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ANALYSIS OF THE EFFECT OF CRITICAL PARAMETERS ON CONING IN HORIZONTAL WELLS

Aliyu Adebayo Sulaimon[1], Norlie Bt Abdullah[1], Suyash Vatsa[2]

[1]Department of Petroleum Engineering, University Teknologi PETRONAS,
[2]Indian Institute of Technology (Indian School Of Mines), Dhanbad, India

Email: aliyu.adebayor@utp.edu.my

ABSTRACT

Water coning is described as an upward movement of water into the perforation in oil-producing wells which lead to water production along with the crude oil. This coning may reduce oil production rate and could substantially increase water production. Hence, many correlations from previous study and available solutions were investigated to estimate the actual critical oil rate to control water-coning in horizontal wells. Specifically, the effects of fluid and rock properties such as viscosity, formation thickness, horizontal permeability, length of horizontal wells and density difference between oil and water on the critical flow rate were investigated. Results show that the oil viscosity and density difference between oil and water have more pronounced effects on coning rate than other parameters. However, while coning tendency becomes more pronounced as the oil becomes more viscous, it is more favorable as the density difference increases (i.e. lighter oil). Moreover, the critical coning rate increases with an increase in the horizontal permeability and the well length. Knowledge of the impact of rock and fluid properties on coning is crucial in the design of mitigation strategies to prevent or effectively manage excessive water influx into the wellbore during oil and gas production.

Keywords: *Water-coning, Oil-critical rate, Correlations, Viscosity, Density Difference, Horizontal wells.*

INTRODUCTION

Producing oil from the horizontal well is characterized by higher deliverability and thus more profitable than a vertical well. This is largely due to the larger drainage area exposed to flow and subsequent reduction in the number of required producing wells. Coning is one of the common problems that occur during oil and gas production when there is excessive water influx into the wellbore [1]. Thus, the occurrence of gas and water coning could eventually lead to loss of production and lower revenue. In addition, the handling cost of produced may become prohibitive along with the associated environmental issues [2]. Usually, a few common practices that are employed by operators include perforating the wells above water-oil contact (WOC) for as far as possible and controlling the production rate so that the wells produced at or below the critical rate. Critical rate is the maximum oil production rate below which gas cusping or water coning will not occur but above which coning is imminent.

According to Ayeni [3] through the article on Empirical Modelling and Simulation of Edgewater and Coning, an unwanted second phase of production with concurrently desired hydrocarbon phase described the coning term as a coning in vertical well because the shape of the interface resembles an upright or inverted cone when the well is produced and shape resembles a crest for a horizontal well. The two major forces that contributed to coning are the interaction of viscous and gravity forces in the reservoir [3],[4]. Due to pressure gradients from the production created viscous forces, thus caused coning to happen. Besides, the gravity forces occurred from the difference of density, which tends to retard water movement. If the gravity force is lower than viscous force, the cone will develop further and immediately breaks into the well.

Ahmadi *et al*. [5] stated that whenever the water is going up and gas is going down in the vicinity of the perforated zone of a production well. Besides, the downward movement of gas and an upward movement of water into the perforations of a producing well defined the coning for gas and water [6],[7]. Ansari and Johns [2] indicated the coning of water and gas can affect the production of oil and gas in oil reservoirs and gas reservoirs respectively. The existence of water coning and gas coning limit the entering oil flow into the perforated zone thus reduced the production. This problem will lead to an increase in water and gas handling cost.

the idea was established by Muskat and Wyckoff [8]. They developed a procedure to predict the maximum flow of oil possible without coning by assuming the same effect of pressure circulation in the actual water coning system with no coning. The assumption was made due to the difficulty in determining the pressure distribution and cone shape simultaneously [9].

Subsequently, a few correlations were introduced for the improvement purpose and also due to different conditions and assumptions but still led to similar correlations (Table 1). At first, Efros [10] developed the critical flow rate correlation by assuming the drainage radius is nearly independent to the critical rate. His correlation also neglected the effect of vertical mobility. This correlation can be applied to horizontal wells. A year after that, Chierici *et al*. [11] came out with the new correlation regarding the critical rate calculation but only applicable to vertical wells. This correlation was worldly known as they based this correlation on a potentiometric study which granted the vertical permeability to be different with horizontal permeability. As the vertical permeability approached zero, the coning phenomena can be distinguished. This correlation also can be used when gas coning and water coning occurred together.

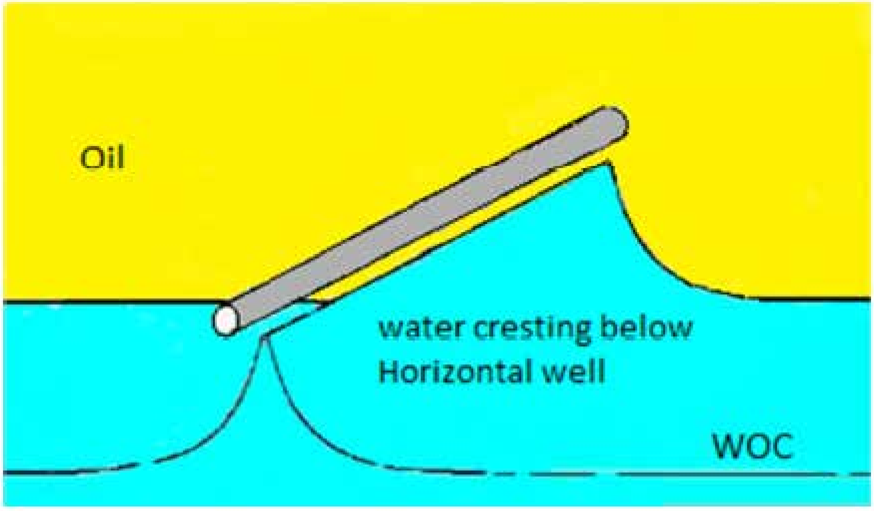


Figure 1 Illustration of water coning and gas coning in horizontal well (Okon et al., 2018)

Correlations for Coning

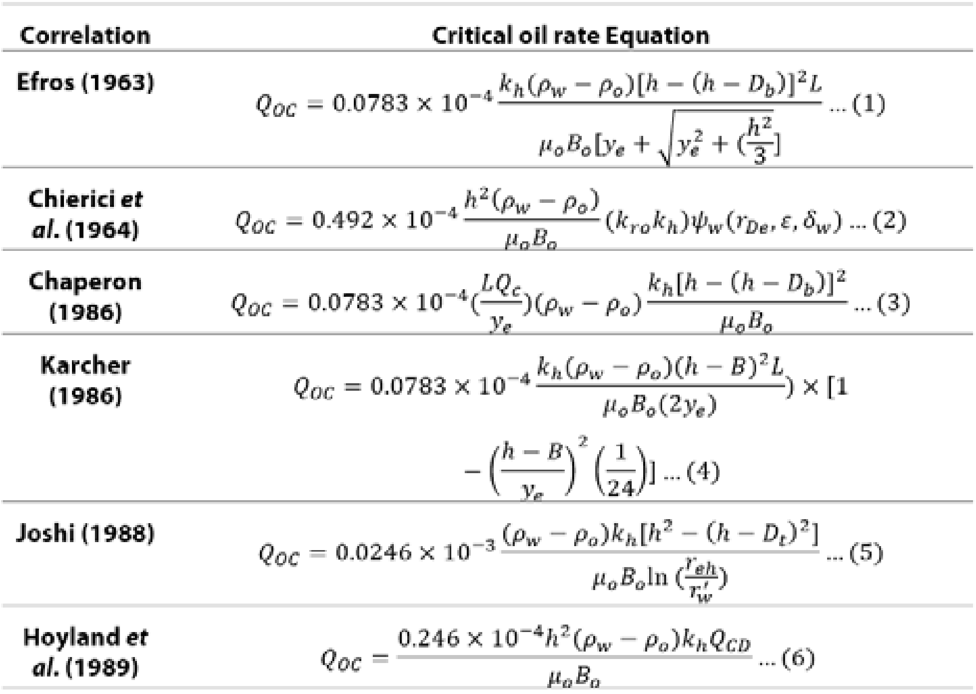
Based on the previous research that has been conducted in order to determine the water breakthrough, a few correlations were developed. Basically, these correlations can solve the oil critical rate equation which finally justified the maximum flow rate the oil can flow without the presence of second phase liquid. More on that, the improvement on that correlations already have been made. Initially, Then, Chaperon [12] derived the critical rate solution for under pseudo-steady-state or steady-state flowing condition for isotropic formations for both vertical and horizontal wells. At the same year, Karcher [13] also did the same thing as [10] which neglected the vertical permeability and only suitable for horizontal wells. Moreover, by suggesting a few parameters to improve the oil critical rate equation introduced horizontal well drainage radius, half the major exist of drainage ellipse and effective wellbore radius specifically for a horizontal well [14]. After that, Hoyland *et al.* [15] presented the calculation of the maximum flow of oil rate without gas and water in an oil gas system by correcting the dimensionless flow rate from [8] with the dimensionless radius and the fractional well penetration ratio.

From all the above methods, Efros's correlation was chosen for this paper since assuming the drainage radius is nearly independent to the critical rate and suitable for isotropic and homogeneous formation. Moreover, Ozkan and Raghavan [16] developed a water breakthrough time correlation in a reservoir with the bottom water drive by assuming fixed pressure boundary at the oil water interface (Table 2).

Coning in Horizontal Wells

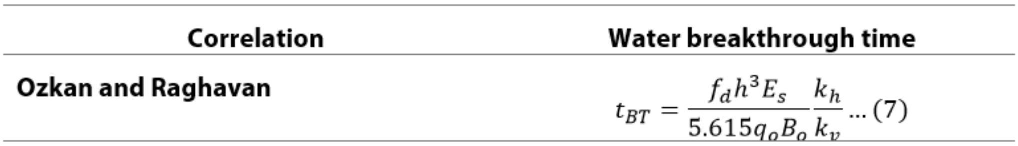
From the production experienced, horizontals well seem to be more effective in producing oil rather than vertical wells. One of the causes behind this situation is the ability to access difficult zones of oil target [17]. They concluded that high productivity via horizontal

Table 1 Correlations of critical oil rate



Correlation	Critical oil rate Equation
Efros (1963)	$Q_{OC} = 0.0783 \times 10^{-4} \frac{k_h(\rho_w - \rho_o)[h - (h - D_b)]^2 L}{\mu_o B_o[y_e + \sqrt{y_e^2 + (\frac{h^2}{3}}]}$ ... (1)
Chierici *et al.* (1964)	$Q_{OC} = 0.492 \times 10^{-4} \frac{h^2(\rho_w - \rho_o)}{\mu_o B_o}(k_{ro}k_h)\psi_w(r_{De}, \varepsilon, \delta_w)$ ... (2)
Chaperon (1986)	$Q_{OC} = 0.0783 \times 10^{-4}(\frac{LQ_c}{y_e})(\rho_w - \rho_o)\frac{k_h[h - (h - D_b)]^2}{\mu_o B_o}$ ... (3)
Karcher (1986)	$Q_{OC} = 0.0783 \times 10^{-4} \frac{k_h(\rho_w - \rho_o)(h - B)^2 L}{\mu_o B_o(2y_e)}) \times [1 - \left(\frac{h - B}{y_e}\right)^2 \left(\frac{1}{24}\right)]$ ... (4)
Joshi (1988)	$Q_{OC} = 0.0246 \times 10^{-3} \frac{(\rho_w - \rho_o)k_h[h^2 - (h - D_t)^2]}{\mu_o B_o \ln(\frac{r_{eh}}{r_w'})}$ ... (5)
Hoyland *et al.* (1989)	$Q_{OC} = \frac{0.246 \times 10^{-4} h^2(\rho_w - \rho_o)k_h Q_{CD}}{\mu_o B_o}$ ... (6)

Table 2 Correlation of water breakthrough time for Horizontal wells



Correlation	Water breakthrough time
Ozkan and Raghavan	$t_{BT} = \frac{f_d h^3 E_s}{5.615 q_o B_o}\frac{k_h}{k_v}$ ... (7)

wells could effectively postpone the times for water and gas to breakthrough. Recham and Touami [4] pointed out that the primary caused for coning to occur is due to high-pressure drawdown. Different cases faced by vertical wells reveal a large pressure drawdown near the wellbore but low-pressure drawdown for horizontal wells due to the long lateral. When compared with vertical wells, the horizontal wells can effectively delay the emergence of the water (gas) cone. However, bottom water reservoirs still faced a major problem in which the bottom water invades the oil zone and finally moves towards the wells [18],[19]. Thus, the coning problem in horizontal wells is slightly reduced compared to vertical wells. Ahmed [6] presented the main goals in applying horizontal wells technology, which was practiced by most of the drillers, is to gain the hydrocarbon recovery from water drive reservoirs and gas cap drive reservoirs. Horizontal wells competently produced higher amounts of oil at the same drawdown with conventional vertical wells. With this capability, horizontal wells provided longer breakthrough time compared with vertical wells at certain production rate.

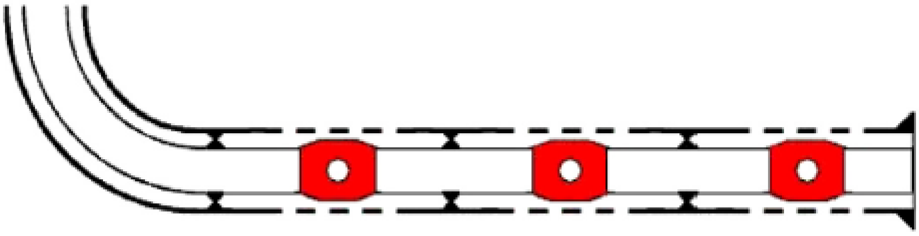


Figure 2 Smart horizontal well consisting of three segments, each having a downhole control valve (Hasan et al., 2013)

Solutions to Coning Problem

A few solutions already implemented to overcome the coning problem. Wang *et al.* [19] presented the study on the theory of bubbling behaviors through nitrogen injection that can block the porous media literally. This experiment was conducted to overwhelm water coning and at the same time increase oil production. Firstly, water flooding is carried out to show the macroscopic distribution of remaining oil in a visualized model filled with glass beads. When the nitrogen is injected via a horizontal well, the appearance of bubbles migrates in porous media is spontaneously replicated and highlight the reflections that change in bubble morphology at different stages. A theory of bubbling characteristics induced by gas permeating via porous medium is skillfully practiced analyzing the mechanisms of anti-water coning by injecting nitrogen.

Automatic control of gas coming from the smart well is one of the available solutions for coning problem [1]. As illustrated in Figure 2, by setting a few downhole valves, this smart well will regulate within the time.

Another available solution that used to solve the coning problem is by predicting the breakthrough time. A lot of methods have been evolved in order to forecast these behaviors and the most deliberated topic is oil critical rate [4]. Equation 6 is used to determine this rate to make sure the flow rate is not exceeding the oil critical rate. By knowing when the water coning happens could help in planning the production to flow properly [5].

Ansari and Johns [2] added that the useful method to decrease the water coning is by perforating vertical wells further above the water-oil contact in oil reservoirs. Same goes to the gas coning is by perforating vertical wells further below the oil gas contact. This application could increase the drawdown pressure from the reservoir pressure to the wellbore pressure.

Based on the previous researches that have been conducted to determine the oil critical rate, some correlations have been developed to determine the critical oil flow rate (Table 1). The pioneering work was initiated by Muskat and Wyckoff (1935). They developed a procedure to predict the maximum flow of oil possible without coning by assuming the same effect of pressure circulation in the actual water coning system with no coning. The assumption was made due to the difficulty in determining the pressure distribution and cone shape simultaneously [9].

Producing oil with the horizontal well is characterized by higher deliverability and thus more profitable than a vertical well. These are largely due to larger drainage area exposed to flow and subsequent reduction in the number of required producing wells respectively. In delivering the best treatment to overcome this problem, the identification of the critical parameters that affect the coning is the important thing that needs to be clarified. From there, these parameters can be controlled to improve oil and gas production. Hence, in this paper, a few critical parameters will be revealed which effect the coning in horizontal wells. All the critical parameters were obtained from the oil critical rate equation [15],[10]. These critical parameters resulted in high oil critical rate or contrariwise. Hence, controlling the effect of critical parameters could improve production efficiency, thus increasing the ultimate recovery.

Initially, the reservoir pressure usually high and allow the fluid to transmit from the reservoir to the surface. After a long production time, the reservoir pressure will drop. Within this period, water will come into the formation and starts to produce through the wellbore due to the disturbance in gravitational force in the reservoir. This phenomenon resulted in the water to produce along with the oil. There were many correlations available to determine the critical coning rate, but until now, there is no research according to the parameters that critically affect the critical coning rate specifically.

Many correlations have been developed to predict the critical coning rate [10]-[15]. However, there have been limited attempts to specifically identify the impact of reservoir rock and fluid properties on the critical coning oil rate. Thus, the main aim of this study is to investigate the existing models or correlations, select the most appropriate and use it to evaluate the effect of the properties under different scenarios on coning in horizontal wells.

The Mathematical Model

For this study, we have selected Efros mathematical model for predicting critical oil rate. The model was chosen due to the reasonable assumption that the drainage radius is independent of the critical rate in horizontal wells. Moreover, the effect of vertical mobility is negligible. The model is used to investigate the effect of different parameters on the critical rate. The Efros model is expressed as shown in Equation (1):

$$Q_{OC} = \frac{0.246 \times 10^{-4} h^2 (\rho_w - \rho_o) k_h Q_{CD}}{\mu_o B_o} \qquad (1)$$

Where:

kh = Horizontal permeability, mD

$p_w - p_o$ = Difference density between water and oil, lb/ft^3

h = Thickness, ft

D_b = Distance between horizontal well and the WOC, ft

L = Horizontal well length, ft

μ_o = Oil viscosity, cP

B_o = Oil formation volume factor, RB/STB

y_e = half drainage length perpendicular to the horizontal well, ft

The parameters under investigation are the fluid viscosity, horizontal permeability, density difference between oil and water, formation thickness and horizontal well length. The half distance between two lines of horizontal wells and the length between the horizontal well and the water-oil contact (WOC) were assumed to be 132 ft and 50 ft respectively. Recham and Touami [4] have shown that the longer the length of a horizontal well, the lower is the coning tendency. Hence, 10 cases were developed based on different variables and range of variables, as shown in Table 3.

Table 3 Ten cases with different critical parameters range

Case	Viscosity, cP	Horizontal Permeability, mD	Reservoir Thickness, ft	Horizontal Well Length, ft	Density difference, lb/ft^3
1	1.0	100	15	500	0.500
2	2.0	200	30	1000	3.000
3	3.0	300	45	1500	5.500
4	4.0	400	60	2000	8.000
5	5.0	500	75	2500	10.500
6	6.0	600	90	3000	13.000
7	7.0	700	105	3500	15.500
8	8.0	800	120	4000	18.000
9	9.0	900	135	4500	20.500
10	10.0	1000	150	5000	23.000

Table 4 Five cases with different critical parameters range

Case	Horizontal Permeability,mD	Viscosity,cP	Mobility Ratio
1	100	0.5	200
	300		600
	500		1000
	700		1400
	900		1800
2	100	0.7	142.857
	300		428.571
	500		714.286
	700		1000.000
	900		1285.714
3	100	0.9	111.111
	300		333.333
	500		555.556
	700		777.778
	900		1000.000
4	100	1.1	90.909
	300		272.727
	500		454.545
	700		636.364
	900		818.182
5	100	1.3	76.923
	300		230.769
	500		384.615
	700		538.462
	900		692.308

The critical effect from each of these parameters will be analyzed to control and predict the coning from happening. In order to identify the trend of the graph easily, the interval values of the investigated values are synchronized. For example, the interval value for viscosity is 1.0 cP. Then, the gradient of the graphs will be easily analyzed. To generate the cases for each of the parameters, the other parameters were constant and changed the value of the investigated values until ten cases. This work will be done for all the parameters.

A further study has been done to investigate the effect of the combination of critical parameters on coning through oil critical rate equation which showed in Table 4. That combination of critical parameters produced mobility ratio (k/μ) which can be justified by dividing horizontal permeability with the viscosity. To execute the mobility ratio, the range of values for viscosity and horizontal permeability were narrow down to the most critical values. The stated values for viscosity and horizontal permeability in Table 4 seems to be most critical and always been used in development.

Then, the critical parameters from the correlation will be investigated more. The combination of the parameters provided new critical parameters. It is essential to obtain the value of oil critical rate above which water coning will occur. Moreover, different production scenarios are also proposed to determine their effect on water coning. When the pressure drawdown decreases, oil production rate also decreases thereby reducing the tendency for water coning. Furthermore, the recovery factor can be increased significantly by decreasing the amount of water produced. Tables 5 to 8 show the rock and fluids' properties used for the analysis.

Calculation Steps

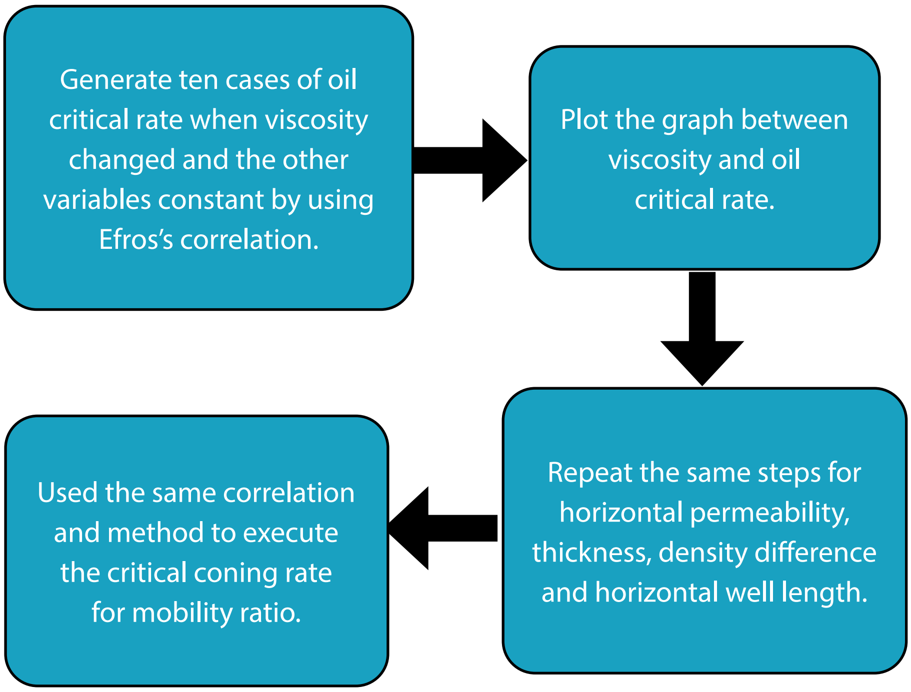


Figure 3 Parameters Calculation Steps

Table 5 Rock Properties

Rock Properties	
Rock compressibility	0.000003 psi^{-1}
Horizontal permeability	500 mD
Vertical permeability	500 mD
Porosity	0.274
Net to Gross Ratio (NTG)	1.0
Pressure	5684 psia
Temperature	260 ˚F

Table 6 Fluid Saturations

Fluid Saturations	
Interstitial water saturation	0.170
Residual oil saturation	0.250

Table 7 Oil Properties

Oil Properties	
Formation Volume Factor	1.376 RB/STB
Viscosity	0.826 cP
Density	43.6 lbm/ft^3

Table 8 Water Properties

Water Properties	
Formation Volume Factor	1.03 RB/STB
Viscosity	0.42 cP
Density	1.5 lbm/ft^3

RESULTS AND DISCUSSION

In this chapter, the results and work progress from the simulation will be displayed. The effect of viscosity, horizontal permeability, density difference, thickness and length of horizontal wells towards coning will be analyzed. Furthermore, the mobility ratio which was obtained from available parameters also will be justified. Figures Four to Eight were generated according to the specified cases and the range of parameters. Each scenario is named from Well 1 to Well 10 for easy designation. Well 1 is characterized by the smallest values of each parameter while Well 10 is defined by the highest range of the parameters.

Effect of Viscosity

For this parameter, the plotted graph in Figure 4 showed the effect of different viscosity values towards the oil critical rate. From the result, the oil critical rate reduced as the viscosity increased. This is due to the viscous oil that is difficult to displace by the fluid caused the production of oil decreased. As the viscosity increased from 1.0 cP to 2.0 cP, the effect of viscosity showed more pronounce. This is due to the first increase of viscosity value that caused the flow of oil to become more difficult compared to the usual flow. After 2.0 cP and above, the value for oil critical rate diminished. This can be concluded that heavy oil resulted in the lowest oil critical rate compared to the light oil which resulted in the highest oil critical rate.

Effect of Horizontal Permeability

Figure 5 shows that increasing horizontal permeability would result in higher critical oil rate. This is due to the tendency of oil to flow in higher permeability condition is increased. When the permeability is high, the ability of the oil to flow in the formation is high. Permeability is one of the controlling factors that control the flow rate of oil. This factor becomes more efficient in horizontal well because of the negligible gravitational effect which is more pronounced in vertical direction hence resulting in more production. From the graph, the different slope between each well is about 0.05.

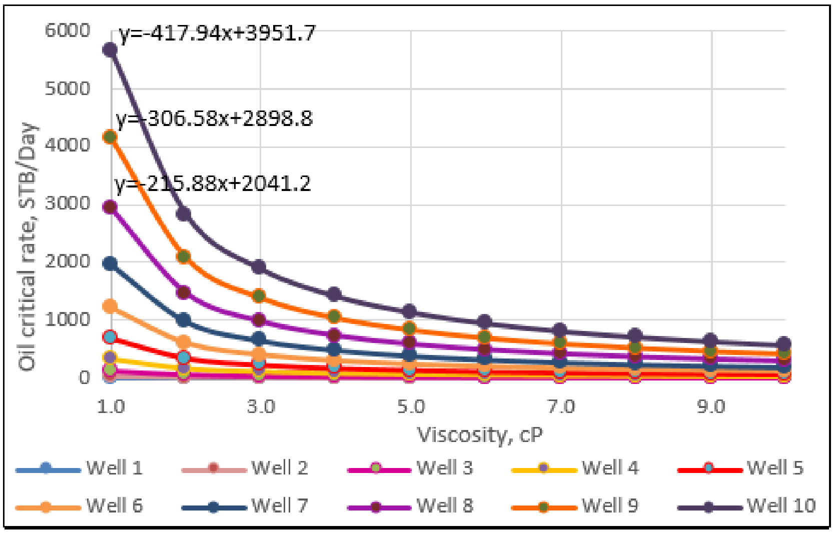


Figure 4 Effect of viscosity on critical coning rate

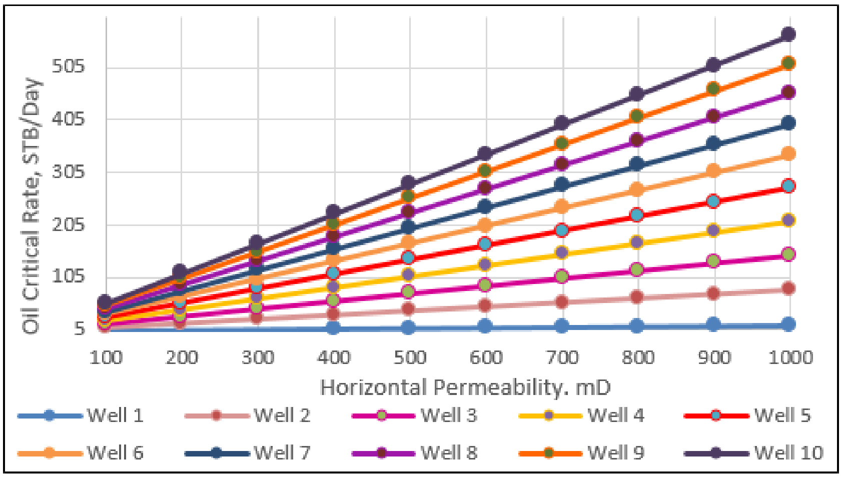


Figure 5 Effect of horizontal permeability on critical coning rate

Effect of Density Difference

For this parameter, the plotted graph in Figure 6 shows that the higher the density difference between oil and water, the higher the oil critical rate. The heavy oil resulted in lower density difference and hence gave lower oil critical rate. This will delay the water coning to happen and conclude that the coning problem is a tendency to happen in heavy oil compared with a light oil [4]. From the plotted graph, the different slope between each well is about 2.10.

Effect of Thickness

Figure 7 shows that the increased thickness of a reservoir gave a lower oil critical rate. The effect of thickness usually due to compaction stress but not very significant for this correlation. Oil critical rate resulted in slightly change with the different thickness which showed the thickness does not affect more to the oil critical rate when using Efros's correlation.

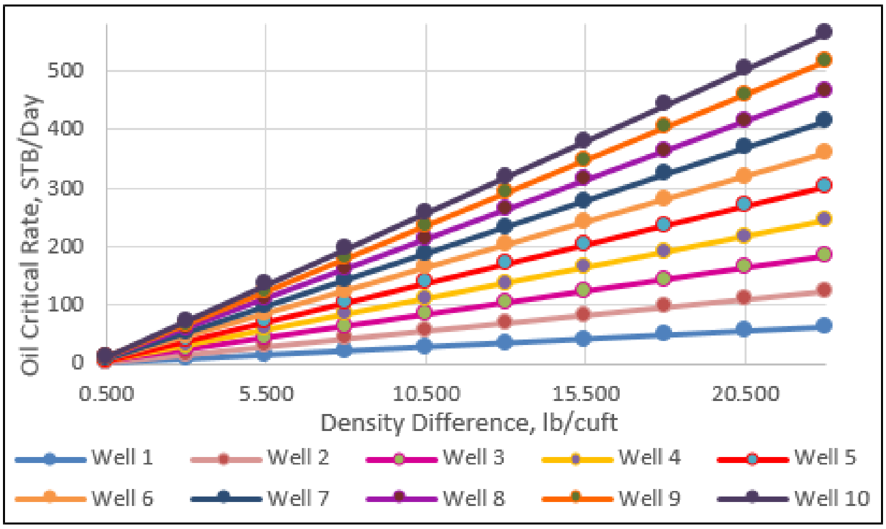


Figure 6 Effect of density difference on the critical coning rate

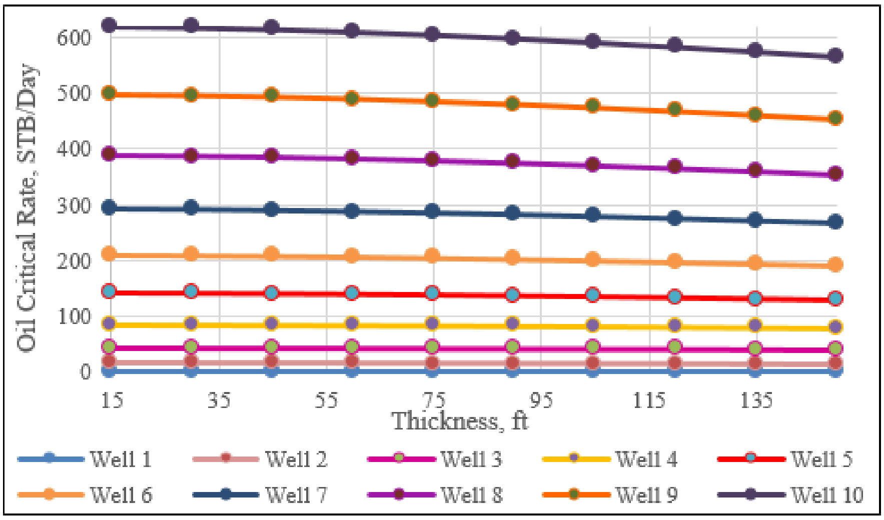


Figure 7 Effect of thickness on critical coning rate

Effect of Horizontal Well Length

Figure 8 shows that the oil critical rate increased as the length of the horizontal well also increased. This is due to the larger drainage area and high permeability caused the tendency of oil to enter the well is higher. This will increase the water breakthrough time for water production [4]. The different slope between each well is about 0.01.

From the analysis of the parameters, the most critical parameters that affect the oil critical rate are the viscosity and the density difference. The formation thickness contributed insignificantly to the coning as shown in Figure 7. Therefore, the production can be planned or controlled before reaching the maximum point of production before the oil flow along with the unwanted phase. If the critical oil rate is high, the

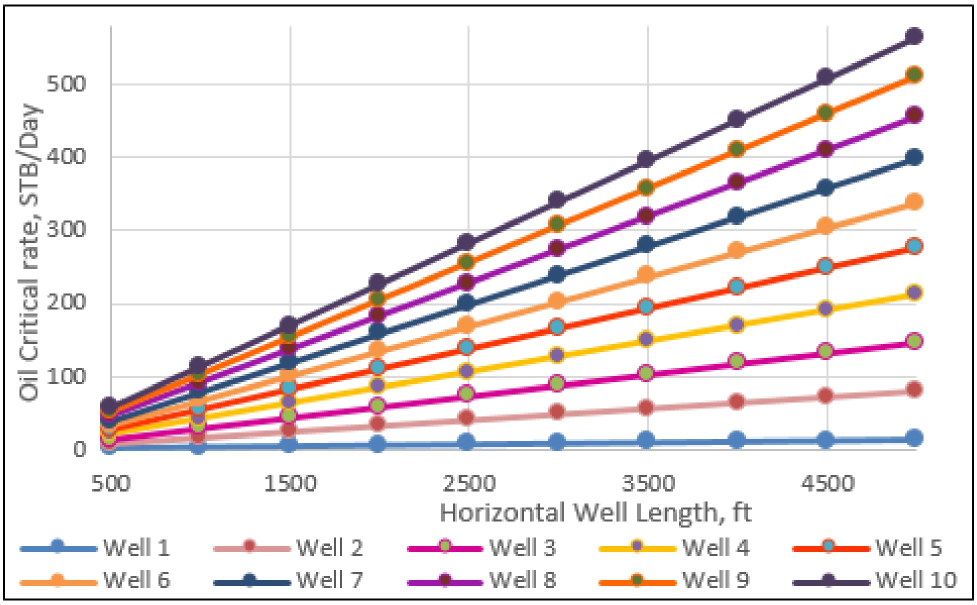


Figure 8 Effect of horizontal well length on critical coning rate

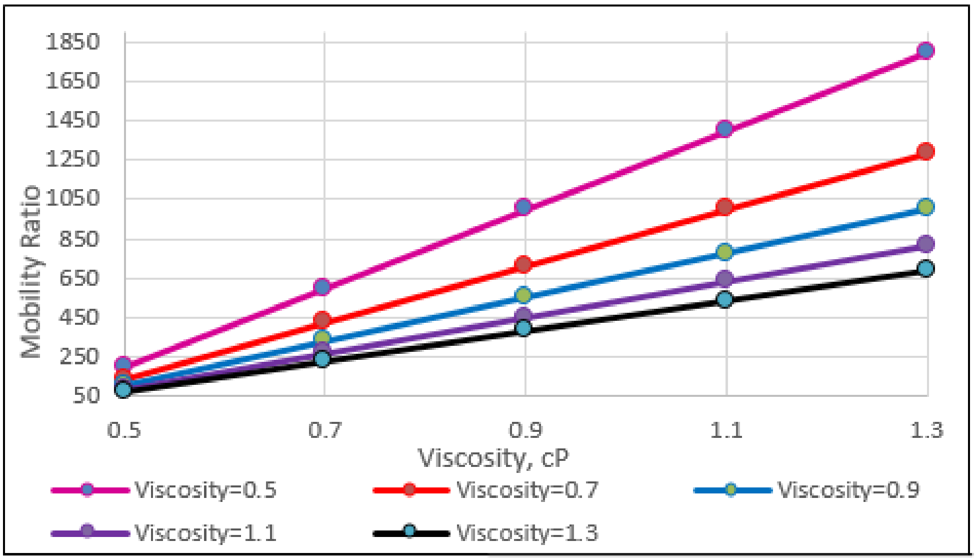


Figure 9 Effect of viscosity on mobility ratio

tendency for coning to occur will take a long time, thus facilitating sustainable gain in production.

Effect of Mobility Ratio

For this parameter, the plotted graph in Figure 9 and 10 show the critical oil rate and mobility ratio values that were generated by using Efros's correlation. The effect of mobility ratio (k/μ) also important to forecast oil critical rate. In order to determine which parameter gives the critical effect on mobility ratio, the graph between viscosity vs oil critical rate and permeability vs oil critical rate were plotted respectively. The effect of viscosity is more significant compared to permeability since the viscosity has the highest slope compared with permeability which is 2000 and 2 respectively.

a particular well. When the wellbore pressure reduces, oil production rate decreases. The consequent reduction in production rate would lead to less water production at the surface since water production is affected by the pressure drawdown in the wellbore. When water production is low, oil recovery could increase.

For full-scale study, we recommend that an integrated field development package be used to model various operating scenarios with different correlations or models. The results should be validated with field data and fine-tuned for future development and management of water coning in wells.

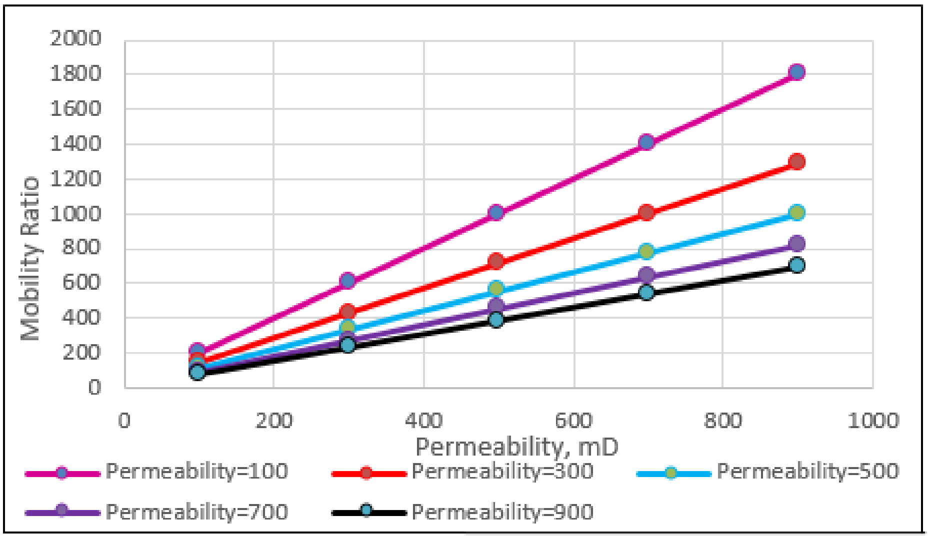


Figure 10 Effect of permeability on mobility ratio

CONCLUSION

Fluid and formation properties play key roles in determining the critical oil rate. Analysis has shown that viscosity has the most significant effect towards oil critical rate, followed by density difference. As the oil critical rate getting higher, the tendency for coning to occur takes a long time thereby resulting in sustained production. Furthermore, water coning problem can be predicted and controlled when the critical parameters are within the specified ranges for

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