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Investigation of gas and water coning behavior for the enhancement of oil production

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Abstract−This study presents the extensive simulation to control the concurrent behavior of gas and water coning in oil reservoir with existence of a bottom aquifer. From simulation results, coning phenomena were observed even with the critical oil rate obtained analytically. It is because the critical rate is calculated using a steady state expression. In order to examine the coning behavior, firstly, we have run for various oil layer thicknesses. The result in case of thin layer shows early breakthrough of gas and water cones and the increase in water-oil ratio from the beginning of production. Meanwhile, for the thick case of 200 ft, there is no water breakthrough observed even though water cone has been already formed because it is stable. Since gas and water cones move mainly in a vertical direction, cone development is affected by a vertical permeability. As a result of runs for vertical permeabilities, the breakthrough time is getting delayed as the vertical permeability is smaller. In the case of a high vertical permeability, the shape of the water cone is developed in a concave form at the beginning. After two years of production, however, this cone shape becomes almost flat since the water-oil contact is elevated uniformly throughout the whole reservoir. In the analysis of coning behavior for different aquifer sizes, it is found that the aquifer size does not affect both cone shape and water-cut. But with a strong bottom aquifer the behavior of gas coning is greatly decreased since the pressure is maintained by the active aquifer. The extent of well penetration into the oil layer has a considerable effect on coning phenomena. As the completion interval is decreased, the breakthrough time is delayed. However, a large pressure drop occurs in the shortest interval so that it worsens the well productivity. The most practical method to control coning is the oil production rate. Production of gas and water can be minimized by keeping oil rates as low as possible. However, a low rate is directly linked to well's economics, and therefore, the optimizing process for the production rate is essential.

Key words: Coning, Critical Oil Rate, Breakthrough Time, Simulation, Productivity

INTRODUCTION

The production of water and gas from oil well is a common occurrence and it increases production cost and reduces the overall oil recovery [1]. The water and gas coning phenomena are the major problem in reservoirs with either a huge gas cap or a strong bottom aquifer. Coning is caused by the imbalance between gravity and viscous forces around the completion interval [2]. The viscous forces drive the oil flow into a wellbore with a pressure drawdown. These dynamic forces tend to lower the gas-oil contact and elevate the water-oil contact in the immediate vicinity of the well. On the contrary, the gravitational forces have a tendency of gas to remain above the oil zone because of its lower density and of water to remain below the oil zone because of its higher density. When the viscous forces at the wellbore exceed the gravitational forces due to an increase of production rates, then gas and water cones grow up toward a perforated interval and ultimately produced into a wellbore. This produced gas and water causes complex flows through a wellbore and a pipeline as well as corrosion problems in facilities, so meticulous engineering should be conducted in the development process [3,4]. Therefore, it is very important to control the rate of oil production so as not to incur the coning, and this rate is termed a critical oil production rate [5]. When oil flows below the critical rate, the cone will not reach the perforation interval and coning will not be considered as a problem.

After the research by Muskat and Wyckoff [6], a number of correlations have been developed for predicting the critical rate as listed in Table 1. They presented an approximate solution of the water-coning problem in a homogeneous isotropic system. Their method assumes a steady-state, constant pressure condition in a partially penetrated well. By utilizing their system, they proposed the graphical method using the analytical solution of the Laplace equation without considering the change of potential distribution with time caused by coning phenomena. Chierici et al. [7] structured an anisotropic potentiometric model consisting of gas, oil and aquifer formations. They suggested graphical procedures to obtain the critical production rate. Meyer and Garder [8] derived the critical oil production rate from radial steady state flow equation in an isotropic system. Meanwhile, Pirson [9] developed the equation of critical rate not incurring both gas and water cones using Meyer and Garder model. Chaperon [10] proposed a simple relationship to estimate the critical rate of a vertical well in an anisotropic formation. She assumed the radial flow away from the well and the hemispherical flow near the well. The relationship accounts for the distance between OWC and GOC. Hoyland, Papatzacos, and Skjaeveland [11] obtained the critical oil production rate for a slightly compressible oil in a steady state flow condition both analytically and numerically.

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Table 1. The calculating methodologies of critical production rate

Methods	Yr.	Formulas	Remark
Muskat Wyckoff	1934	$Q_{oc}=\dfrac{4\pi k\Delta P\sum a_n b_n}{\mu_o\left\{\Phi_e-\dfrac{4}{t}\sum a_n b_n \log\dfrac{4t}{r_e}\right\}}$	Isotropic
Meyer Garder	1954	$Q_{oc}=0.246\times10^{-4}\dfrac{k_o(h^2-h_p^2)}{\mathrm{Ln}\left(\dfrac{r_e}{r_w}\right)\mu_o B_o}[\Delta\rho]$	Isotropic
Chierici Ciucci	1964	$Q_{oc}=0.0783\times10^{-4}\dfrac{k_o(h^2-h_p^2)}{\mu_o B_o}[\Delta\rho]\,\mathrm{fn}(h,r_w,r_e)$	Anisotropic
Pirson	1977	$Q_{oc}=0.246\times10^{-4}\dfrac{k_o(h^2-h_p^2)}{\mathrm{Ln}\left(\dfrac{r_e}{r_w}\right)\mu_o B_o}\mathrm{fn}(\rho_g,\rho_o,\rho_w)$	Isotropic
Chaperon	1986	$Q_{oc}=0.0783\times10^{-4}\dfrac{k_h(h-h_p)^2}{\mu_o B_o}[\Delta\rho]q_c^*$ $q_c^*=\left[0.7311+1.943\dfrac{h}{r_e}\sqrt{\dfrac{k_h}{k_v}}\right]$	Anisotropic
Hoyland Papatzacos	1989	$Q_{oc}=0.246\times10^{-4}\dfrac{k_h h^2}{\mu_o B_o}[\rho_w-\rho_o]q_{CD}$	Anisotropic

They assumed an infinite conductive system with a constant pressure at outer boundary and used a partially penetrating well.

However, these analytical critical rates have a tendency to underestimate the production rate uneconomically [12]. Furthermore, analytical critical rates cannot take into account anisotropicity, wettability, capillary pressure and unsteady-state condition [13]. Thus, it is difficult to apply them as an operational guideline in the actual fields. With the purpose of removing undesirable gas and water cones, several methods have been applied in gas and oil fields: injecting oil back to the reservoir [14], injecting polymers or gels to form a barrier between oil and water zones [15,16], producing oil and water separately with both downhole water sink wells [17,18] and downhole water loop installations [19]. But these extensive methods will not be covered in the study. Basically, we focus on the analysis of how reservoir characteristics and well operating conditions affect coning phenomena in a reservoir experiencing gas and water coning simultaneously. In this study, a reservoir simulation has been performed to investigate the sensitivity of various reservoir parameters and operational conditions on coning behavior in oil reservoir contacted with a bottom aquifer. Also, this study presents conformance control method to minimize the coning problem effectively.

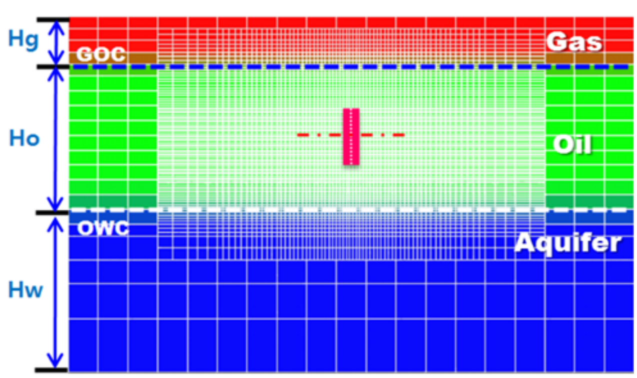

Fig. 1. Reservoir model for coning study as a base system.

SIMULATION SYSTEM

To analyze the coning behavior of oil reservoir in the presence of an active bottom aquifer, a two-dimensional model using Eclipse® 100 black oil simulator [20] was constructed as shown in Fig. 1 with the reservoir characteristics listed in Table 2. The local grid refinement around the well was set up for the purpose of investigating movements of the gas and water coning more in detail. This basic

Table 2. Input data for the simulation study of base system

Parameters		Values
No of cell (X-Z)		101×20 (LGR: 55,593)
Thickness [ft]	H_g	50
	H_o	125
	H_w	125
Permeability [md]	Horizontal	400
	Vertical	4
Porosity		0.25
Initial pressure [psia]		4,400
Bubblepoint pressure [psia]		5,600
Depth [ft]		8,985
Production rate [STBD]		500
Perforation depth [ft]		37.5
Density [lb/ft^3]	Gas	0.07
	Oil	54.6
	Water	63

system is a reservoir with an initial pressure of 4,400 psia which is lower than a bubblepoint pressure of 5,600 psia. The thickness of oil zone and the bottomwater aquifer is 125 ft and the gas cap is 50 ft. A vertical permeability is set to 4 md and a horizontal permeability is 400 md. The well is completed in the middle of oil layer with the perforation interval of 30% of oil zone thickness. The oil production rate was calculated as 500 STBD using Eq. (1). This equation (Chaperon [10]) was applied by considering the anisotropicity of this system.

$$Q_{oc}=0.0783\times10^{-4}\frac{k_h(h-h_p)^2}{\mu_o B_o}[\Delta\rho]\left[0.7311+1.943\frac{h}{r_e}\sqrt{\frac{k_h}{k_v}}\right] \quad (1)$$

SIMULATION RESULTS AND DISCUSSIONS

As the simulational result of the afore-mentioned basic system (Fig. 2), it shows that a water cone starts contacting the wellbore at 230 days, while the breakthrough of gas cone occurs at 170 days, where the cone shape presents a sharp concave. As the oil production continues with a constant oil rate, the cone tip approaches the center of the well and the cone becomes convex. After three years of production, the gas production reaches 16 MMSCFD and the produced water is about 360 STBD, while the water cut increases up to 42% as shown in Fig. 3.

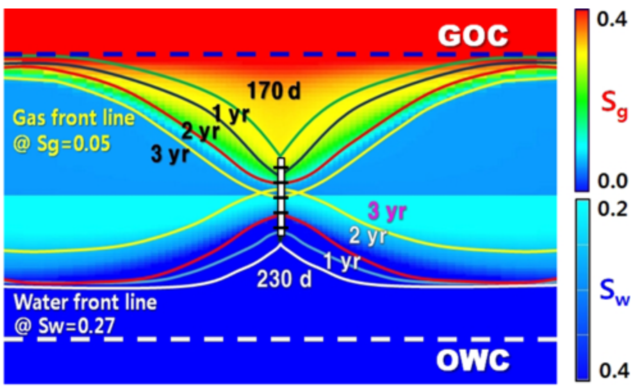

Fig. 2. Movement of gas and water cones with the time.

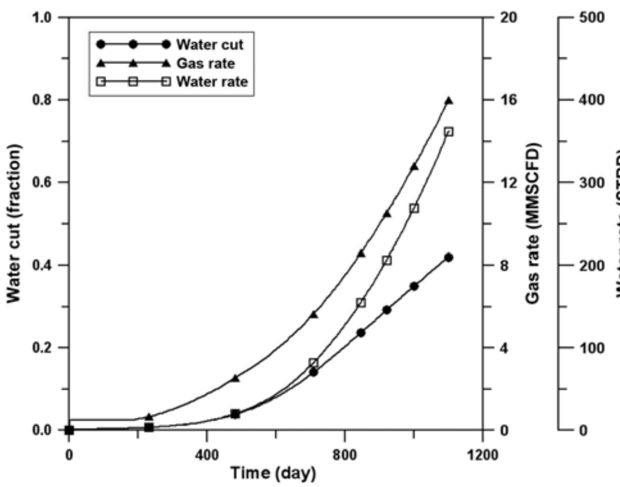

Fig. 3. Gas and water production.

In the simulation results using the critical rate calculated by Chaperon, the water cut was 42%, and hence the analytical solution for critical rate is greater than the rate obtained by simulation. In the analysis of oil producing behavior as shown in Fig. 4, the gas drives considerably the oil production at the beginning of production. After a water cone is generated at the well, the oil production is greatly influenced by the bottom aquifer. It is also observed from Figs. 2 and 5 that a productive interval is gradually reduced due to the growth of the gas and water cones simultaneously, and it yields 482 psia of pressure drop near the wellbore after three years of production with 500 STBD.

This time, we have run about reservoir characteristics such as oil

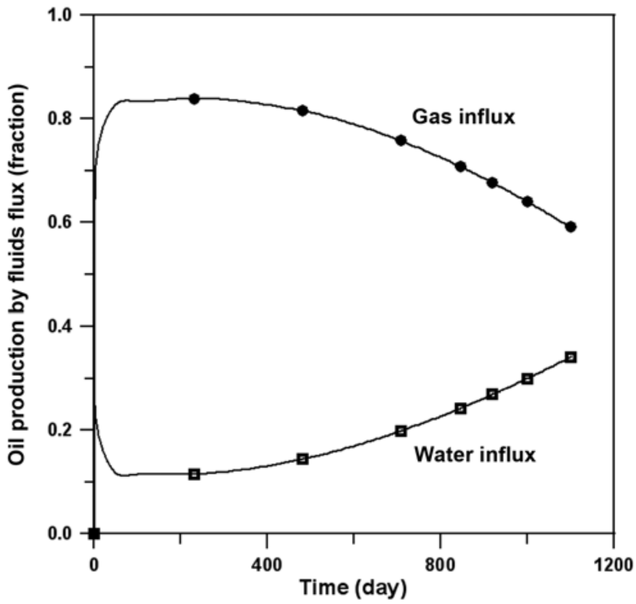

Fig. 4. Fraction of oil among total produced fluid by gas and water influx.

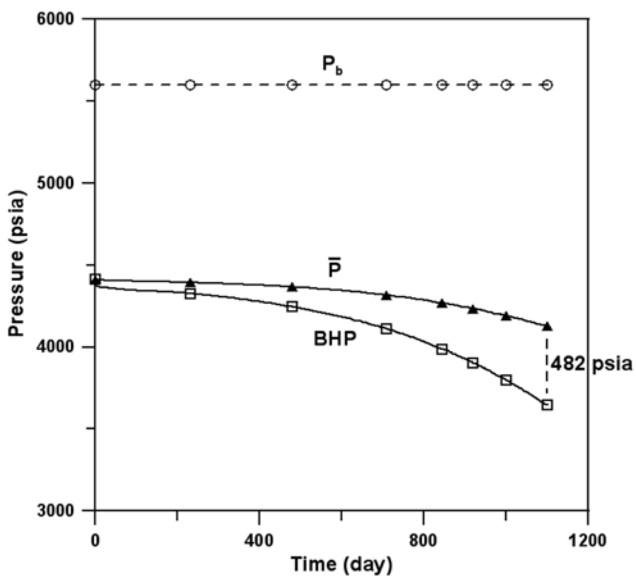

Fig. 5. The pressure behaviors of reservoir and well with the production.

layer thickness, vertical permeability, aquifer size in order to analyze their sensitivity to gas and water coning problems [21].

1. Effect of Oil Layer Thickness

Since a movement of cones follows the path from gas-oil interface or oil-water interface to the perforated interval at wellbore, coning behavior is affected directly by the thickness of oil formation. Therefore, the focus of a first investigation is to find the effect of pay zone thickness on a growth of gas and water cones. Four different cases of oil layer are considered: 100 ft, 125 ft, 150 ft and 200 ft.

Fig. 6 shows a general dependency of four cases such that the cone breakthrough time becomes longer as oil zone becomes thicker [22]. In the case of a thin oil layer as 100 ft, it is certain that the breakthrough time of gas and water cones has occurred at early producing time. Because of a decrease in an oil interval by the encroaching cones toward the well, after three years of production, the water-oil ratio dramatically increases to 90% and hence there is a significant pressure drop of 3,400 psia at the wellbore which consequently worsens the oil productivity (Fig. 7). However, when the oil pay thickness is increased to 150 ft, 200 ft in this system, the breakthrough time of gas and water cones is delayed with the decrease in water cut. In particular, for the thickest case 200 ft, it is observed that water cone did not invade the producing section of the well as shown in Fig. 8. This cone is stably present under the wellbore without the breakthrough.

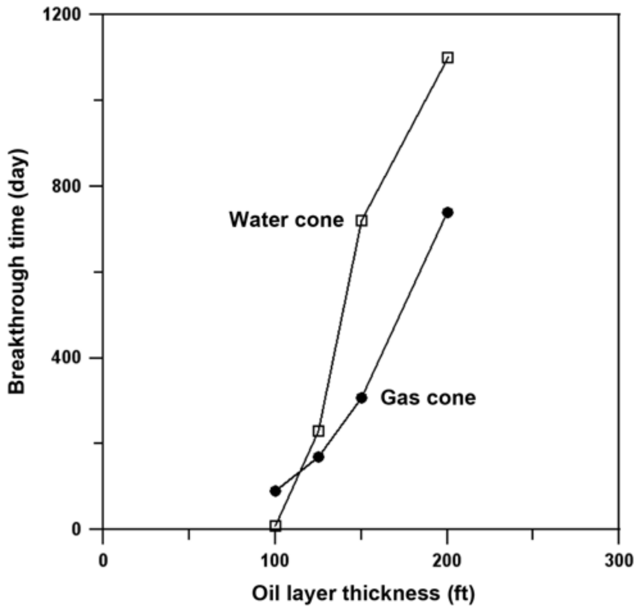

Fig. 6. Breakthrough time with different oil layer thickness.

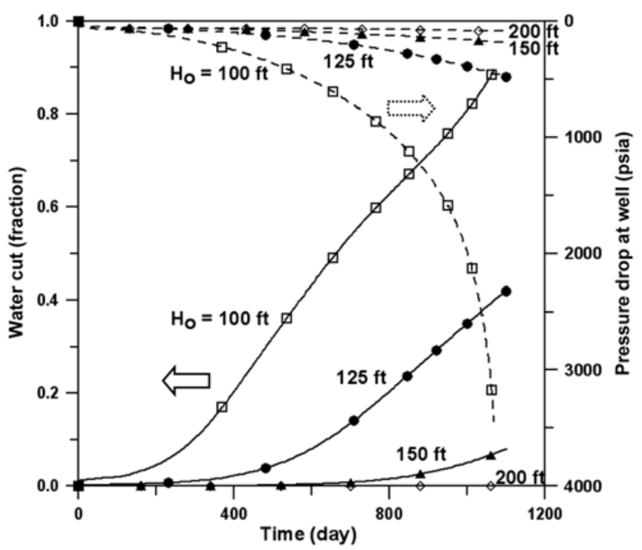

Fig. 7. The results of pressure drop at well and water cut for various thickness of oil layer.

2. Effect of Vertical Permeability

As mentioned earlier, the mechanism of coning occurrence is caused by an imbalance between the viscous force generated by pressure gradient and the gravitational force created due to fluid density. It is evident that the degree or rapidity of the coning behavior may significantly depend upon the vertical permeability. A number of simulations for various values of vertical permeability from 4 md to 100 md are selected.

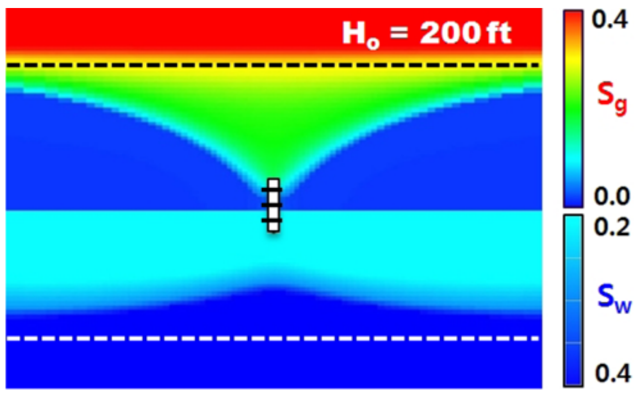

Fig. 8. The oil saturation distribution in the case of 200 ft of oil layer.

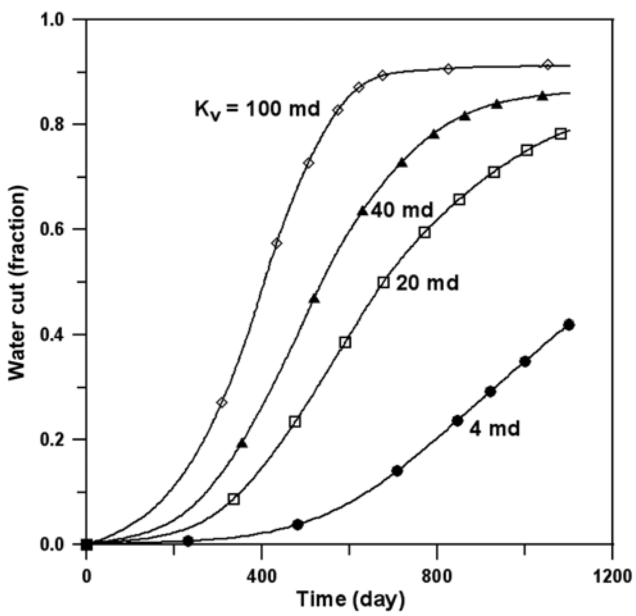

Fig. 9. The result of water cut for various values of vertical permeability.

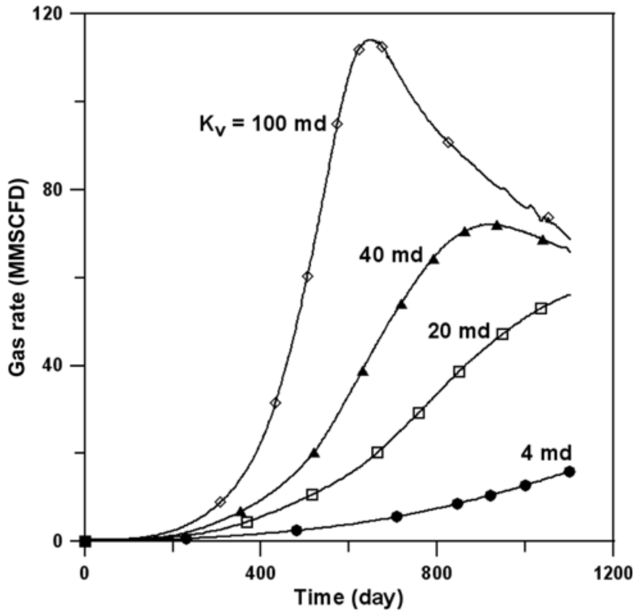

Fig. 10. The result of gas production rate for various values of vertical permeability.

From the results of Fig. 9, as the vertical permeability is greater, and the water coning occurs at the earlier time of production [22]. Specially, in case of the greatest vertical permeability of 100 md, the water cut reaches almost 90% and the produced gas is more than 100 times compared to that of 4 md system. Therefore, gas production starts decreasing at 670 days while gas rates of other cases are still increasing (Figs. 9 and 10). Another important point is the growth of the cone shape. Generally, water cone grows with a concave shape around the wellbore during the whole period of production. However, when vertical permeability is getting greater, the water cone initially develops with a concave shape at early times, but after two years of production, this cone shape appears to be almost flat as if the cone is disappearing since the water-oil contact is elevated uniformly throughout the whole reservoir as it can be seen in Fig. 11. It may be that a greater vertical permeability accelerates the water influx from the bottom aquifer. For this reason, water production is much higher than that of lower permeability to produce the oil at a constant rate and reservoir pressure is depleted rapidly.

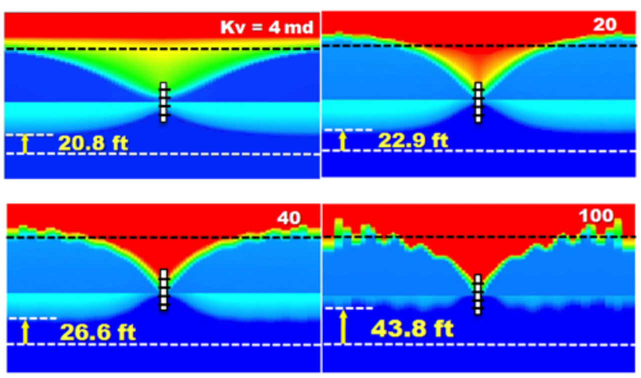

Fig. 11. The results of gas and water coning for various values of vertical permeability (after 2 year of simulation).

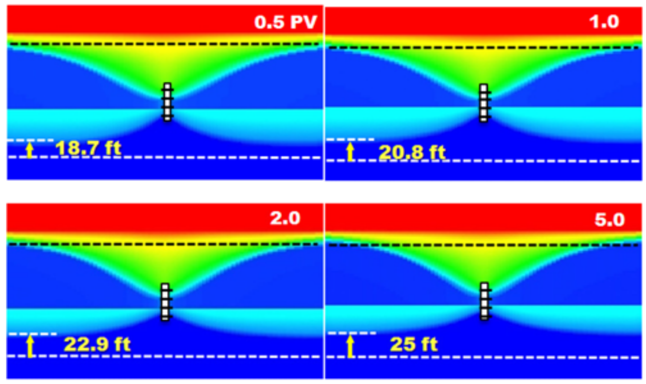

Fig. 12. The results of gas and water coning for various cases of aquifer size.

3. Effect of Aquifer Size

In the study, the effect of aquifer sizes was tested by considering different ratios of the pore volume of the aquifer to that of the oil zone. It is intended to vary the aquifer potential differently. The strength of aquifer affects the amount of water influx and the pressure change of a reservoir [23]. However, in calculation of critical production rate analytically, only viscous force and gravitational force are considered without including the aquifer size. We therefore ran the model to investigate the impact on coning behavior of varying aquifer sizes over the range from 0.5 to 5 times of oil reservoir pore volumes.

The results in Fig. 12 show that the aquifer size does not affect the development of gas and water cones. It is also obvious that the changes of both breakthrough time and water-cut are not significant with the aquifer sizes (Fig. 13) [19,24]. However, in case of the largest aquifer with five times greater than oil pore volumes (5 PV), the gas production rate is reduced to 10 MMSCFD which is lower compared to the case of 0.5 PV as 19 MMSCFD from the results of Fig. 14. In addition, it was found that the stronger the supports of the aquifer, the higher the upward progression of an aquifer

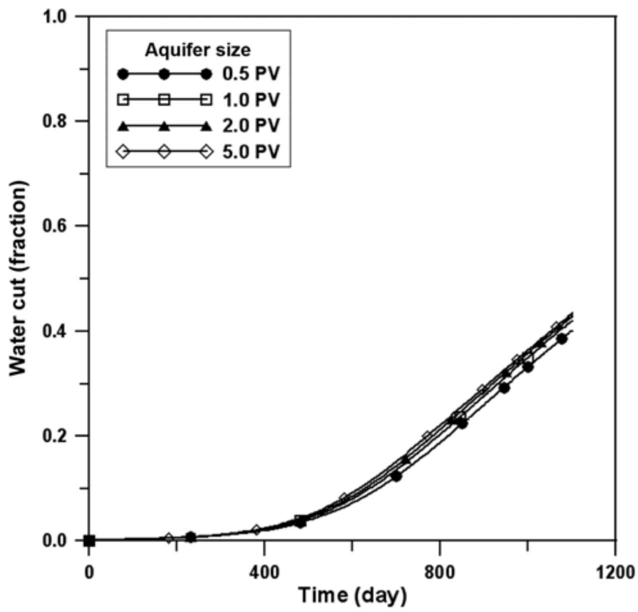

Fig. 13. The results of water cut for various cases of aquifer size.

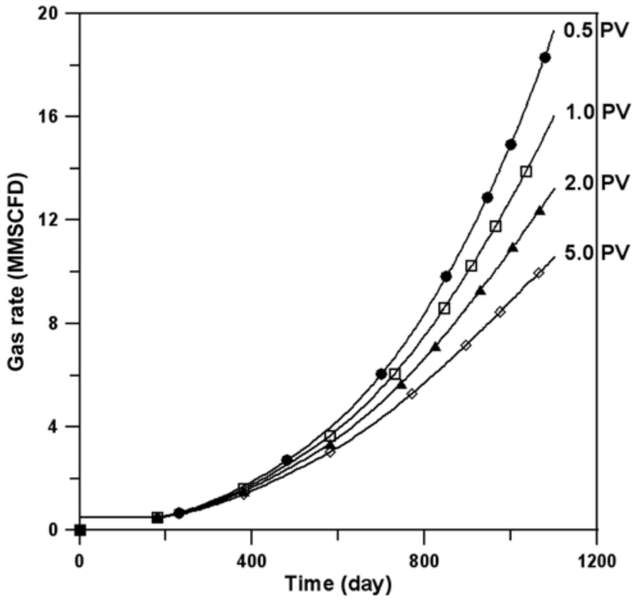

Fig. 14. The results of gas production rate for various cases of aquifer size.

from its original oil-water contact (Fig. 12). Accordingly, the effect of aquifer size can be explained as that a strong aquifer supports the reservoir pressure to some extent, which reduces the rapid depletion of reservoir pressure and reduces gas mobility. The presence of a strong aquifer appears to play the key role in reducing both the growth of gas cone and gas production, although it has very little effect on water cut as well as water encroachment.

After reviewing the effects of reservoir characteristics to the coning, we have run about operational conditions such as well penetration and oil production rate to investigate the sensitivity to coning behavior.

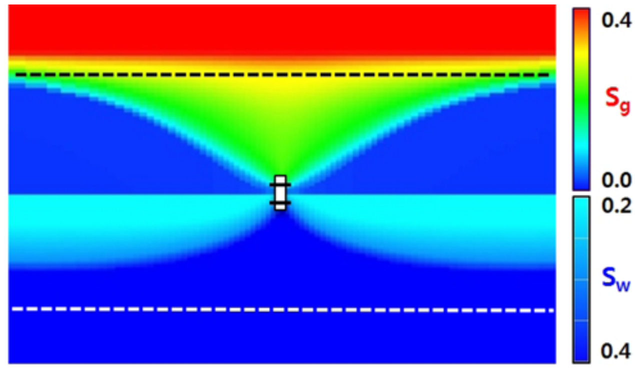

Fig. 16. The result of coning in the case of completion interval of 12.5 ft.

4. Effect of Well Penetration

Pressure drawdown is a function of distance between well penetration and oil-water contact. If this distance increases, the viscous force will be decreased and the cone will be stabilized even with the case of high production rates. Therefore, the design of completion interval has considerable effect on coning behavior similar to the oil layer thickness. Four different cases were run with perforation interval.

As a result of simulation presented in Fig. 15, as the completion interval is designed to be shorter, the breakthrough time is delayed. When the perforation interval is the shortest case as 12.5 ft, although the water cut is not changed much as 40% comparing to 42% of the base system, oil productivity is significantly decreased by examining the large pressure drop of 852 psia (Figs. 16 and 17). The oil producible interval at the wellbore is also reduced due to gas and water cones. On the other hand, in cases of longer perforating intervals such as 62.5 ft and 87.5 ft, the water breakthrough almost immediately happens as the production is commenced, and that affects the oil productivity adversely [25].

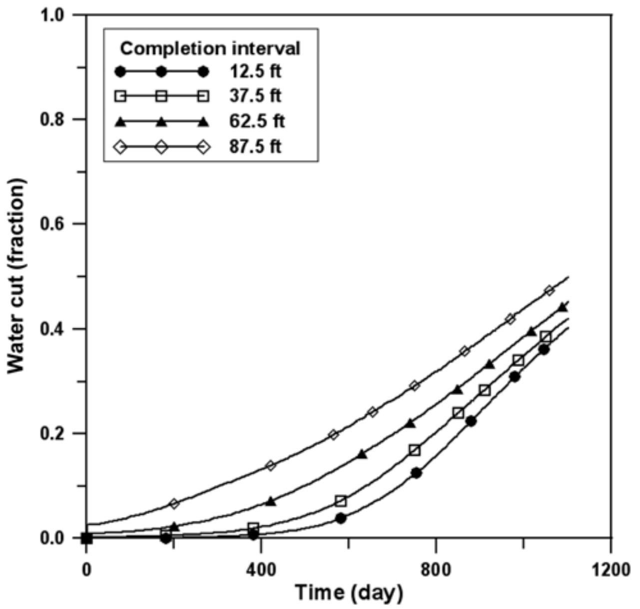

Fig. 15. The results of water cut for various cases of completion interval.

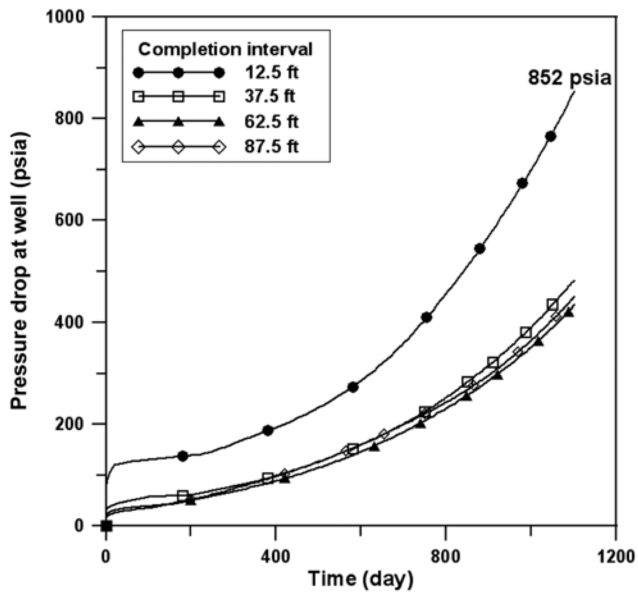

Fig. 17. The pressure drop at well for various cases of completion interval.

5. Effect of Oil Production Rate

Since the growth rate and size of gas and water cones affects oil production, the optimization of production rate is essential for controlling the coning behavior [5,23,24]. In this sense, several simulation runs were performed with oil production rates ranging from 100 to 600 STBD.

As we can observe from Fig. 18, the less the oil rate, the less the water cut takes place with delaying a breakthrough time significantly. For oil rate of 200 STBD, the water cut has approached almost to zero and there is no water breakthrough into the well, although the water cone has been already formed below well penetration as shown in Fig. 19. In other words, the water cone remains in a stable condition at this oil rate. However, for 600 STBD compared to 500 STBD of the base system, the water cut is increased from 42% to 60%, and the sizes of gas and water cones grow together, encroaching the center of the producing interval. Therefore, a severe pressure drop over 1,000 psia occurs at the wellbore. By this result, we understand that the development of gas and water cones can be easily avoided by controlling the production rate as low as possible. However, this low production is neither practical nor profitable in the aspect of the well's economics. Therefore, the process to optimize the production rate is essential by considering both operational conditions and long-term economics.

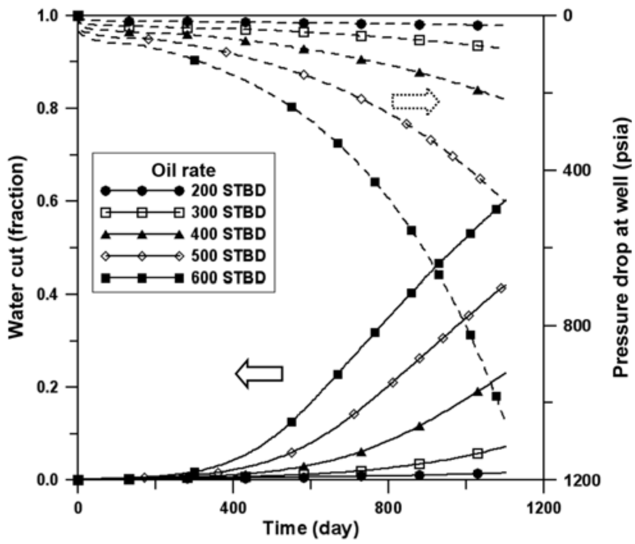

Fig. 18. The results of water cut and pressure drop at well for various values of oil production rates.

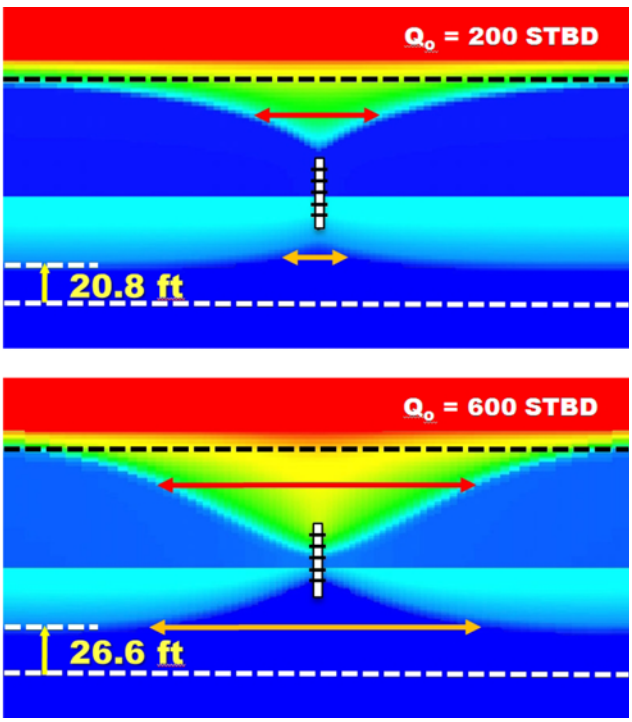

Fig. 19. The result of coning for oil production rates of 200 and 600 STBD.

CONCLUSIONS

An extensive simulation has been performed to understand the concurrent behavior of gas and water conings in an oil reservoir and the following conclusions are drawn:

1. The coning tendency is generally more severe in thin oil layers which yield the early breakthrough of gas and water cones, and it increases in water-oil ratio while reducing the oil producible interval. In the case of 200 ft oil thickness, which is the thickest case in this study, there is no water breakthrough observed even though the water cone has been already formed. This cone is stably present at the below of the bottom of well penetration depth.

2. In the case of a high vertical permeability system, the shape of the water cone is initially developed in a concave form. After two years of production, however, this cone shape becomes almost flat so that the cone disappears since the water-oil contact is elevated uniformly throughout the whole reservoir.

3. The behavior of gas coning is mainly dependent upon aquifer size. In the analysis of the simulation result, the aquifer size does not affect both cone shape and water-cut as well. When a strong bottom aquifer is activated into a reservoir, the gas coning behavior is greatly decreased since the pressure is maintained by the active aquifer.

4. The extent of well penetration into the oil layer has a considerable effect on the coning phenomena. As the completion interval is designed to be shorter, the breakthrough time of coning is delayed. However, a large pressure drop occurs in the shortest interval case so that it worsens the well productivity. On the other hand, in the case of longer perforating interval, the water breakthrough almost immediately happens as production is commenced, and that affects the oil productivity adversely.

5. The most effective method for controlling the coning behavior is the oil production rate. By adjusting the oil rate as low as possible, less water cut takes place with delaying breakthrough time of the two cones significantly. But the low rate is directly linked to the well's economics, and therefore, the optimizing process for the production rate is essential by considering both operating conditions and long-term economics in advance.

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NOMENCLATURE

a_n : density of hypothetical flux element [lb/ft^3]
B_o : oil formation volume factor [rb/stb]
b_n : depth of a hypothetical flux element of density a_n [ft]
BHP : bottomhole pressure [psia]
BT : breakthrough time [day]
GOC : gas-oil contact
h : oil formation thickness [ft]
h_p : perforated interval [ft]
H_g : gas formation thickness [ft]
H_o : oil formation thickness [ft]
H_w : aquifer formation thickness [ft]
k_h : horizontal permeability [md]
k_o : oil effective permeability [md]
k_v : vertical permeability [md]
OWC : oil-water contact
q_{CD} : dimensionless critical oil rate
Q_{oc} : critical oil rate [stb/d]
P_b : bubblepoint pressure [psia]
$P_{average}$: average pressure of reservoir [psia]
P_{Drop} : pressure drop at the well [psia]
PV : pore volume [cubic feet]
r_e : drainage radius [ft]
r_w : the wellbore radius [ft]
S_g : gas saturation
S_w : water saturation
t : thickness of oil layer
ΔP : total pressure drop in the oil zone, psia
Φ_e : potential function in the oil zone
ρ_g : gas density [lb/ft^3]
ρ_o : oil density [lb/ft^3]
ρ_w : water density [lb/ft^3]
$\Delta\rho$: density difference, ρ_w-ρ_o [lb/ft^3]

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