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Original Article

Prediction of Gas Coning in Hydrocarbon Reservoir using tNavigator

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Abstract

Gas coning is a phenomenon caused by gas penetration from the gas cap, which reduces oil production. It is a near-wellbore phenomenon associated with high production rates. The gas coning issue would have a negative impact on the oil industry's operations and economics. Thus, it is critical to monitor such a problem in order to increase the productivity of oil recovery and postpone the breakthrough time by employing some analytical methods and simulation software and investigating this problem to find the best solution. In this study, an analytical and numerical approach was used in this research for the purpose of gas breakthrough time investigation and monitoring the gas-oil ratio (GOR). tNavigator embedded flow equation was used as a novel 3D compositional simulation principle in the software to predict the time of gas flow from grid cell to another reaching the perforation interval, for the purpose of utilizing the sensitivity analysis of certain parameters which had sufficient impact on GOR value and breakthrough time (tBt). Results show that the Oil column is the one of the most effective parameters in the sensitivity analysis and its one of the important factors to be focus on while producing from gas cap reservoirs.

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1 Introduction

In 1994, Hatzignatiou and Mohamed [1] both explained that coning in vertical wells or cusping in horizontal wells in hydrocarbon reservoir is considered to be a production problem, because it mainly influences the oil production performance. The gas from the gas cap layer will pass through the perforated interval into the well during the production operation. Because the oil and gas in the reservoir exist at a constant pressure, attempting to extract oil from it would result in pressure depletion around the wellbore in the oil zone (voidage area). The gas will respond to pressure drops due to the pressure difference between oil and gas as shown in Fig. 1.

Because of the gravitational forces that can segregate the fluids forming the GOC interface, the gas will try to stay above the oil zone because it is less dense than the oil, but in order to counterbalance the pressure gradient created by oil production, these forces will lower the GOC near the wellbore perforation zone.

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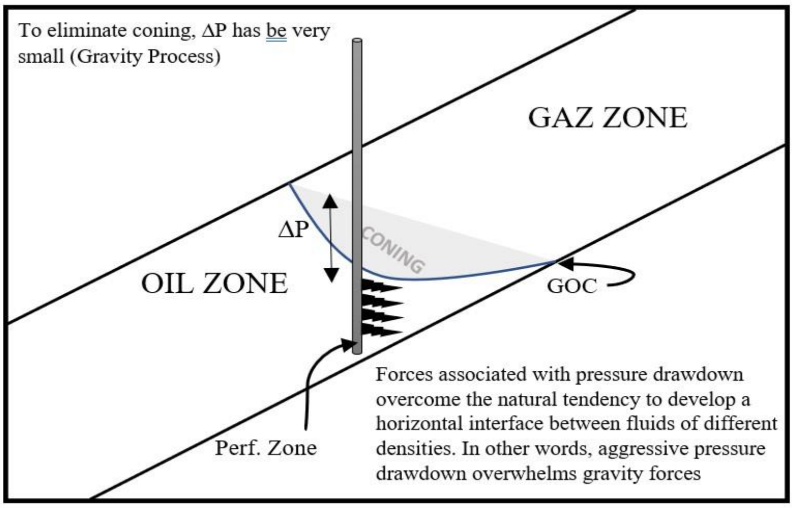

Fig. 1 The Downward Coning of Gas Caps.

Coning phenomena can be affected by a variety of factors, including the density of the fluids in the reservoir (oil and gas), pressure draw-down, gas viscosity, formation characteristics such as permeability, porosity, and flow rate. More precisely, the ability of the gas to cone is proportional to the density differential between the gas and the crude oil, and inversely proportional to the viscosity of fluids and the reservoir permeability [1]. However, in order to minimize gas coning, the following procedures are being followed:

- lowering the production rate to below the critical rate [Maintain the production rate to not exceed the critical rate]
- well productivity should be enhanced [Stimulate the well performance]
- the penetration length should be at the bottom of the pay zone, as far away from the top of the gas coning as possible, to delay the breakthrough of the gas
- increase the distance between the GOC and the perforated interval, and infill drilling.

Shutting down the well to stabilize the situation after the coning happens and the gas has broken through the oil well is a poor move. This can only be fixed if the gravity equilibrium conditions are met. It is incredibly difficult to remove the gas after it has been produced due to its features. Basically, three main correlations should be focused on in order to solve the coning issues:

- the calculation of critical rate.
- prediction of breakthrough time.
- calculation of the well performance after the breakthrough occurs – monitoring [GOR]

After a certain time of production, the local GOC will be lowered near the perforation area around the wellbore. Hence the gas will breakthrough into the well, and the GOR will be very strongly rate-dependent with the production rate. After reaching the breakthrough time, the gas will be created and will begin to increase, resulting in a sufficient reduction in oil output as well as early depletion of the drive mechanism.

Producing oil wells with coning issues that contribute to the production of an unfavourable gas phase would not be profitable, since the gas must be separated at the surface, which will require an additional cost to the operations. Additionally, the production of gas will effect on the drive mechanism of the reservoir and causing it to deplete rapidly, affecting on the recovery of the oil.

In a research by Isemin [2], it was observed that typically the gas produced from a gas reservoir by the gas well production has a valuable market. However, the gas produced from an oil well due to the coning phenomenon is unacceptable due to the large pay difference between the gas and the oil [Gas price is less than the oil price]. In order to achieve the targeted obtaining revenue, a financial plan is set for an oil well production. For example, a plan provided before the GOC lowered toward the perforated interval and the well start produced gas, this contributed in making an effective decision, whether to capture and store the produced gas at early time and/or delay the breakthrough time by tracking the GOR to a certain level.

Based on study by Olabode et al [3], once the gas phase started to produce along with oil well production, it's very essential to monitor the gas-oil ratio in order to predict breakthrough time of gas and to have a background on production performance. Furthermore, if the GOR increase to a level that makes the production become less valuable; This resulted in increasing the associated gas which makes the flaring strategies preferred in such situation. As a consequence, the environmental impact increased due to the greenhouse gases emitted from the process of gas flaring.

The gas produced from the reservoir would have an impact on the early drive mechanism depletion, as the gas cap assists in the oil extraction and as a result, the well can shut in and closed at an early stage. However, in order to have a proper solution to this issue, the analytical calculation should take into consideration the time of the coning to be grown and breakthrough into the well, as well as the production rate that can allow only one phase to be produced; Also, the numerical solution can be used by a simulator software tool that used in monitoring the well performance after the breakthrough by measuring the GOR in timely manner and contribute in sensitivity runs to analyse the effects of the reservoir parameters on delaying breakthrough time. In summary, the present study aimed to compare different Gas Coning correlations in order to identify the pros and cons of each correlation. Then to select different gridding strategy for dynamic simulation modelling (using a reservoir simulator) to find the best method in gas coning simulation. Finally, to investigate the impact of different rock and the fluid properties, as well as operational parameters, on gas coning prediction.

2 Methodology

The overall methodology of this study is described in Fig. 2a. Furthermore, the following steps will be implemented by the authors in order to achieve the current study objectives.

1. Collection of Two data sets:

- Different data sets: For the purpose of testing equation's parameters, principles, assumptions and validation.
- One data set: For the purpose of comparison between different correlations in order to determine the highest critical rate.

2. Analysis: (The findings of the analysis will lead to the achievement of the first objective)

- Four correlation models with the same parameters were selected to perform further analysis.
- Statistical analysis was performed by comparing the calculated critical oil rate with the simulated reservoir model (base case) which was generated from tNavigator software.

3. The implementation of the second and third objectives will be delivered by building a reservoir simulation model, which was created using Eclipse 300 code that had been modified.

- A simple reservoir model using a single well runs by tNavigator simulation software.
- A certain value of solution gas ratio will be specified in the model.
- Different gridding techniques were applied to the simulated model in order to monitor the GOR by predicting gas coning breakthrough time.
- Examining well performance through grid block perforations of gas-oil coning
- Sensitivity analysis was performed upon the parameters that may affect the GOR and the reservoir performance such as reservoir geometry, fluid properties, reservoir characterization - [oil flow rate, porosity effect, permeability effect, local grid refinements effect, perforated interval, density difference, etc].
- The simulated results were tabulated and analyzed in terms of breakthrough time by monitoring the GOR; A set of Rs value equal to 1.27 in RSVD table.

The application of correlations is implemented by using different data set gathered [4] for each correlation in order to check the validity, the principle of the equations, and the parameters used in each correlation for critical rate calculation. However, with a view of comparing the correlations among each other, one data set is needed to deliver the objective.

According to Onwukwe et al [5], some reservoir rock and fluid parameters were chosen based on the low and high value ranges shown in Table 1 to provide a comparison between certain correlations with similar parameters used to calculate the critical rate. In addition, the selected parameters for this paper are highlighted in Table 2 based on Table 1 as well as the reservoir simulation model's parameters set in the code. For example, the gas density value is selected based on the simulation model code.

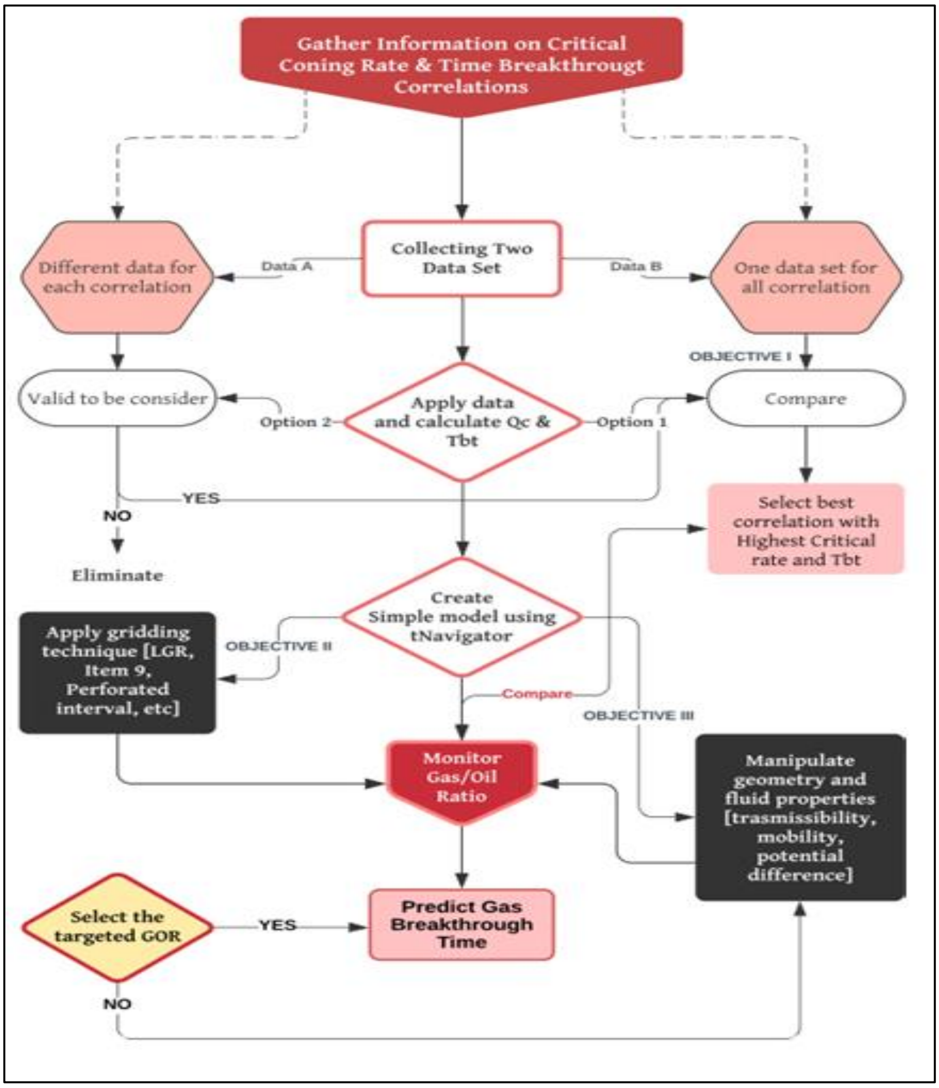

Fig. 2(a) Methodology flow chart.

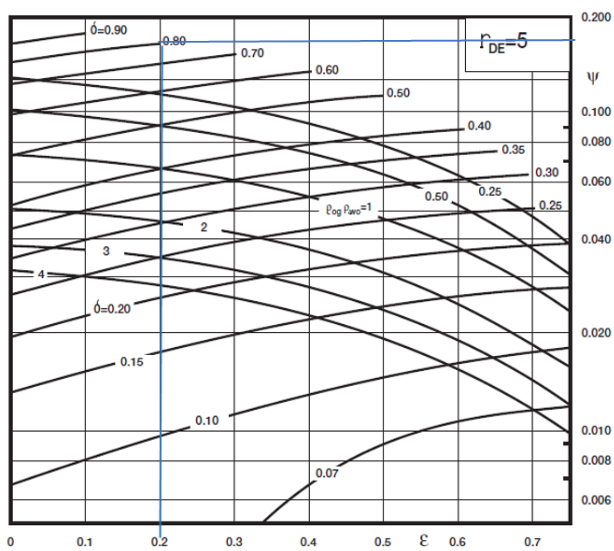

Fig. 2(b) The dimensionless radius (r_{De}) of 5.

The permeability of reservoir is considered to be different in a vertical and horizontal direction. The vertical permeability was much lower than the horizontal permeability because the reservoir is an anisotropy formation. In addition, the formation volume factor of oil (B_o), the relative permeability (k_{ro}), oil viscosity (μ_o), and gas viscosity (μ_g) have been calculated based on the average value from the data set in the model.

Table 1 Ranges of data by Onwukwe et al. [5].

Parameters	Given data		Unit
	Low	High	
ρ_o	47.2	58.64	lb/ft^3
ρ_g	6.45	13.52	lb/ft^3
ρ_w	62.42	66.52	lb/ft^3
k_h	100	5000	ft
h_o	20	80	ft
μ_o	0.24	1.05	cp
B_o	1.05	3.25	bbl/stb
A	50	800	Acres
L	500	1800	ft
r_w	0.25	0.455	ft

Table 2 Selected data based on Simulation Model and Table 1.

Parameters	Selected data	Unit
k_v	20	md
k_h	200	md
ρ_o	49.6302	lb/ft^3
ρ_g	0.062428	lb/ft^3
h_o	150	ft
D_e	3300	ft
r_e	1650	ft
r_w	0.25	ft
$h_p=h-D_t$	30	ft
$D_t=h-h_p$	120	ft
B_o	1.415	bbl/stb
kr_o	0.382	md
μ_o	0.738	cp
k_o	199.262	md

3 Results and Discussion

3.1 Calculation of Meyer and Garder [6] Critical Rate

The critical rate is calculated using Eq. (1):

$$Q_{OC} = 0.246\times10^{-4}\left[\frac{\rho_0-\rho_g}{\ln\left(r_e/r_w\right)}\right]\left(\frac{k_0}{\mu_0 B_0}\right)\left[h^2-\left(h-D_t\right)^2\right] \tag{1}$$

where:

D_t = The space or the distance between the GOC and the beginning of Perforation (ft)

Q_{oc} = The critical rate of the oil (stb/d)
k_o = The effective permeability of the oil (md)
h = The thickness of the oil zone (ft)
r_w and r_e = The radius of the wellbore and the drainage radius respectively (ft)
ρ_g and ρ_o = The gas density and the oil density respectively (lb/ft^3)

3.2 Calculation of Chierici-Ciucci [7] Critical Rate

The value of the dimensionless radius will be valid to apply in the correlation only if the range between $5 \le r_{De} \le 80$. The dimensionless radius, r_{De} was written as:

$$r_{De} = \frac{r_e}{h}\sqrt{\frac{k_h}{k_v}} \tag{2}$$

The value of the dimensionless perforation will be valid to apply in the correlation only if the range between $0 \le \varepsilon \le 0.75$. The dimensionless ratio of gas coning, δ_g was written as:

$$\varepsilon = h_p / h \tag{3}$$

The value of the dimensionless perforation will be valid to apply in the correlation only if the range between $0.070 \le \delta_g \le 0.9$.

$$\delta_g = D_t / h \tag{4}$$

The critical rate of the oil, Q_{oc} was written as:

$$Q_{og} = 0.492 \times 10^{-4} \frac{h^2\left(\rho_0 - \rho_g\right)}{B_0 \mu_o}\left(k_{ro} k_h\right)\Psi_g\left(r_{DE}, \varepsilon, \delta_g\right) \tag{5}$$

where:
Q_{og} = The critical rate of oil in the G-O system (stb/d)
k_h = The permeability in a horizontal direction (md)
ψ_g = The dimensionless function of gas
ψ_w = The dimensionless function of water
ρ_o and ρ_g = The density of the oil and the density of the gas, respectively (lb/ft^3)

By referring to the graph of r_{De} equal to 5 in Fig. 2b, to calculate the dimensionless function of gas.

3.3 Calculation of Chaperson [8] Critical Rate

By applying Eq. (6) for calculating the function of a:

$$a = \frac{X_A}{h}\left(\frac{k_v}{k_h}\right)^{1/2} \tag{6}$$

Calculating q_c^*:

$$q_c^* = 0.7311 + \left(1.943 / \alpha''\right) \tag{7}$$

By applying Eq. (8) for calculating the critical rate of oil:

$$Q_{OC} = 0.0783 \times 10^{-4} \frac{k_h\left(h - h_p\right)^2}{\mu_0 B_0}[\Delta\rho] q_c^* \tag{8}$$

where:
X_A = location of the constant pressure boundary (ft)
k_v and k_h = The permeability in vertical direction and horizontal direction, respectively (md)
h = Thickness of oil reservoir (ft)
h_P = Perforated interval (ft)
q_c^* = dimensionless flow rate
B_o = Oil volume factor
μ_o = Oil viscosity (cp)
$\Delta\rho$ = Difference of gas and oil density (lb/ft^3)

3.4 Calculation of Hoyland et al [9] Critical Rate

Calculating the dimensionless radius by using Eq. (9):

$$r_{De} = \frac{r_e}{h}\sqrt{\frac{k_v}{k_h}} \tag{9}$$

where:
k_v and k_h = The permeability in vertical direction and horizontal direction, respectively (md)
h = The thickness of the oil zone (ft)
r_e = The drainage radius (ft)

The dimensionless critical coning rate, by referring to the graph in Fig. 3:

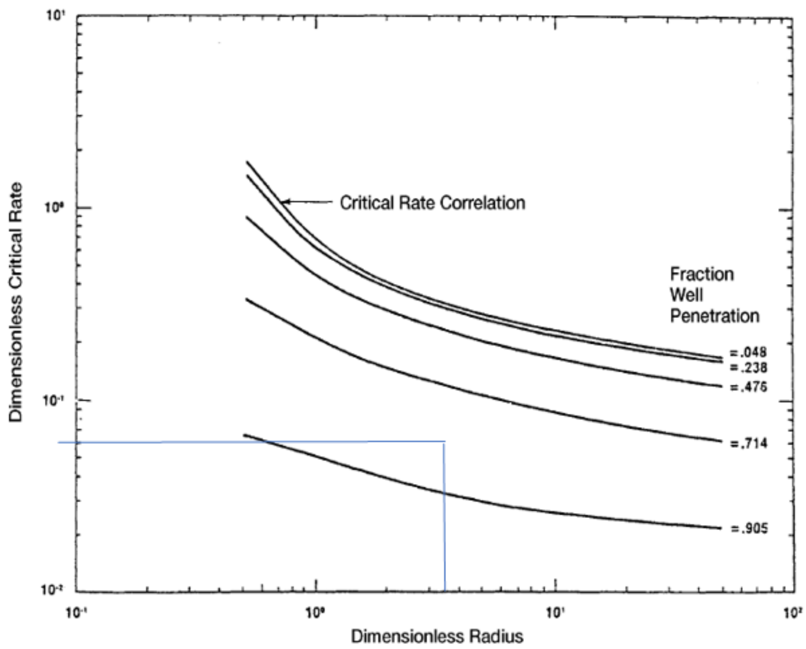

Fig. 3 The q_{CD} determination.

By applying Eq. (10) for calculation the critical rate of oil

$$Q_{OC} = 0.246\times10^{-4}\left[\frac{h^2(\rho_w-\rho_0)k_h}{\mu_0 B_0}\right]q_{CD} \tag{10}$$

where:
h = Thickness of oil reservoir (ft)
ρo = Oil Density (lb/ft^3)
ρg = Gas Density (lb/ft^3)
k_h = The permeability in horizontal direction (md)
μo = Oil viscosity (cp)
Bo = Oil volume factor
q_{CD} = Dimensionless critical flow rate

Comparing the results of each correlation helps us to optimize the critical rate that allows producing oil without the undesired gas phase. The results shown in Table 3 describe the values of critical oil flow rate with different intervals of perforation and different distances from the GOC to the top of perforation interval. The first column of the table has been ignored because of the zero value of perforation in this case, which means no production. Note that the $h_p = h - D_t$, where h is the oil column.

In Fig. 4, the correlations relation shows different values of oil rate against the dimensionless perforated interval. The behaviour of the critical coning rate depends on the conditions of each correlation and the assumptions that have been taken into account while the generation of equations. To put it another way, the variations in the values are due to the assumptions made for each correlation.

Table 3 Results of critical rate with different intervals for each correlation

Dt	hp	Dimensionless Perf. Interval	Meyer and Garder [6]	Chierici Ciucci [7]	Chaperson [8]	Hoyland et al. [9]
150	0	0.000	595.253	642.314	2156.952	3152.720
145	5	0.033	594.591	600.207	2015.552	2946.042
140	10	0.067	592.607	559.527	1878.945	2746.370
135	15	0.100	589.300	520.275	1747.131	2553.704
130	20	0.133	584.671	482.449	1620.111	2368.043
125	25	0.167	578.718	446.052	1497.884	2189.389
120	**30**	**0.200**	**571.443**	**411.081**	**1380.450**	**2017.741**
115	35	0.233	562.845	377.538	1267.809	1853.099
110	40	0.267	552.924	345.422	1159.961	1695.463
105	45	0.300	541.680	314.734	1056.907	1544.833
100	50	0.333	529.114	285.473	958.646	1401.209
95	55	0.367	515.224	257.639	865.178	1264.591
90	60	0.400	500.012	231.233	776.503	1134.979
85	65	0.433	483.478	206.254	692.621	1012.374
80	70	0.467	465.620	182.703	613.533	896.774
75	75	0.500	446.440	160.579	539.238	788.180
70	80	0.533	425.937	139.882	469.736	686.592
65	85	0.567	404.111	120.612	405.028	592.011
60	90	0.600	380.962	102.770	345.112	504.435
55	95	0.633	356.490	86.356	289.990	423.866
50	100	0.667	330.696	71.368	239.661	350.302
45	105	0.700	303.579	57.808	194.126	283.745
40	110	0.733	275.139	45.676	153.383	224.193
35	115	0.767	245.376	34.970	117.434	171.648
30	120	0.800	214.291	25.693	86.278	126.109
25	125	0.833	181.883	17.842	59.915	87.576
20	130	0.867	148.152	11.419	38.346	56.048
15	135	0.900	113.098	6.423	21.570	31.527
10	140	0.933	76.721	2.855	9.586	14.012
5	145	0.967	39.022	0.714	2.397	3.503
0	150	1.000	0.000	0.000	0.000	0.000

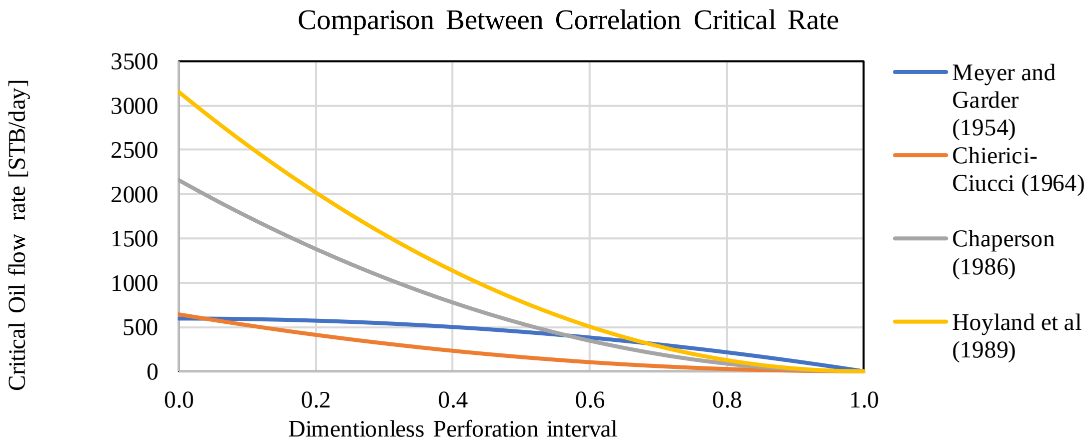

Fig. 4 Comparison Between Correlation's Critical Rate (Generated by Excel).

As shown, the Hoyland et al and the Chaperson correlations follow an approximately similar trend, as they approach less values in perforation interval the Hoyland gives high results in critical oil flow rate, and that's mean it allows more oil produced without the breakthrough of gas. The expected time of the breakthrough in Hoyland method will definitely be more than the breakthrough time of Chaperson correlations Chaperon [8].

The highest values of critical rate for Hoyland method can be explained by referring to the assumptions made while generating the correlation, which were a state that the reservoir considered to be homogenous with isotropic formation (where the permeability in vertical and horizontal are similar) [9]. However, the authors superimpose the criteria used in Muskat and Garder on a one-phase solution, but the results from this method are very conservative while depressing the dimensionless penetration, there is no significant difference in the critical rate. The reason behind the constant shape of cone might be due to the assumptions of the radial flow and the dependency of the reservoir radius [6].

In addition, Hoyland method had its own dimensionless radius and critical rate for fractional well graph, which was used to determine the value of dimensionless critical rate (q_D) by finding the value of dimensionless radius and the fractional well penetration. Nonetheless, the Chierici-Ciucci [7] used a graph of dimensionless radius equal to 5 in this case, which depends on the values of the dimensionless function of gas (ψ_g) and the dimensionless perforation [7].

Also, the Chierici-Ciucci [7] and Meyer methods [6] were found to be very close in values but different in the trend pattern. This difference can be described as the value of dimensionless penetration decrease the rate of oil calculated by Chierici [7] slightly increase, while the Meyer and Garder [6] trend increase with approximately conservative levels.

3.5 Simulation with E3 code & tNavigator software

Compositional simulator, tNavigator under E3 were used to run simulation for this study. The simulated field is a simple box model with total size of 11 × 11 × 10 in X, Y, and Z, respectively as represented in Fig. 5. The initial reservoir pressure at a depth of 8000 ft is 4682 psia whereby the reservoir temperature is 212 °F (Default value for E300). Table 4 shows the geological data properties of the built model. The signal vertical well has been completed for the purpose of oil production, and monitoring the changes occur in solution gas - oil ratio which help in predicting breakthrough time. The location of the well and the perforation interval for the base case are [6, 6, 7] and [6, 6, 8].

The compositional of three phases tNavigator simulation model were used to simulate gas coning phenomena in order to predict breakthrough time of the gas phase in a signal vertical well that is placed in an oil zone between a one water layer and three gas layers. The following assumptions made while constructing the model:

- No flow across the outer boundary
- No transition zone between water and oil
- Homogenous reservoir model with anisotropy formation

- Capillary pressure is negligible
- Frictional losses in the wellbore considered to be negligible

In this study, tNavigator software comes in handy as it is used to obtain the time breakthrough of gas that observed by monitoring certain GOR were initially set and defined in Eclipse 300 data code. The fluid properties listed in Table S1 to Table S6 (Supporting information) were defined into the system, including water phase relative permeability, gas phase relative permeability, oil relative permeability for three-phase, and all PVT fluid properties. The reservoir model considered to be a saturated reservoir, since it contains gas cap phase in its initial condition. In this study the terminology used as a live oil. In Fig. S1 (Supporting information), shows the type of model used in this study based on the Eclipse phase envelope. For the phase envelope areas that contains 100 percent liquid or vapour, the type of simulation fits the black oil model. But in this case study, the reservoir model properties fall in the area inside the curves bounded by the bubble points and dew points curves, which consider to be a live oil and the varying gas-oil ratio to mimic small compositional changes. Hence the E3 code used to simulate gas coning phenomena. Assigning the compositional model allowed the following conditions:

- Flow equation for each cell subject to MBE
- Iterative solution of cubic EOS for each component in each cell
- Iterative flash component mixture to equilibrium conditions for each cell

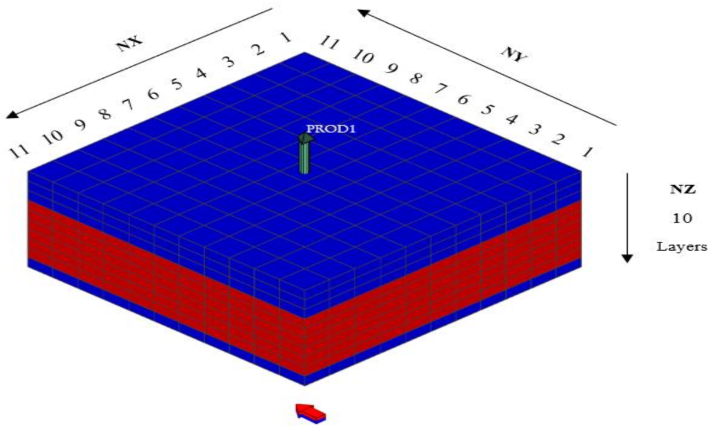

Fig. 5 3D View of Simulation Model with (Initial Oil Saturations) [Generated by tNavigator].

Table 4 Geological properties of reservoir.

Property NX = 45 ; NY = 49 ; NZ = 5	Value	Unit
Total number of grids	1210	Grids
Active grids block	1210	Grids
Maximum amount porosity	0.24	Fraction
Horizontal Permeability PERMX; PERMY	200	Fraction
Vertical Permeability PERM Z	20	Fraction
Value of NTG	1	Fraction
Initial reservoir pressure at 8,000 ft	4682.29	Psi
Gas / Oil Contact depth - GOC	8075	ft
Water / Oil Contact depth – WOC Depth to the top of formation	8255 8000	ft ft
Original Oil In Place (OOIP)	41.8045	M. Stb
Original Gas In Place (OGIP)	101.743	M.Mscf
Original Water In Place (OWIP)	27.4077	M. Stb

3.6 Sensitivity analysis

Several runs were implemented using tNavigator simulation to investigate the most affected parameters to the GOR and time breakthrough. Fourteen parameters included the local grid refinement (LGR) were tested to build 40 simulation cases provided in Table 5. Also, in order to check the accuracy of each correlation chosen, runs are made using input reservoir simulation data with the same ranges of the parameters' values used to calculate the critical rate of each correlation. In addition, there are different parameters other than those used in correlation that has been analysed based on the effect of the GOR value set in E3 code.

Oil flow rate effect

Fig. 6 depicts the results from four cases were runs by the critical flow rates which were calculated by correlation equations represented in Table 5 in bold line. The numbers indicated that when the flow rate increased, the time needed or gas to breakthrough decreased and the GOR value increased as well. For the flow rate of (2017.74 stb/day) the breakthrough time of gas was after 145 days, while the (1380.5 stb/day) occurred after 296 days, and with no breakthrough for both flow rates (571.4) and (411.1 stb/day). An attempt of higher oil rate than Hoyland selected to check at which time of oil production the critical rate falls into (2017.74 stb/day), but the fact is that the production rate of (3000 stb/day) remain constant until the reservoir simulation run ends.

Horizontal and vertical permeability effect

Fig. 7 shows that the horizontal permeability is inversely proportional to GOR and directly proportional to time needed for gas breakthrough to the production well. Because horizontal permeability affects both the x and y directions, the time for breakthrough will increase as permeability increases. Because gas conning occurs in the voidage area near the wellbore, the flow will be affected by the amount of permeability considered in the tNavigator flow equation while running the model. Since horizontal permeability is the connection of porous media within one layer, therefore the amount of oil moving from one grid to another within the same layer at high permeability will be higher, which doesn't allow gas to get closer to wellbore area compared to low permeability values. For example, permeability of (200 md) has the longest oil flow time with no gas breakthrough or interruptions compared to permeability (50 md) that had a small uninterrupted oil production interval and a fast gas breakthrough. Furthermore, the GOR value increased with the increase of gas production as it is a proportional relationship between the two factors. Where Fig. 8 shows how the vertical permeability act opposite horizontal permeability which mean proportional to GOR and inversely proportional to gas breakthrough time to perforated interval. Considering vertical permeability affects z-direction; consequently, the breakthrough time will be longer as permeability decreases. Because gas conning occurs downward vertical movement (Cusping), then the flow of gas will be faster in terms of movement and transition from one layer to another till it reaches the perforation interval which is the exact opposite of horizontal permeability where movement occurs in same layer. The amount of gas and oil flow from one layer to another is increased extremely with the increase of vertical permeability. Thus, more gas is produced in the production operation.

Oil and Gas density effect

Fig. 9 shows how the increase in oil density delays gas breakthrough time as production is often affected by the density of fluids, gravity and pressure. When oil density increases, the oil will move faster vertically towards the perforation due to gravity, but still will move slower compared to lighter oils due to pressure difference on the horizontal scale and that will delay gas breakthrough time accordingly. For more convenient numbers on breakthrough time to the eyes, check Table 5. On the other hand, Fig. 10 shows how the increase in gas density reduces the time needed to breakthrough as production also is affected by the density of fluids and pressure. When gas density increases, the gas will move faster vertically towards the perforation due to gravity, as gas conning phenomena is connected to how gas moves towards the perforated interval by clinging its way down surrounding the production well, due to the properties different between gas and oil, which makes the trend pattern of gas to stuck to the well and accordingly moved downward as a 'cone shape' illustrated in Fig. 22.

Oil and Gas viscosity effect

Fig. 11 shows the effects of oil viscosity on gas breakthrough time and GOR which indicates that as oil becomes viscous (increased flow resistance), the gas will have the opportunity to break through the oil towards the perforation interval, for that reason the observation of gas ratio had increased when oil viscosity is equal to (0.94 cp) highest value. Also, Fig. 12 represent the relationship of gas viscosity, GOR, and gas breakthrough time. When gas viscosity at the lowest value of (0.01550 cp), the breakthrough time started at an early stage and GOR was the highest among other gas viscosities. It makes sense as when gas viscosity decreases, the resistance of gas to flow is decreased as well which allows gas to move more smoothly around production well towards the perforation interval.

Oil column effect

Fig. 13 shows the impact of oil column (distance from GOC to the end of perforation interval) on GOR and gas breakthrough time as gas will need more time to reach the perforation. Logically, gas produced from a gas cap reservoir can only occur if the GOC level is near to the perforation interval, which allows the cone shape to breakthrough. The higher the value of oil column (210 ft) the less the impact of GOR and no gas breakthrough (in this case), on the other hand, the lowest oil column (120 ft) showed a huge increase in GOR and early gas breakthrough (after 22 days from production start).

Perforated interval effect

Fig. 14 explains that when perforation interval is equal to (60 ft), the highest GOR is observed with an early gas breakthrough time of 22 days because the perforation interval was very close to the GOC which allowed gas production to directly start with oil production at GOR of 1.32 larger than 1.27 (base GOR). While the lowest perforation interval (15 ft) delayed the breakthrough time causing GOR to drop to the lowest level.

Bottom hole pressure effect

Fig. 15 shows how the bottom hole flowing pressure is an essential parameter in production and how it affects the GOR and gas breakthrough time. In case of BHP equal to 4500 psia, the gas breakthrough occurred in spike-like shape instead of continuous production because reservoir pressure dropped to 4498 psia below the BHP at 412 days as shown in Fig. 23. On the other hand, when all other pressure values remained below the reservoir pressure of 4680 psia, the gas breakthrough time was similar at 114 days and a maintained increase in GOR value with no spikes or interruptions

Porosity effect

Fig. 16 shows that when the porosity increased the effect became inversely proportional to GOR and directly proportional to time needed for gas breakthrough to the production. The concept behind that is similar to the horizontal permeability.

Wellbore diameter effect

Fig. 17 shows similar pattern which all observed that gas breakthrough occurs from 114 to 145 days for wellbore diameters 0.25, 0.35, 0.41 and 0.45 ft respectively. Almost there was no effect among these values on GOR as well as breakthrough time when wellbore radius had become larger.

Rock compressibility effect

Fig. 18 shows when the rock has much ability to compress, then the GOR will be decreased and the time breakthrough delayed. This is because compressibility affects the permeability and porosity which has been explained earlier.

Local grid refinement

Local Grid Refinement is a technique that allows dividing a local grid with a different resolution than the original grid in a particular area of interest (Fig. 19), (Fig. 20), and (Fig. 21). The attributes of the cells in the local grid may be inherited from the global cells, or they may be specified directly. LGR has been used in this study to determine the effect of fluid distribution among the grids, and how it affects the GOR and time breakthrough as shown in Fig. 24. The reason behind the effect of refinement grid cell is that the saturation of fluids had become more specified among the local grid blocks (initial grid); For example, without the LGR techniques, a one grid cell considered to have a fixed saturated value of the oil or gas, this would lead to uncertainty amount of produced fluid. Hence, the GOR value effected when LGR was applied to the grids near the wellbore and in the perforation interval. In addition, the location of the LGR plays an important role in the impact on breakthrough time.

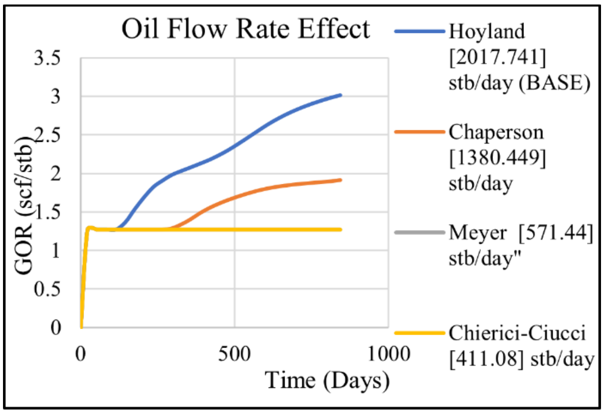

Fig. 6 Effect of increasing oil flow rate on GOR.

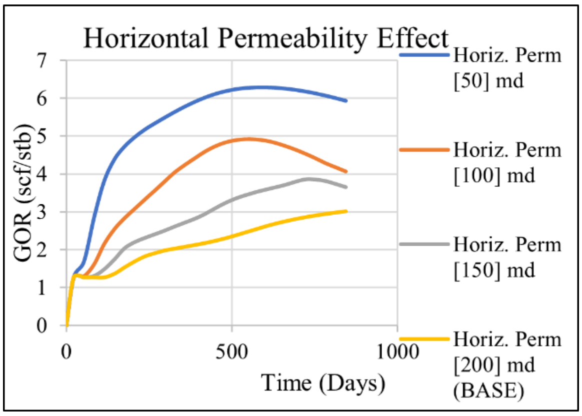

Fig. 7 Effect of decreasing horizontal permeability on GOR.

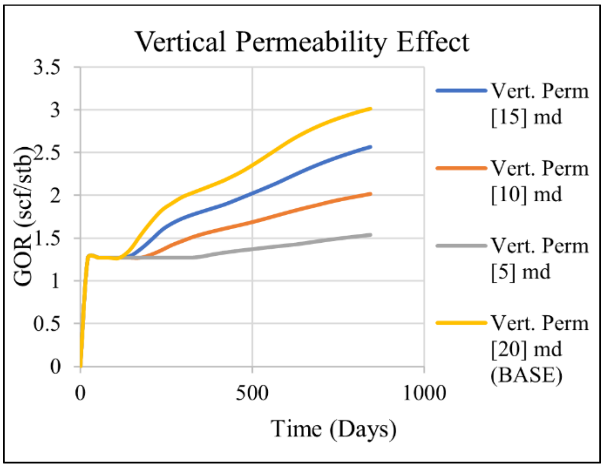

Fig. 8 Effect of decreasing vertical permeability on GOR.

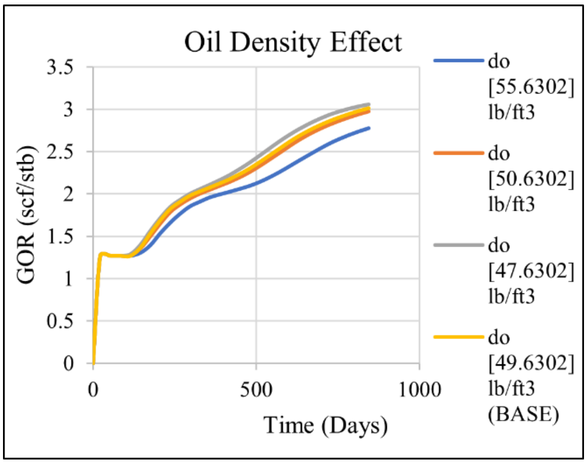

Fig. 9 Effect of changing Oil density on GOR.

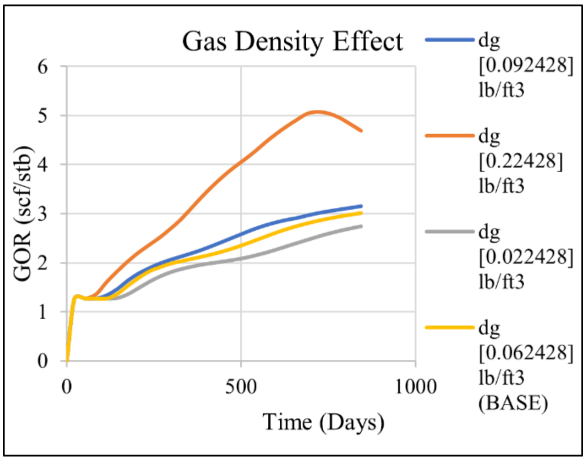

Fig. 10 Effect of changing Gas density on GOR.

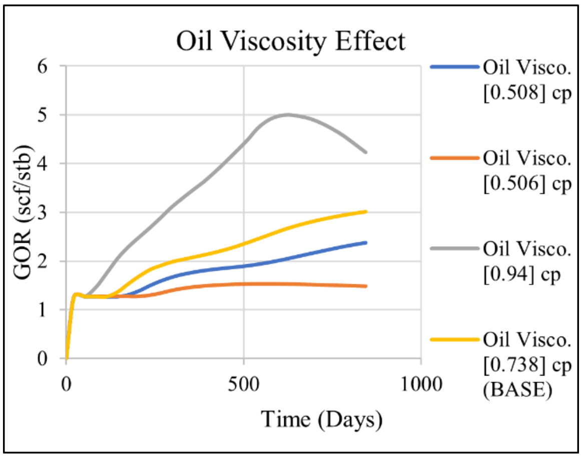

Fig. 11 Effect of changing Oil viscosity on GOR.

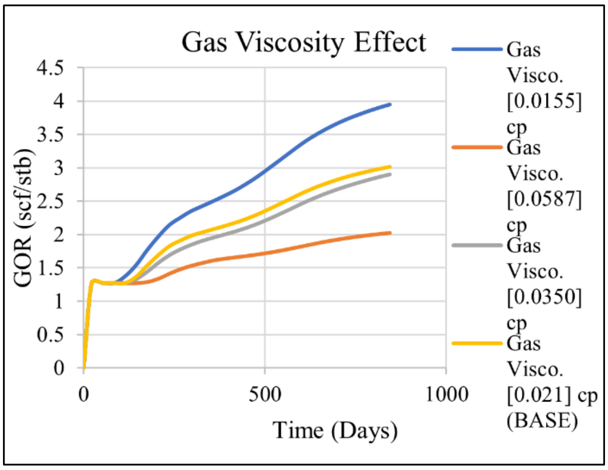

Fig. 12 Effect of changing Gas viscosity on GOR.

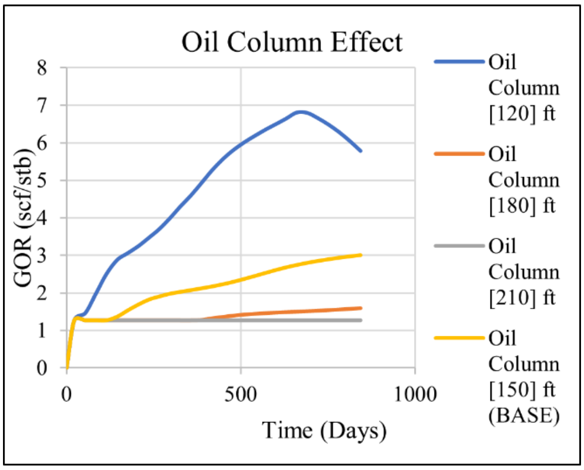

Fig. 13 Effect of changing Oil column on GOR.

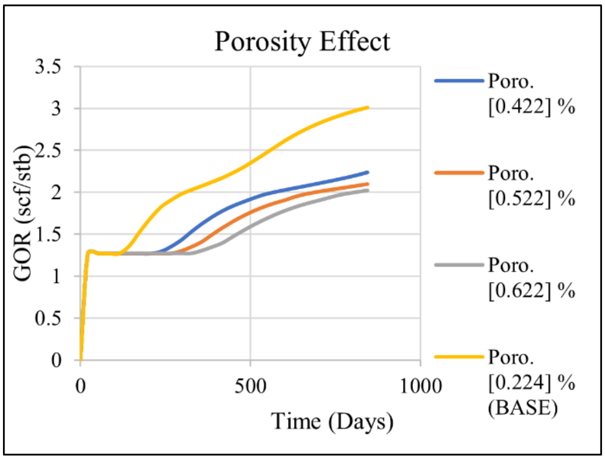

Fig. 14 Effect of changing perorated interval on GOR.

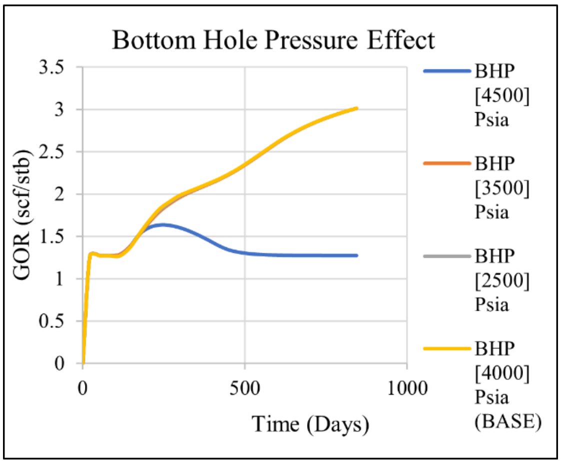

Fig. 15 Effect of changing Bottom Hole Pressure on GOR.

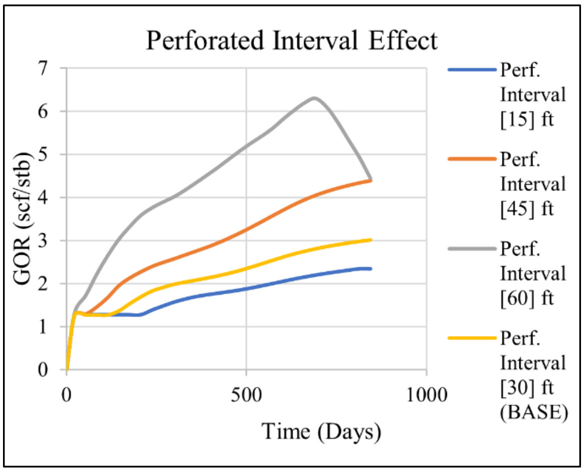

Fig. 16 Effect of increasing porosity on GOR.

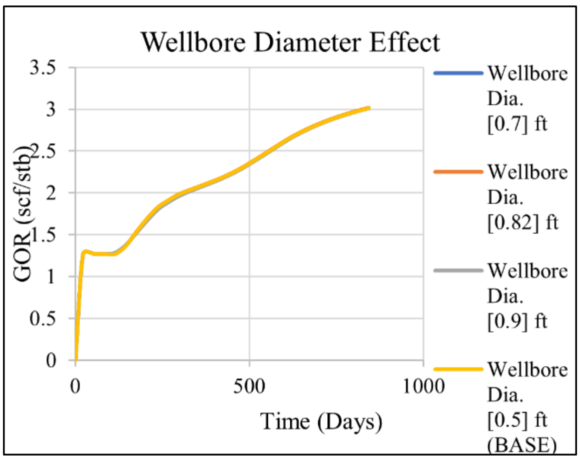

Fig. 17 Effect of increasing wellbore diameter on GOR.

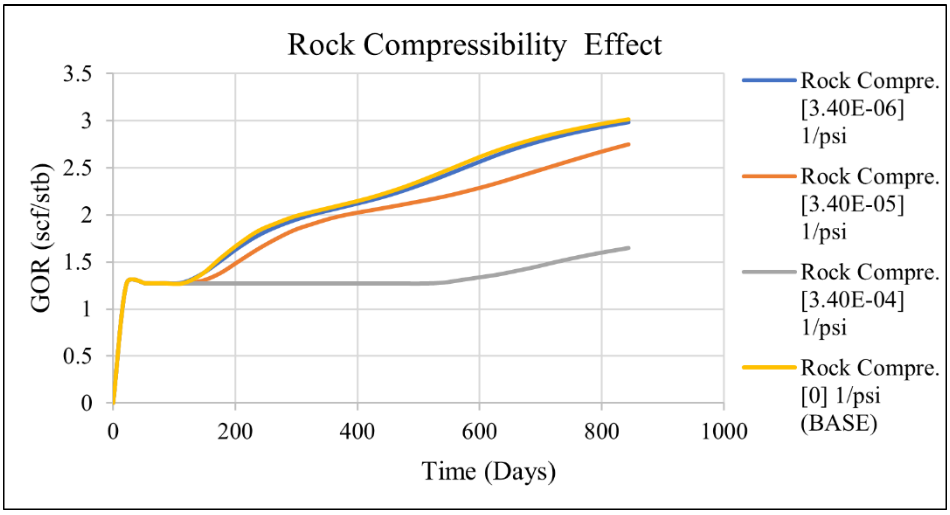

Fig. 18 Effect of increasing rock compressibility on GOR.

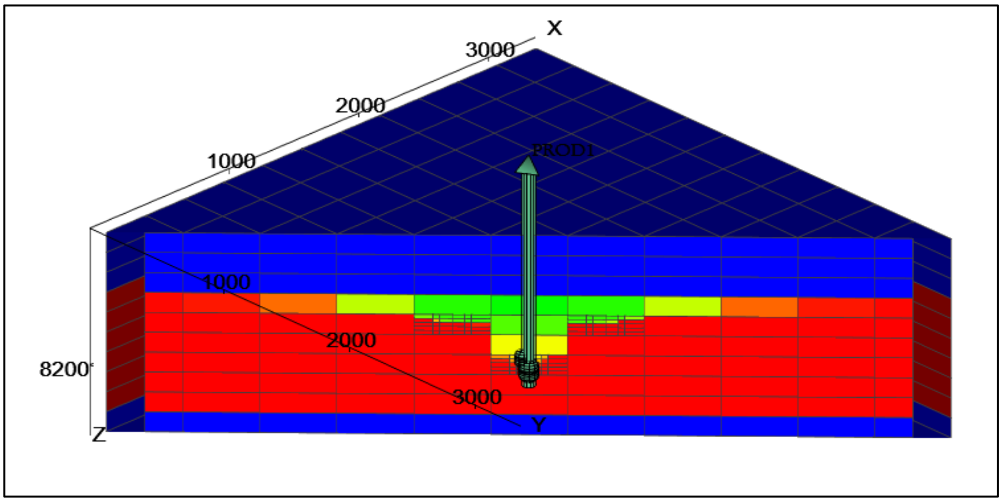

Fig. 19 Cross-section of the all three LGR's applied to model.

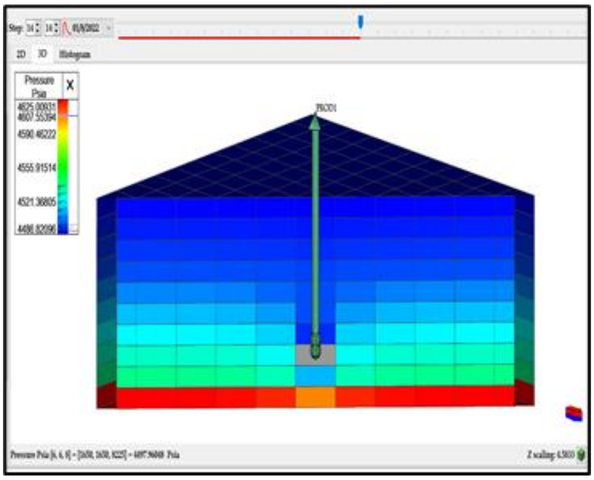

Fig. 20 Placing well in Local Grid Refinements.

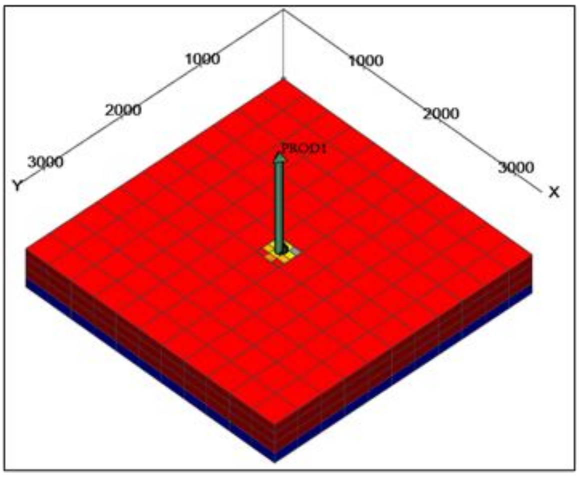

Fig. 21 Perforated interval in LGR.

4 Conclusion

A numerical simulation was used to evaluate the effect of various parameters on the GOR and breakthrough time. The parameters were selected based on several categories. Some of the parameters are geometry-related (reservoir rock), while others are fluid properties. The wellbore radius, well location, and bottom hole pressure are all considered potential differences (operation parameters).

- Increasing flow rate led to an early gas breakthrough and high GOR value.
- Horizontal permeability is inversely proportional to GOR and directly proportional to time needed for gas breakthrough to the production well. For vertical permeability act opposite horizontal permeability.
- The increase in oil density delays gas breakthrough time, while gas density reduces the time needed to breakthrough as production is often affected by the density of fluids, gravity and pressure.
- When Oil becomes viscous (increased flow resistance), the gas will have the opportunity to break through the oil towards the perforation interval, on the opposite side, gas viscosity at the low value results in breakthrough time at an early stage and GOR observed at a high level.
- Impact of oil column (distance from GOC to the end of perforation interval) on GOR and gas breakthrough time as gas will need more time to reach the perforation.
- When BHP values remained below the reservoir pressure of 4680 psia, the gas breakthrough time was similar at 114 days and a maintained increase in GOR value with no spikes or interruptions.
- When porosity increased the effect became inversely proportional to GOR and directly proportional to time needed for gas breakthrough to the production.
- Almost there were no effect on GOR as well as breakthrough time, when wellbore radius had different values
- When the ability of rock to compress increases, the GOR will be decreased and the time breakthrough delayed.
- LGR gridding techniques had sufficient impact on the GOR and the time needed for gas to breakthrough.

5 Recommendation

Permeability, porosity and rock compressibility as well as oil column and perforated interval played a critical role on the coning phenomena in a hydrocarbon reservoir with a gas cap. Therefore, reservoir management should take into account and focus on those parameters to conduct a study before any decision made.

This study mainly focused on a part of gas coning problem associated with critical coning rate and the time of gas breakthrough into the production well. As this study shows, the value of the critical coning rate is low and uneconomic according to the oil demand in the world. Therefore, most oil wells flow at a rate higher than critical coning rate and subsequently it causes gas production. For this reason, flowing a well at a rate somewhat around the critical coning rate may not be an applicable solution. Therefore, further investigations on well performance after gas breakthrough should be sought and monitored by the GOR.

Also, developing methods by which the gas production can be decreased are highly recommended as shown in sensitivity analysis; The well design, type of well, perforation design and the location of the interval, as well as the distance between perforated interval and the gas oil contact, all these factors should be analysed.

In addition, there are other factors that may affects the amount of gas produced, such as heterogeneity of a reservoir and its characterization, as well as fluid properties. Heterogeneity of a reservoir include the distribution of permeability and porosity, the characteristic of rock type and its ability to compress, the pressure, temperature, volume of fluids and many more, need to be carefully analysed when planning production operation.

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Table 5 Data Input in tNavigator simulation and breakthrough time results.

Case/ Unit	qo	kh	kv	ρo	ρg	μo	μg	ho	hp	BHP	ø	rw	c	tBT
	stb/day	md	md	lb/ft^3	lb/ft^3	cp	cp	ft	ft	Psia	%	ft	1/psi	day
(BASE)	**2017.741**	**200**	**20**	**49.6302**	**0.062428**	**0.738**	**0.021**	**150**	**30**	**4000**	**0.227**	**0.25**	**0**	145
qo1	1380.45													296
qo2	571.443													-
qo3	411.081													-
Kh1		150												84
Kh2		100												53
Kh3		50												53
Kv1			15											145
Kv2			10											206
Kv3			5											357
ρo1				55.6302										145
ρo2				50.6302										145
ρo3				47.6302										114
ρg1					0.092428									114
ρg2					0.22428									84
ρg3					0.022428									145
μo1						0.506								175
μo2						0.508								237
μo3						0.949								53
μg1							0.0155							114
μg2							0.035							145
μg3							0.0587							175
ho1								120						22
ho2								180						387
ho3								210						-
hp1									15					206
hp2									45					53
hp3									60					**22**
BHP1										4500				114
BHP2										3500				114
BHP3										2500				114
ø1											0.422			237
ø2											0.522			296
ø3											0.622			357
rw1												0.35		114
rw2												0.41		145
rw3												0.45		145
c1													3E-06	114
c2													3E-05	145
c3													3E-04	540

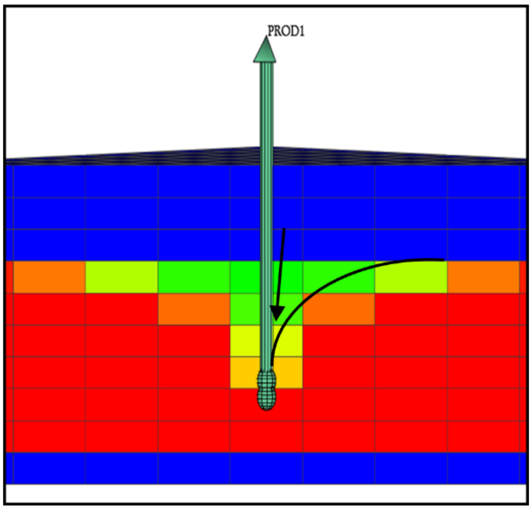

Fig. 22 Illustration of Gas movement pattern due to its density.

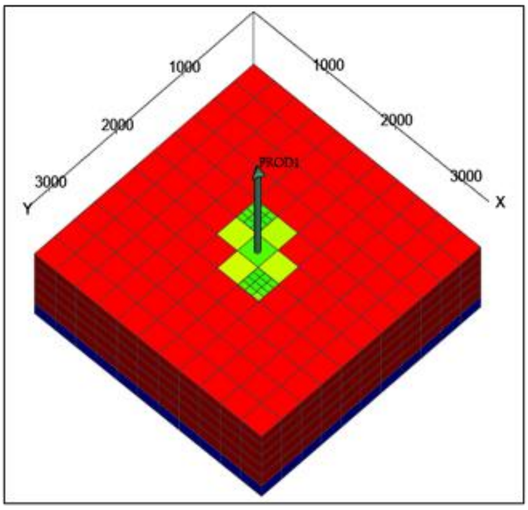

Fig. 23 BHP at time (step 14) dropped below 4500 psia within grid [6, 6, 8].

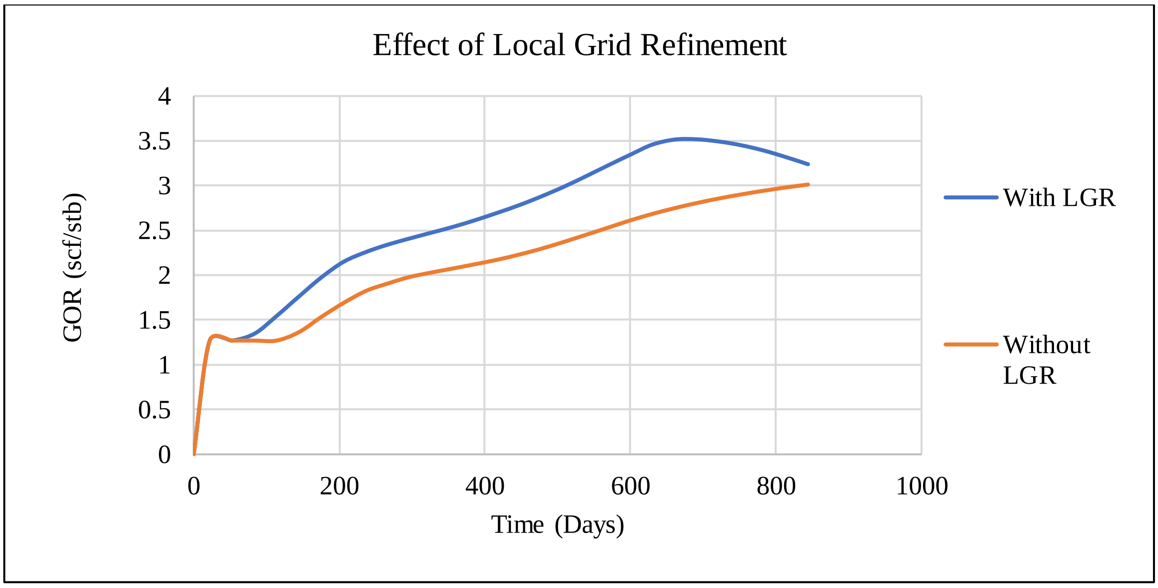

Fig. 24 GOR trend vs time with &without using LGR techniques.

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Supporting Information

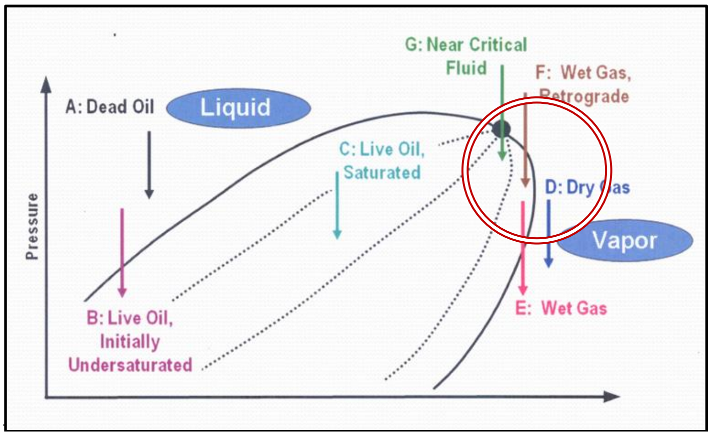

Fig. S1 PVT terminology in reservoir simulation model (Adapted from Eclipse training and exercise guide, Version 2.0, p.100).

Table S1 Water relative permeability.

Saturation of Water (Sw)	(Krw)
0.12	0
1	0.00001

Table S2 Gas relative permeability.

Saturation of Gas (Sg)	(Krg)
0	0
0.02	0
0.05	0.005
0.12	0.025
0.2	0.075
0.25	0.125
0.3	0.19
0.4	0.41
0.45	0.6
0.5	0.72
0.6	0.87
0.7	0.94
0.88	0.98

Table S3 Oil relative permeability.

Saturation of Oil (So)	(Kro)
0	0
0.18	0
0.28	0.0001
0.38	0.001
0.43	0.01
0.48	0.021
0.58	0.09
0.63	0.2
0.68	0.35
0.76	0.7
0.83	0.98
0.86	0.997
0.88	1

Table S4 PVT properties of water.

Pressure Psi	FVF rb/stb	Compressibility 1/Psi	Viscosity cP
4014.7	1.029	3.13E-06	0.31

Table S5 PVT properties of dry gas.

Pressure Psi	FVF rb/stb	Viscosity cP
14.7	166.666	0.008
264.7	12.093	0.0096
514.7	6.274	0.0112
1014.7	3.197	0.014
2014.7	1.614	0.0189
2514.7	1.294	0.0208
3014.7	1.08	0.0228
4014.7	0.811	0.0268
5014.7	0.649	0.0309
9014.7	0.386	0.047

Table S6 PVT properties of live oil.

Pressure Psi	RS Mscf/stb	FVF rb/stb	Viscosity cp
14.7	0.001	1.062	1.04
264.7	0.0905	1.15	0.975
514.7	0.18	1.207	0.91
1014.7	0.371	1.295	0.83
2014.7	0.636	1.435	0.695
2514.7	0.775	1.5	0.641
3014.7	0.93	1.565	0.594
4014.7	1.27	1.695	0.51
5014.7	1.618	1.827	0.449
9000	1.8	1.83	0.305