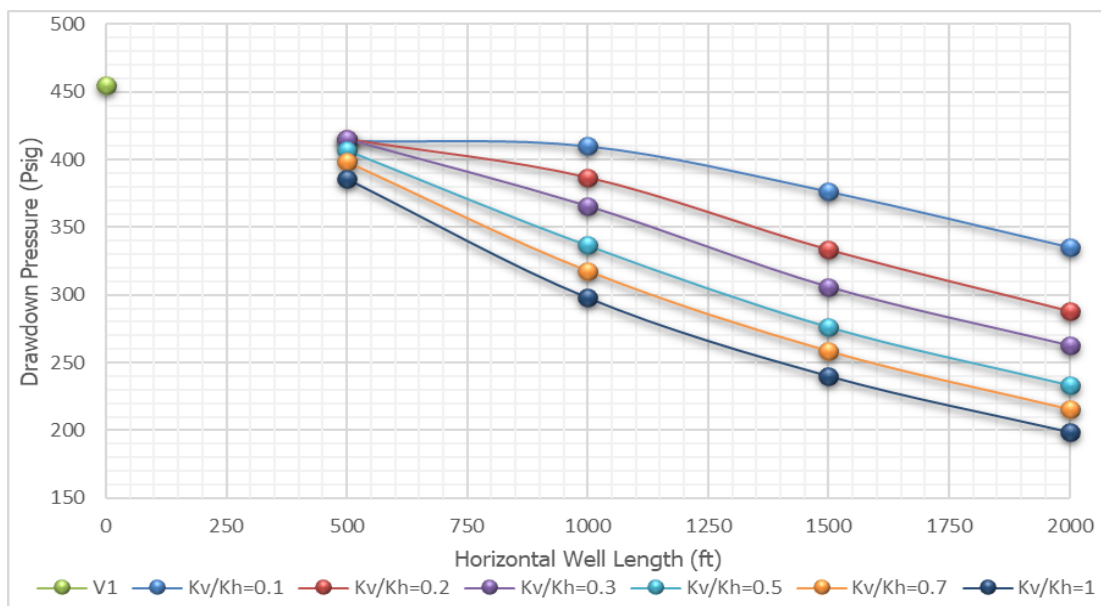


Fig.2. The effect of horizontal well length on drawdown pressure

3.1. Effect of Horizontal Well Length on Breakthrough Time

The increment in horizontal well length results in an increment in t_{BT} for all horizontal wells. When producing with the optimum production rate, the t_{BT} reaches up to 340 days with 2000 ft long horizontal well at 0.1 permeability ratio reservoir, although t_{BT} is lower in the 500 ft long horizontal well (H1) than in the vertical well (V1) in all studied permeability ratios above 0.1, as shown in Fig.3. Drilling a horizontal well with length ≥ 580 , 780, and a minimum of 840 ft, at permeability ratios = 0.2, 0.3, and a minimum of 0.5, respectively, results in a horizontal to vertical well t_{BT} ratio more than unity, as shown in Fig.4. t_{BT} ratio ranges between 2.7 to 3.3 when 2000-ft horizontal well (H4) is used.

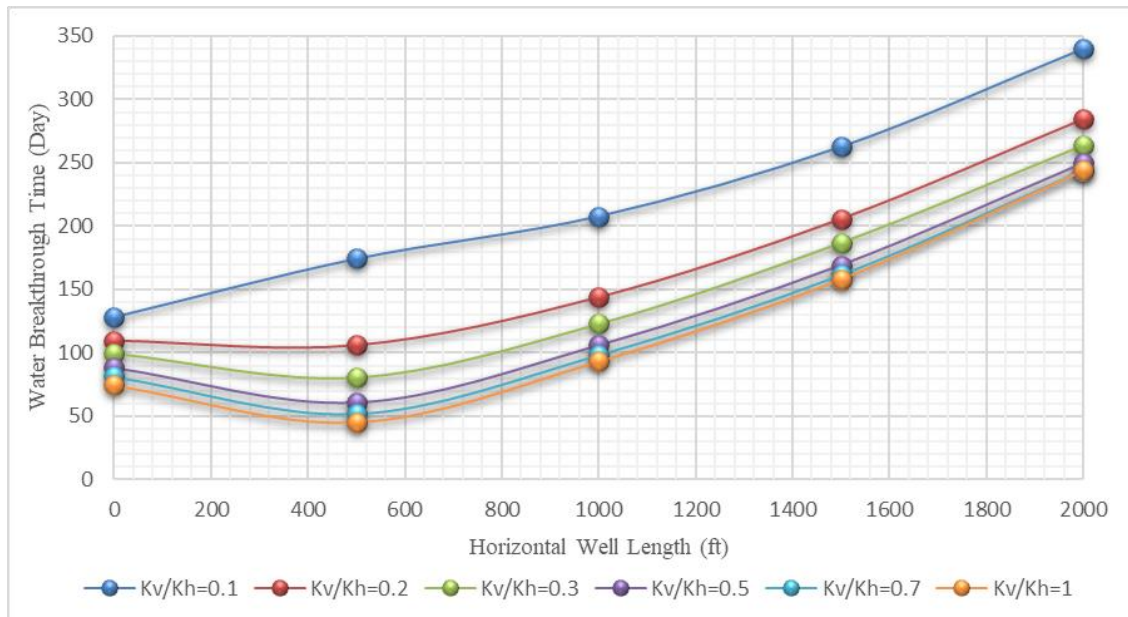


Fig.3. The effect of horizontal well length on t_{bt} with optimum production rate

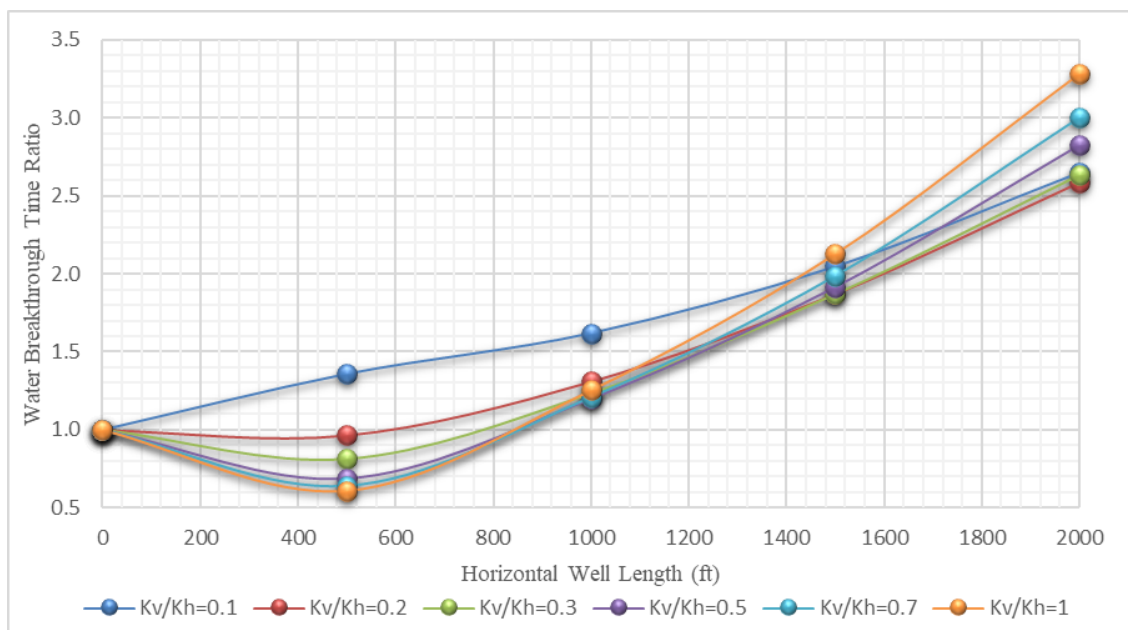


Fig.4. The effect of horizontal well length on t_{bt} ratio with optimum production rate

Fig.5 shows that the effect of horizontal well length on t_{BT} follows the same trend when using different production rates. For example, when producing with 1500 STB/Day from a reservoir with 0.2 permeability ratio, t_{BT} is 120, 471, 1044, and 1825 days, for lengths= 500, 1000, 1500, and 2000 ft, respectively. The same effect of horizontal well length on t_{BT} is observed when the production rate is doubled. For example, with permeability ratio= 0.2, t_{BT} is 32, 129, 295, and 530 days, for lengths= 500, 1000, 1500, and 2000 ft, respectively.

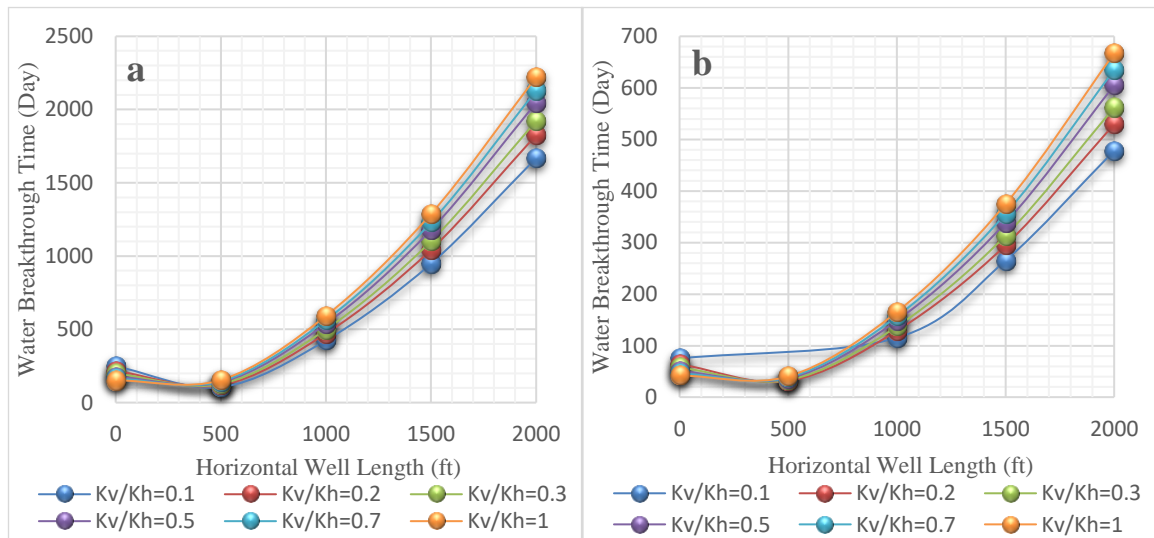


Fig.5. The effect of well length on t_{bt} with production rates of (a) 1500 stb/day, (b) 3000 stb/day

The long horizontal wells are more effective in increasing t_{BT} , compared to V1, in high permeability ratio reservoirs. When a 2000 ft horizontal well is modeled in a reservoir with a permeability ratio of 1, the t_{BT} is increased by up to 14.7 and 15.7 folds, with production rates of 1500 and 3000 STB/Day, respectively, compared to only 6.7 and 6.3 folds, at permeability ratio= 0.1, as shown in Fig.6.

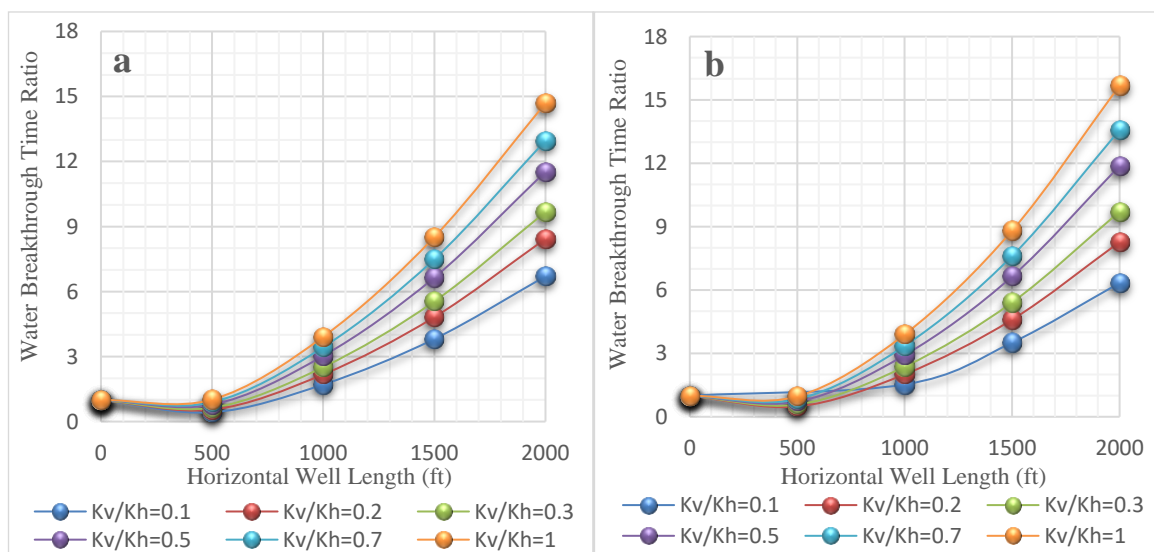


Fig.6. The effect of well length on t_{bt} ratio with production rates of (a) 1500 stb/day, (b) 3000 stb/day

3.2. Effect of Permeability Ratio on Breakthrough Time

The water t_{BT} increases for horizontal wells as the permeability ratio increases, with all studied production rates (1500, 2000, and 3000 STB/Day) except the optimum production rate, while for V1, higher permeability ratio results in lower t_{BT} . When producing with the optimum production rate, the relationship is the same for both types of wells, i.e., less t_{BT} always accompanies higher permeability ratio, with a clear advantage for horizontal wells in increasing t_{BT} in all permeability ratios, compared to V1, except when the horizontal well length is 500 ft (H1), and the permeability ratio is less than 0.2, as shown in Fig.7.

It is observed -also- from Fig.7 that t_{BT} values when using V1 and H1 have very close values with all studied production rates, except the optimum, when the permeability ratio is above 0.5. In addition to that, in all cases of horizontal wells, increasing the well length of a longer well results in a greater increment in t_{BT} , compared to increasing the length of a shorter well.

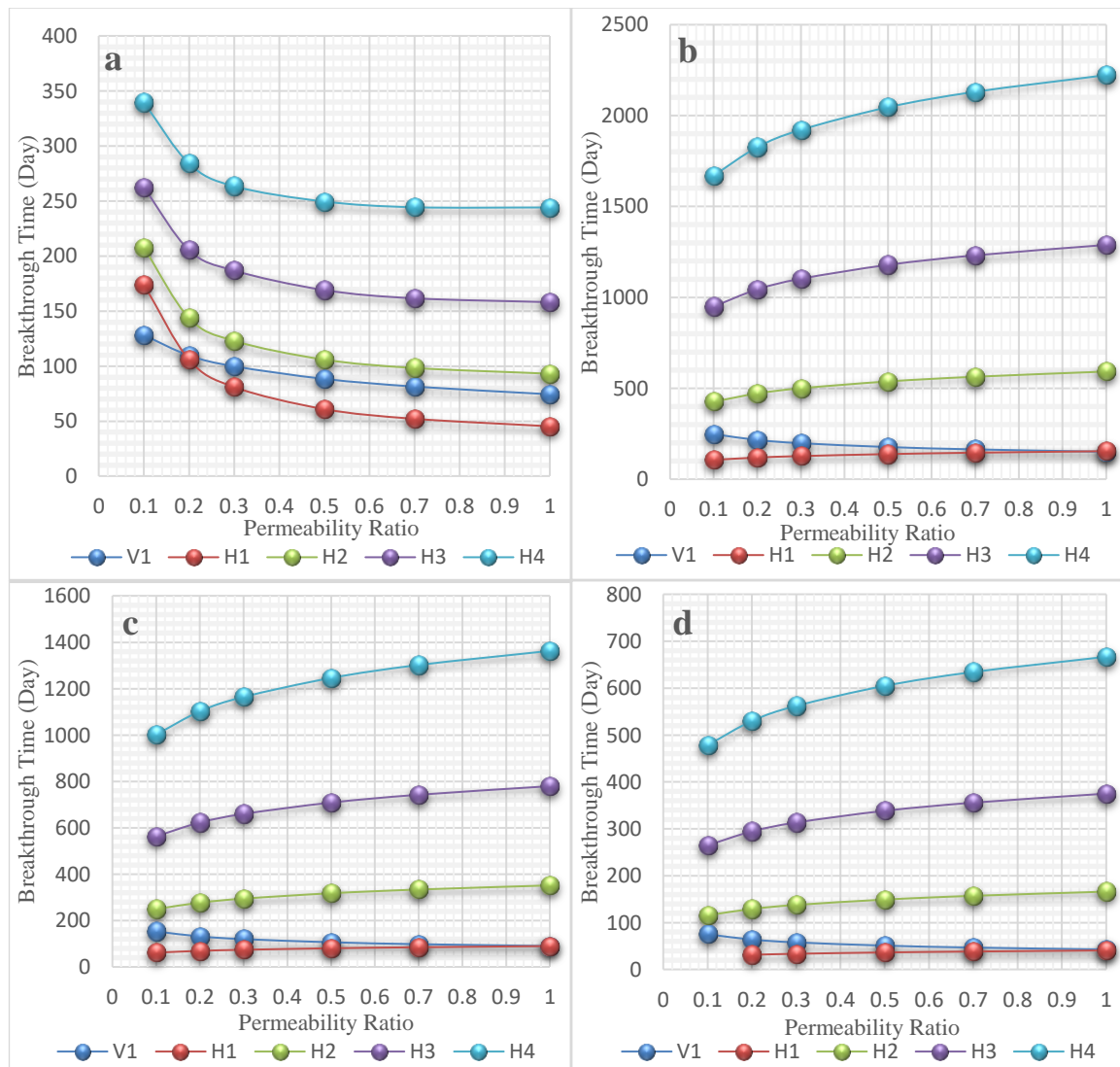


Fig.7. The effect of permeability ratio on t_{bt} with production rates of (a) optimum stb/day, (b) 1500 stb/day, (c) 2000 stb/day, (d) 3000 stb/day

The permeability ratio affects both types of wells, hence comparing the t_{BT} when using horizontal wells and that when using the vertical well, i.e., using t_{BT} ratio, will provide a clear idea regarding the degree of improvement in t_{BT} achieved by the horizontal wells with different permeability ratios. Fig.8 shows that by producing with the optimum production rate for each well, horizontal to vertical t_{BT} ratio is above one for all cases, except H1 with a permeability ratio ≥ 0.2 . Also, higher permeability ratio results in lower t_{BT} ratio, yet this affect reduces when the horizontal well length is increased. In other words, longer horizontal wells are recommended with all permeability ratios to increase the t_{BT} ratio; which ranges -for H4- between 2.6 and 3.3.

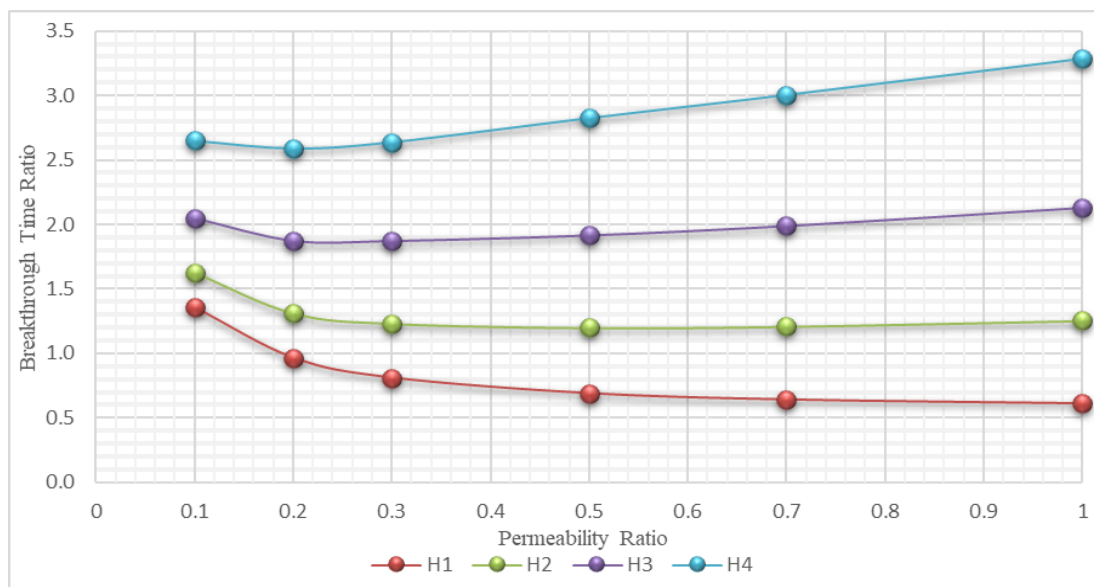


Fig.8. The effect of permeability ratio on t_{bt} ratio when producing with the optimum production rate

Using 1500 STB/Day and 3000 STB/Day instead of the optimum production rate results in an increment in t_{BT} ratio when the permeability ratio increases. For example, when using H3, the t_{BT} ratio increases from 3.8 to 8.5 and from 3.5 to 8.8, when the production rate= 1500 and 3000 STB/Day, respectively, as shown in Fig.9. The t_{BT} ratio is above unity in all cases of horizontal wells except in the case of H1. Yet, when the permeability ratio= 1 and production rate= 1500 STB/Day, even H1 has a t_{BT} ratio greater than unity. The maximum increment in t_{BT} ratio is 15.69, and it is achieved when using H4 with a production rate of 3000 STB/Day.

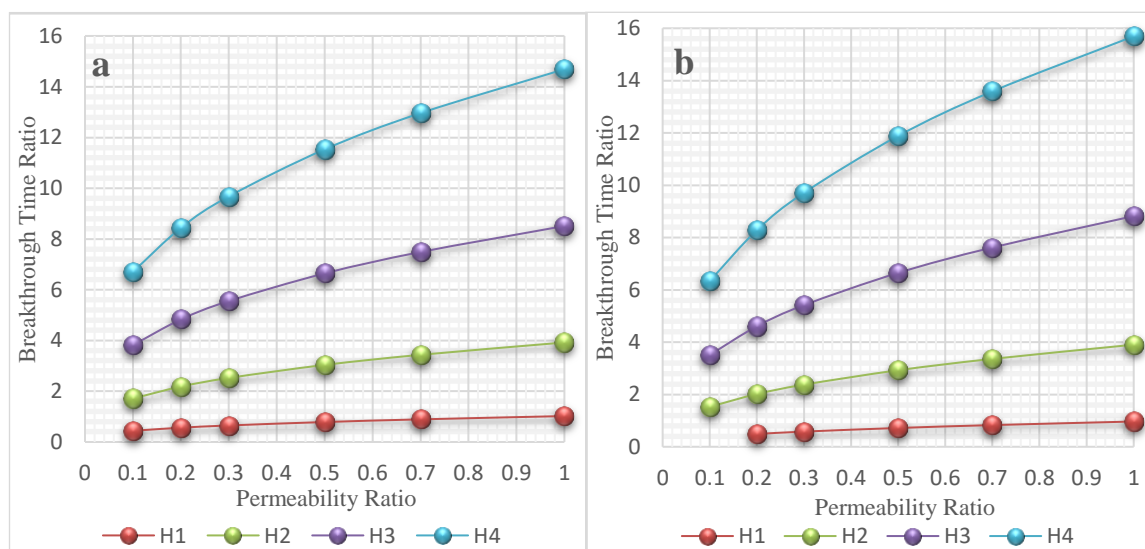


Fig.9. The effect of permeability ratio on t_{bt} ratio with production rates of (a) 1500 stb/day, (b) 3000 stb/day

3.3. Effect of Production Rate on Breakthrough Time

Four different production rates (optimum, 1500, 2000, and 3000 STB/Day) are used for V1, H1, H2, H3, and H4, and their effect on the t_{BT} is studied in four different permeability ratios (0.1, 0.3, 0.5, and 1), with the exception of 3000 STB/Day for H1 at a permeability ratio= 0.1; since this production rate is higher than the absolute open flow of the well.

It is observed, from Fig.10, that water t_{BT} decreases with the increment of production rate in all wells. This reduction is observed with all permeability ratios, and although it is most significant in horizontal wells with high lengths as a number of days (shown in Fig.10); because of their originally high t_{BT} values, longer wells are less affected by the increment in production rate, as shown in Fig.11 when the production rate is doubled from 1500 STB/Day to 3000 STB/Day. In addition to that, higher permeability ratios reduce the effect of increasing the production rate in horizontal wells, unlike the case of the vertical well. Hence, the maximum reduction in t_{BT} (more than 73.5%) is observed in H1 with the lowest studied permeability ratio. However, even with the largest studied production rate for H4, this 2000-ft horizontal well still has a higher t_{BT} than that of V1 when producing with the lowest studied production rate in all permeability ratios.

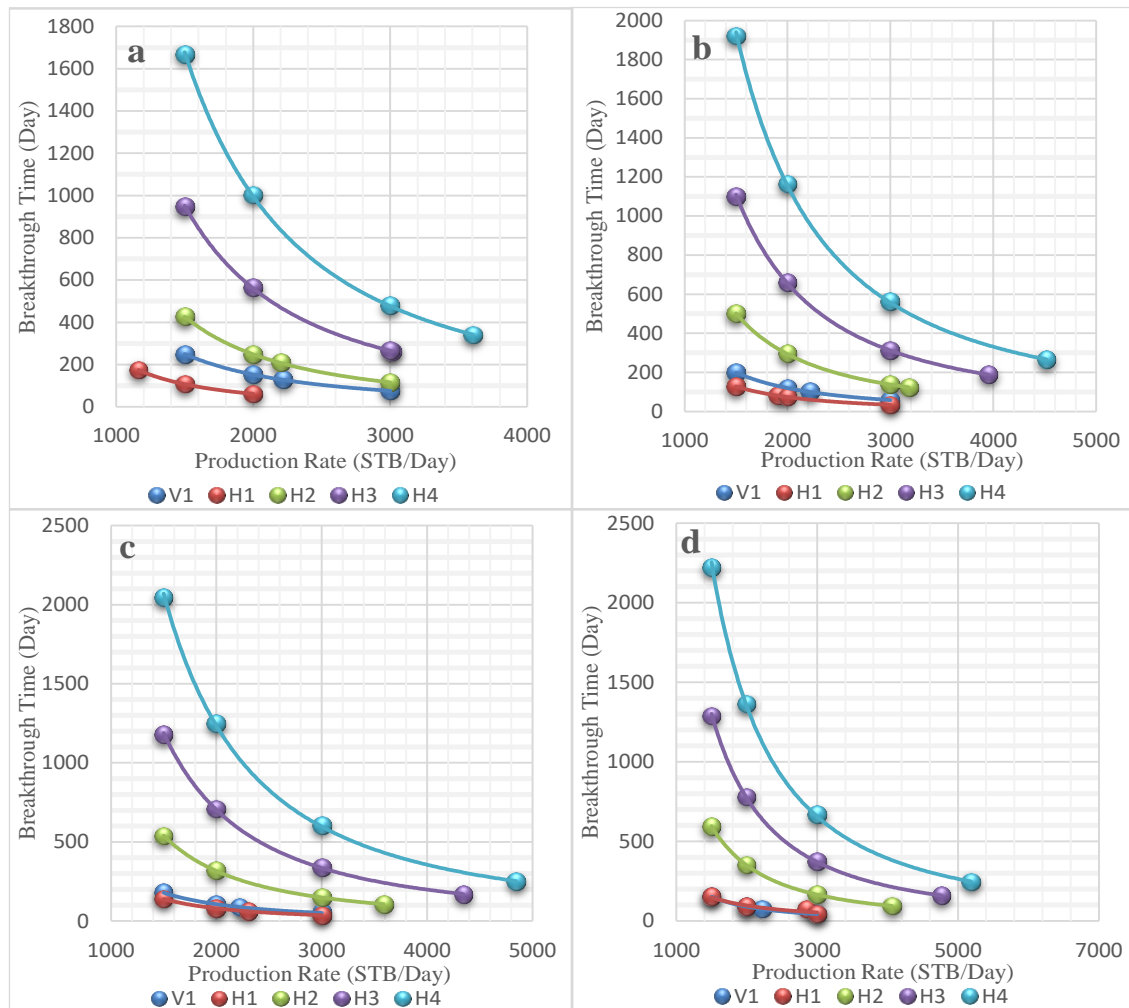


Fig.10. The effect of production rate on t_{bt} with permeability ratios of (a) 0.1, (b) 0.3, (c) 0.5, (d) 1

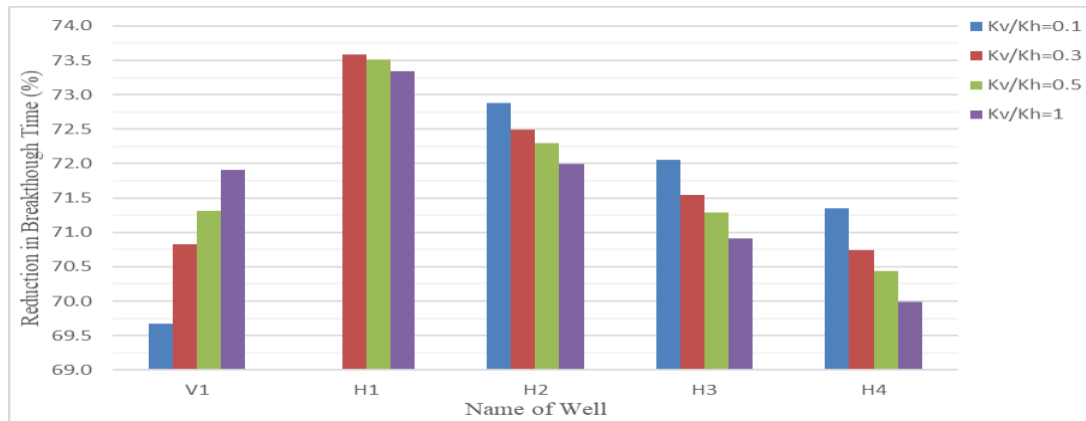


Fig.11. Reduction percentage in t_{bt} when production rate is doubled in different wells

3.4. Effect of Production Rate Ratio on Breakthrough Time Ratio

As changing the production rate from the optimum value changes the water t_{BT} , the ratio of each of the three different studied production rates to the optimum production rate, i.e., production rate ratios, are studied in terms of their effect on the t_{BT} ratio, which is -in this section- the ratio of t_{BT} originated from a certain production rate to the t_{BT} originated from the optimum production rate. A correlation describing the effect of production rate ratio on t_{BT} ratio can be obtained from plotting the latter against the first, as shown in Fig.12. This correlation (Equation 4) can be used to calculate water t_{BT} when the production rate is changed depending on the optimum production rate and the corresponding t_{BT} .

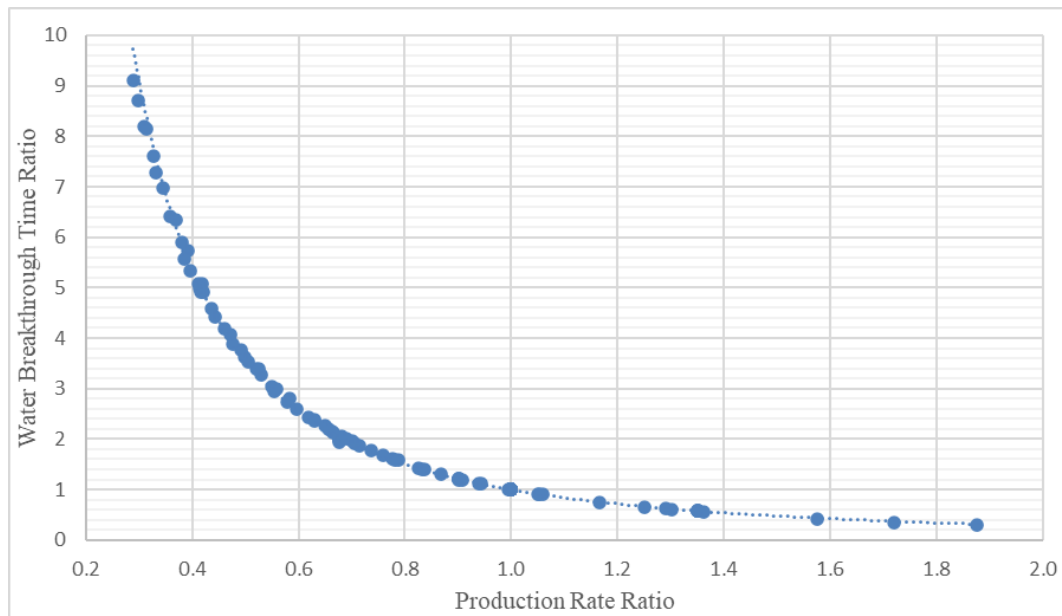


Fig.12. t_{BT} Ratio vs. Production Rate Ratio

$$\frac{t_{BT\ new}}{t_{BT\ opt.}} = 0.9988 \left(\frac{Q_{o\ new}}{Q_{o\ opt.}} \right)^{-1.833} \tag{4}$$

Where $t_{BT\ new}$ is the new value of t_{BT} at the new production rate (Day), $t_{BT\ opt.}$ is the t_{BT} at the optimum production rate (Day), $Q_{o\ new}$ is the new production rate (STB/Day), and $Q_{o\ opt.}$ is the optimum production rate (STB/Day).

This correlation is based on 90 different values and it is valid for horizontal well lengths ranging between 0 (vertical) and 2000 ft, with permeability ratios between 0.1 and 1.0, and production rate ratios between 0.29 and 1.88. The average error is 1.73% and the maximum error is 6.70% with 85.56% of the results have less than 3% error.

4. Discussion

Although the optimum production rate of most of the studied cases of horizontal wells is higher than that of the vertical well (Fig.1), lower drawdown pressures are required to produce with these flow rates (Fig.2), resulting in higher t_{BT} values in all studied cases except when the well length is 500 ft and the permeability ratio is above 0.1 (Fig.3). This exception is explained by the fact that short horizontal wells have higher drawdown pressures and less drainage areas (Table 2), hence, less potential than longer wells. When the permeability ratio increases, it decreases t_{BT} and increases the horizontal well's potential simultaneously, yet its affect appears to be less significant on the latter because of the relatively small drainage area created by the 500-ft long horizontal section, which is -in turn- comparable to the reservoir thickness on which the vertical well potential depends.

Permeability ratio and t_{BT} are negatively correlated; since water coning/creeping depends significantly on vertical permeability. Yet, in high permeability ratio reservoirs, longer horizontal wells are more effective in increasing t_{BT} , compared to the vertical well (Fig.6), due to the high potential of long wells accompanied by relatively low drawdown pressures which overcome the effect of high permeability ratio in decreasing water t_{BT} . Although higher permeability ratios result in lower t_{BT} ratios when producing with the optimum rate, this affect is less significant when the horizontal well length is increased (Fig.7-a), due to the increment in drainage area and reduction in drawdown pressure. t_{BT} ratio is above one in most cases (Fig.8), since the vertical well's production rate depends mainly on the horizontal permeability, unlike that of the horizontal well, while water coning depends mainly on vertical permeability.

Production rate and t_{BT} have a negative correlation (Fig.10), due to the higher drawdown pressure required to increase the production rate. Using production rates other than the optimum results in an increment in t_{BT} ratio, because of the fact that most horizontal wells have higher potential than the vertical well, and with increasing the permeability ratio, while fixing the production rate, the horizontal well's potential increases which leads to lowering the drawdown pressure, hence, increasing the t_{BT} ratio even more.

5. Conclusions

Horizontal wells are successful in delaying water breakthrough significantly, depending on a number of factors including horizontal well length, permeability ratio, and production rate. Horizontal well length is positively correlated to increasing breakthrough time (t_{BT}), with all permeability ratios and production rates. Yet, when compared to the t_{BT} of the vertical well, a minimum horizontal well length must be determined depending on both the vertical permeability and production rate. With using the optimum production rate of each case, it was found that a well length of more than 840 ft will result in a t_{BT} ratio of more than unity in all permeability ratios. Permeability ratio has a negative correlation with t_{BT} , yet horizontal wells with 1000 ft length or more will have a t_{BT} ratio of more than unity. Reducing production rate results in increasing the t_{BT} in all cases. The effect of increasing production rate is less on longer horizontal wells' t_{BT} . Similarly, longer horizontal wells are less prone to permeability ratio increment. It is recommended to convert the studied vertical well in Khurmala field to a 2000-ft long horizontal well in order to increase t_{BT} by a factor of 2.7 to 3.3; depending on permeability ratio, and with using optimum production rate. The t_{BT} reaches up to 15.7 folds when lower production rates are used. The developed correlation can be used to estimate the t_{BT} depending on the

optimum production rate, its corresponding t_{BT} , and the proposed production rate, with an average error of 1.73%.

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References

- Alhousseini, A.K. and Hamd-Allah, S., 2022. Estimation of initial oil in place for Buzurgan Oil Field by using volumetric method and reservoir simulation method. *Iraqi Geological Journal*, 55 (2C), 106-120.
- Ali, F.F., Hamoudi, M.R. and Abdul Wahab, A.H., 2021. Comparison between homogenous and heterogeneous reservoirs: a parametric study of water coning phenomena. *UKH Journal of Science and Engineering*, 5 (1), 119-131.
- Alkhalissi, R.M.J., 2015. Single well coning problem and applicable solutions. *Iraqi Journal of Chemical and Petroleum Engineering*, 16 (2), 53-56.
- Al-Mudhafar, W.J., Wojtanowicz, A.K. and Rao, D.N., 2017. Hybrid Process of Gas and Downhole Water Sink - Assisted Gravity Drainage (G&DWS-AGD) to Enhance Oil Recovery in Reservoirs with Water Coning. Carbon Management Technology Conference, Houston, Paper 502487-MS.
- Al-Mozan, H.D.K. and Al-Jawad, M.S., 2020. Reservoir modeling for Mishrif Formation in Nasiriyah Oilfield. *Iraqi Geological Journal*, 53 (1E), 1-15.
- Asaad, I.Sh., Al-Haj, M.A. and Malak, Z.A., 2022. Depositional setting of Khurmala Formation (Paleocene-Early Eocene) in Nerwa Section, Berat Anticline, Kurdistan Region, Northern Iraq. *Iraqi Geological Journal*, 55 (1F), 20-39.
- Awadeesian, A.M.R., Awadh, S.M., Al-Dabbas, M.A., Al-Maliki, M.M., Al-Jawad, S.N., and Hussein, M.A., 2019. A modified water injection technique to improve oil recovery: Mishrif Carbonate Reservoirs in Southern Iraq Oil Fields, Case Study. *Iraqi Geological Journal*, 52 (1), 125-146.
- Benamara, A. and Tiab, D., 2001. Gas Coning in Vertical and Horizontal wells, a Numerical Approach. SPE Rocky Mountain Petroleum Technology Conference, Keystone, Colorado, SPE, 71026-MS.
- Doan, Q.T. and Ali, S.M.F., 1995. Horizontal Wells - Are They Worth the Cost? Petro Vietnam '95 Conference, Ho Chi Minh, SPE, 30154-MS.
- Garroucha, A.A., Lababidib, H.M.S. and Ebrahima, A.S., 2004. An integrated approach for the planning and completion of horizontal and multilateral wells. *Journal of Petroleum Science and Engineering*, 44, 283-301.
- Hatzignatiou, D.G. and Mohamed, F., 1994. Water and Gas Coning in Horizontal and Vertical Wells. 45th Annual Technical Meeting of the Petroleum Society of CIM, Calgary, PETSOC-94-26.
- Karim, K.H., Daoud, H.S. and Kuradawy, A.R.H., 2018. Record of Khurmala Formation (Late Paleocene-Early Eocene) in the Sulaimaniah Governorate, Kurdistan Region, Northeast Iraq. *Iraqi Geological Journal*, 51 (1), 34-55.
- Khan, S.A., Hassan, F.A., Wang, J., Gan, J., Liu, Y., Patz, J.F., Abdulshbeb, S.K. and Al Lawe. E.M., 2020. Redevelopment of a Supergiant Southern Iraqi Oil Field with Horizontal Wells. Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, SPE, 202692-MS.
- Kozikhin, R.A., Fattakhov, I.G., Kuleshova, L.S., Andreev, V.E., Safiullina, A.R., Gabbasov, A. Kh. and Andaryanov, I.G., 2020. Improvement of the efficiency of horizontal wells. IOP Conference Series: Materials Science and Engineering, 952. Available from: doi:10.1088/1757-899X/952/1/012056.
- Ma, T., Chen, P. and Zhao, J., 2016. Overview on vertical and directional drilling technologies for the exploration and exploitation of deep petroleum resources. *Geomech. Geophys. Geo-energ. Geo-resour.* 2, 365-395.
- Menouar, H. and Huang, W.S., 1993. Horizontal Well Design in Wafra Field, Ratawi Oolite Reservoir. SPE Middle East Oil Technical Conference and Exhibition, Bahrain, SPE, 25597-MS.
- Menouar, H.K. and Hakim, A.A., 1995. Water Coning and Critical Rates in Vertical and Horizontal Wells. SPE Middle East Oil Show, Bahrain, SPE, 29877-MS.
- Omeke, J.E., Livinus, A., Uche, I.N., Obah, B. and Ekeoma, E., 2010. A Proposed Cone Breakthrough Time Model for Horizontal Wells in Thin Oil Rim Reservoirs. 34th Annual SPE International Conference and Exhibition, Tinapa – Calabar, Nigeria, SPE, 140743-MS.

- Ozkan, E. and Raghavan, R., 1990. A Breakthrough Time Correlation for Coning Toward Horizontal Wells. Europec 90, The Hague, Netherlands, SPE, 20964-MS.
- Permadi, P., 1996. Fast Horizontal-Well Coning Evaluation Method. SPE Asia Pacific Oil and Gas Conference, Adelaide, Australia, SPE, 37032-MS.
- Permadi, P. and Jayadi, T., 2010. An Improved Water Coning Calculation for Horizontal Wells. SPE/RO&G Russian Oil and Gas Technical Conference, Moscow, SPE, 133162.
- Razak, M.M., Hassan, A.F. and Radhi, A.A., 2022. Using Smart Completion Technology to Control Water Coning Problems and Increase Oil Recovery in a Southern Iraqi Oilfield. *Journal of Petroleum Research and Studies*, 34 (2), 88-101.
- Saavedra, N.F. and Reyes, D.A., 2001. Drainage Area for Horizontal Wells with Pressure Drop in the Horizontal Section. SPE Latin American and Caribbean Petroleum Engineering Conference, Buenos Aires, SPE, 69431-MS.
- Shadizadeh, S.R. and Ghorbani, D., 2001. Investigation of water/gas coning in natural fractured hydrocarbon reservoirs. Canadian International Petroleum Conference, Calgary, Paper 2001-014.
- Shedid, S.A. and Zekri, A.Y., 2001. Sensitivity Analysis of Horizontal Well Productivity under Steady-State Conditions. SPE Asia Pacific Improved Oil Recovery Conference, Kuala Lumpur, Malaysia, SPE, 72121.
- Wang, B., Markitell, B.N., and Huang, W.S., 1993. Case Studies of Horizontal Well Design and Production Forecast. SPE Middle East Oil Technical Conference and Exhibition, Bahrain, SPE, 25567-MS.
- Wu, G., Reynolds, K. and Markitell, B., 1995. A Field Study of Horizontal Well Design in Reducing Water Coning. International Meeting of Petroleum Engineering, Beijing, China, SPE, 30016-MS.