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Estimation of Water Breakthrough Using Numerical Simulation

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Abstract— Water coning is one of the most important phenomena that affect the oil production from oil reservoirs having bottom water aquifers. Empirical model has been developed based on numerical simulator results verified for wide range variation of density difference, viscosity ratio, perforated well interval, vertical to horizontal permeability ratio and well to reservoir radius ratio; the effect of all these parameters on breakthrough time of raising water have been recorded for five different oil flow rate. Since, the model reflects the real situations of reservoir-aquifer zone systems; in which the aquifer has a specific strength to support the reservoir pressure drop depending on its characteristics and water properties. Moreover, the numerical model has been constructed using very fine grids near the wellbore especially in vertical direction, so that very accurate results can be obtained. and (625)runs were performed to generate the breakthrough time model using the numerical simulator verifying all parameters affecting on breakthrough time. The results show that water coning is complex phenomena that depends on all reservoir and fluid properties; the dynamic critical flow rates affected simultaneously by both of the displacing fluid zones. The results show that the breakthrough time of the presented formula provides extreme accuracy with many numerical simulator cases of same reservoir and fluid properties; thus, the suggested formula can be considered as an alternative, quick and easy use tool than numerical simulation models, which consumes time and efforts.

Keywords— water coning ,critical oil flow rate ,breakthrough time.

1. Introduction

Water coning is a usual issue that is faced in reservoirs having an aquifer, particularly at the bottom. Coning is happened due to the non-equilibrium between gravitational and viscous forces near the perforation interval. The viscous forces drive the oil to flow into a producing well with a pressure drawdown. These dynamic forces tend to remove the WOC and GOC towards the vicinity of the wellbore. It seriously impacts the productivity of the well and the degree of depletion and influence the total recovery of the reservoirs (1).

Although a lot of correlations have been applied to eliminate water production, water coning, is as yet a major problem in several oil fields each over the world. There are a lot of studies has been done in order to gain understanding and better management procedures of this problem. water coning studies in steady state case has been made by (6) , pointed to the essential physical concepts implied the behavior of the WOC when oil is only outputted from a well partially penetrating the reservoir while the water stabilize in the lower portion of the pay zone .

From (6) outputs ,they improved that, water-oil production rate might be protected for a short- perforated well. Moreover; whenever the wellbore penetration increasing, the water-oil production rate reduced. They also indicated that, it was impossible to control bottom water when producing from a thin oil interval unless the production rate of the well was reduced to non-economically small values.

(5), introduced a method for the critical oil rate needed to obtain a stable water cone. (10)concluded that the critical oil rate for a well was a function of many variables such as density difference of oil and water, the length of well penetration(hp), and the oil zone thickness.

(2), suggested a set of working curves to calculate the critical oil rate.By applying a potentiometric analyzer study These curves were created and applying the water coning mathematical theory as derived by (6).

(8), suggested new analytical solutions that neglect capillary pressure, that guide to segregated flow .It was applied to vertical wells where the fluids in this location are in vertical balance.(7), presented empirical methods have been derived to predict critical oil rate and breakthrough time of water in both vertical and horizontal wells. First, investigate the coning performance at various formations and fluid properties for all types of wells vertical and horizontal.

(9), investigated the analytical comparisons of water coning before and after water breakthrough time. with respect to two theoretical models developed, and the analytical comparisons of water coning were concluded and compared through the corresponding calculation. The outputs explain that there was a high variation in the pressure drop and critical oil production rate before water breakthrough time for the oil and gas reservoirs in the same water cone elevation.

(4), to eliminate water coning issue, it is important to produce at a suitable oil flow rate, due to economical considerations production in a critical rate,at critical oil rate the build-up cone is stable but is at a location of initial breakthrough, it is non-economically.

2. Simulation Modeling

As well as the pressure drawdown is responsible of coning development, since the flow rate will be the main controlling factor of cone development. Several methods have been introduced to compute the critical oil inflow. Generally, these methods could be classified into two sets: the first set calculate the maximum allowable oil inflow without water coning analytically depends on the balance conditions of viscous and gravitational forces. The second set calculate through empirical from experiment simulations. A single well with a bottom aquifer was built using numerical simulation model ECLIPSE-100 version 2012 is employ in this work to study breakthrough time resulted from water coning in homogenous and anisotropy oil reservoirs. A vertical well with a radius of 0.333 ft is centered in circular homogeneous, but anisotropic reservoir model is used in this study as shown in Fig.1 ..Very fine grid around the wellbore was used in radial direction rw=0.333ft and theta ϕ=60° ,while in the vertical direction (0.5 ft) was established for the aim of investigating movements of the water coning more in detail .The attributes of the base case model (input data) are summarized in Tables1,2and 3. The simulations were run on both the base case, and models in which the important variables were individually varied.

2.1 *Simulation Work*

To analyze the water coning manner of oil reservoir in an existence of a strong bottom aquifer, a 3D model by applying Eclipse 100 black oil simulator (3) was generated as shown in Fig.1 with the fluid properties listed in Table1,The reservoir properties in Table2 and relative permeability data inTable3. These data were used to make the input data file that open in simulator then run to gain the result file. To estimate the water coning progress with time in the radial oil reservoir with active bottom aquifer model, three parameters were chosen as output file , that is, (Water Cut ,FWCT, Water Production Rate FWPR ,and Oil Production Rate, FOPR).These variables are connected.

2.2 *Parameters Affecting In Breakthrough Time*

Some of reservoir and fluid properties that may impact in breakthrough and coning progress are;

1- Anisotropy ratio (k_v/k_h).

2- perforation ratio (h_p/h)

3- reservoir radius to well radius (r_e/r_w)

4- viscosity ratio (μ_o/μ_w)

5- density difference ($\Delta\rho$)

These parameters are applied in simulator to evaluate the coning phenomenon.

2.2.1 Base-case

The fluid and reservoir properties for the base case are listed in Tables (1) and (2), while the relative permeability data shown in table (3).These data were used to make the input data file that open in simulator then run to gain the result file. To estimate the water coning progress with time in the radial oil reservoir under active bottom aquifer model. Three parameters were chosen, that is, (Water Cut ,FWCT, Water Production Rate FWPR ,and Oil Production Rate, FOPR) and the important reservoir and fluid properties that selected to estimate time of breakthrough are(r_e/r_w=7500/0.333 , h_p/h=0.35, K_v/k_h=0.5 , $\Delta\rho$=13.85, μ_o/μ_w=3.33) with five values of oil flow rate as shown in Table 4.and Fig. (from 2 to 6).From Fig.(from 2 to 6) we show that as flow rate value increased, time of breakthrough water is decreased.

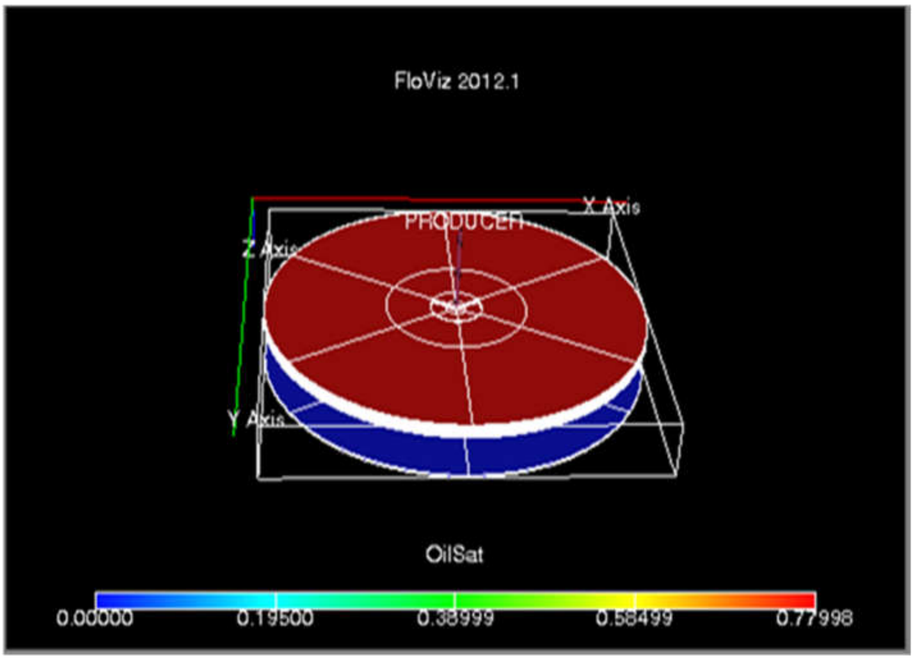

Figure 1: Reservoir model

Table 1: Reservoir fluid properties (Base -case).

Water Density (ρ_w), lb/ft^3	63.8
Water Viscosity (μ_w), cp	0.3
Oil Density (ρ_o), lb/ft^3	45.95
Oil Viscosity (μ_o), cp	1
Formation Volume Factor (B_o), RB/STB	1.2

Table 2: Reservoir model properties (Base-case).

Reservoir Thickness (h), ft	100
Drainage Radius (r_e), ft	7500
Perforation Interval(h_p), ft	35
Well Radius (r_w), ft	0.333
Rock Porosity,ϕ	0.2
Horizontal Permeability (k_h), md	100
Vertical Permeability(k_v) md	50
Rock Compressibility (C_f), psi^{-1}	2×10^{-6}
Initial Water Saturation (Swi)	0.22
Production Rate, B/D	800, 1500, 2500, 3500, 5000

Table 3: Relative Permeability Data

Sw	**K_{rw}**	**K_{ro}**	**P_c**
0.22	0	1	0
0.38	0.05	.0.637	0
0.4	0.11	0.4	0
0.5	0.228	0.287	0
0.6	0.352	0.197	0
0.7	0.5	0.11298	0
0.8	0.65	0.05	0
0.9	0.83	0.00	0
1	1	0.00	0

Table 3: Base case oil flow rate versus breakthrough time.

Q_o (B/D)	**T_{BT} (days)**
800	924
1500	424
2500	195
3500	125
5000	80

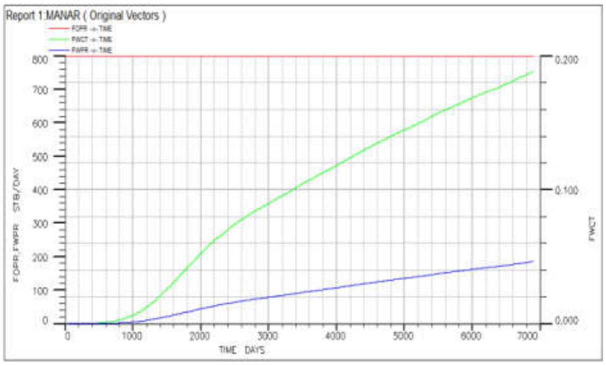

Figure 2: water cut, water production, pressure and oil production vs. time, Q_o=800 BPD

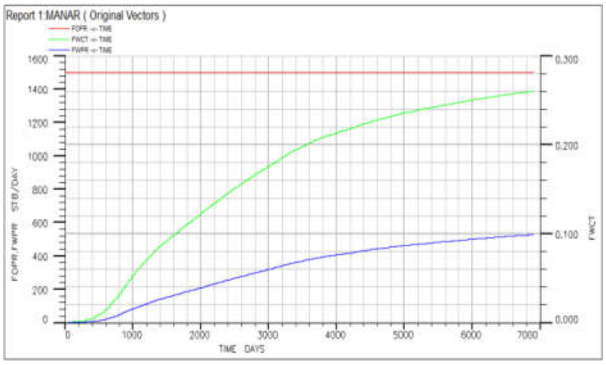

Figure 3: water cut, water production, pressure and oil production vs. time, Q_o=1500 BPD

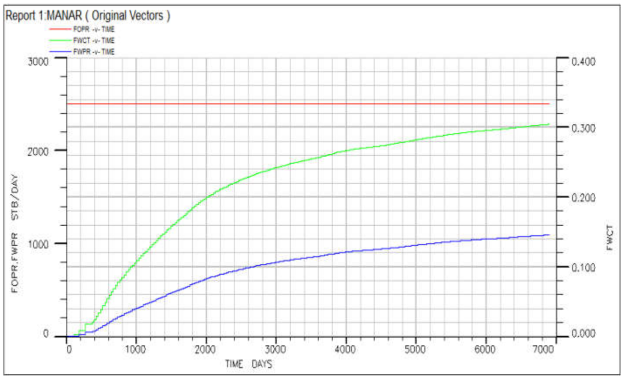

Figure 4: water cut, water production, pressure and oil production vs. time, Q_o=2500 BPD

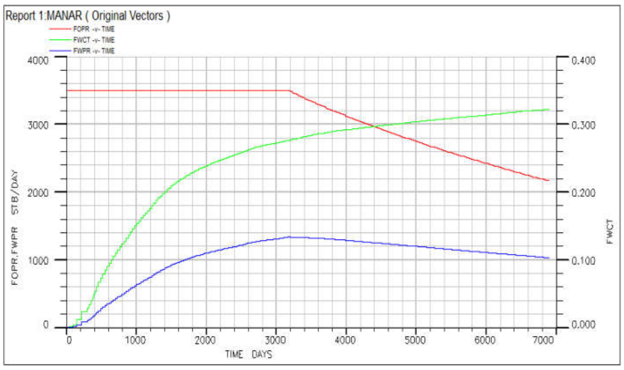

Figure 5: water cut, water production, pressure and oil production vs. time, Q_o=3500 BPD

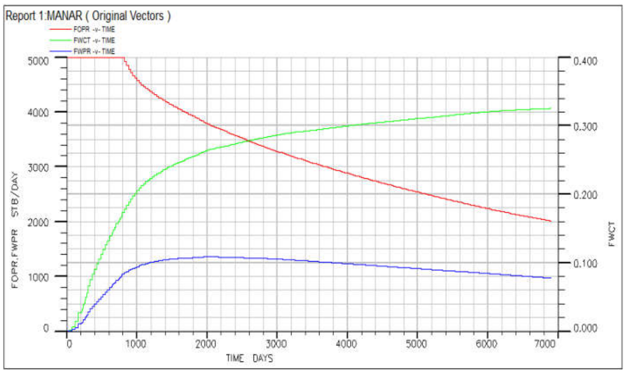

Figure 6: water cut, water production, pressure and oil production vs. time, Q_o=5000 BPD

3. Breakthrough Development Model

creating the breakthrough time model requires (625) runs performed using the numerical simulator verifying all parameters affecting on breakthrough time.

3.1 *Perforation Ratio (h_p/h)*

Perforation ratio means the ratio of perforated interval (hp) to pay zone thickness (h) in the reservoir. Perforated ratio is affected on coning behavior and breakthrough time. To evaluate its effect five cases were selected by changed hp/h from 0.1 to 0.65. On the other hand every case includes five scenarios listed as oil flow rate from 800BPD to 5000BPD. Figures(7-10) shows the effect of perforation ratio (hp/h) on breakthrough time and oil flow rate.

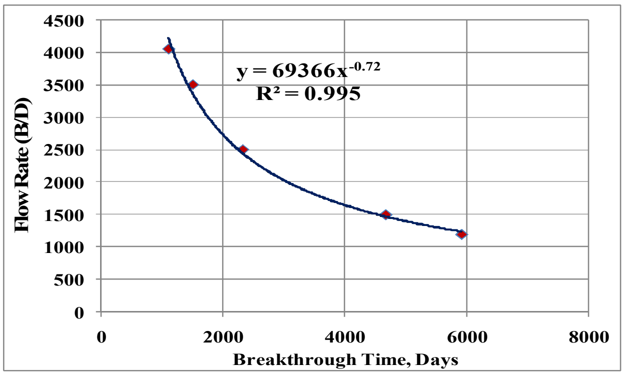

Figure 7: shows the effect of perforation Ratio (h_p/h) on breakthrough time for different oil flow rate at h_p/h= 0.25

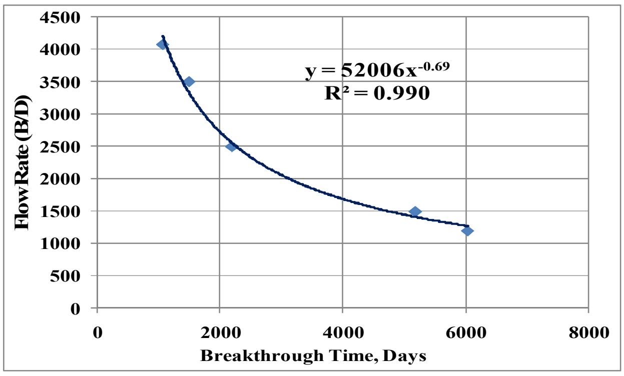

Figure 8: shows the effect of perforation Ratio (h_p/h) on breakthrough time for different oil flow rate at h_p/h= 0.3

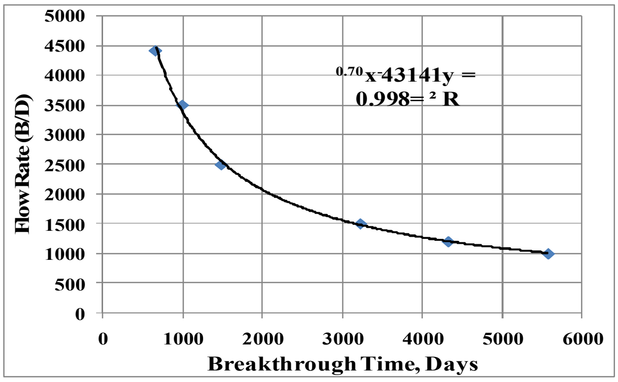

Figure 9: shows the effect of perforation Ratio (h_p/h) on breakthrough time for different oil flow rate at h_p/h= 0.4.

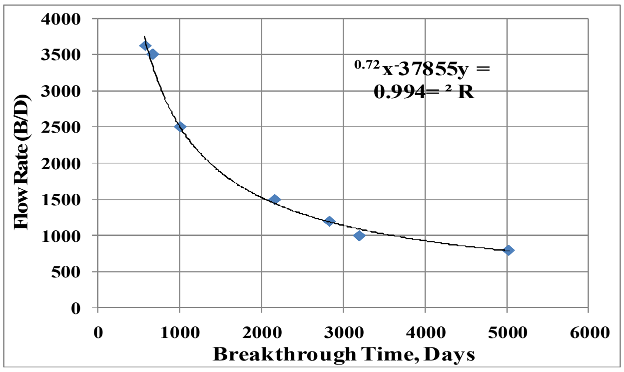

Figure 10: shows the effect of perforation Ratio (h_p/h) on breakthrough time for different oil flow rate at h_p/h= 0.5

3.2 *Anisotropy Ratio (k_v/k_h)*

Anisotropy ratio means the ratio of the vertical to the horizontal permeability (k_h) in the reservoir.To estimate the anisotropy ratio impact on coning behavior in reservoir five cases were selected by changed k_v/k_h from 0.1 to 0.75 every case includes five scenarios represented by oil flow rate from 800 BPD to 5000BPD.

3.3 *Density Difference (Δρ)*

Density difference is water density minus oil density in reservoir. To evaluate its effect, five cases were selected by changed Δρ from 5 lb/ft^3 to 17.85 lb/ft^3.On the other hand, every case includes five scenarios listed as oil flow rate from 800 BPD to 5000 BPD.

3.4 *Viscosity Ratio(μ_o/μ_w)*

Viscosity ratio means oil viscosity to water viscosity in reservoir. To evaluate its effect, five case were selected by changed μ_o/μ_w from 1 cp.

to 50 cp.On the other hand, each case includes five scenarios listed as oil flow rate from 800 BPD to 5000 BPD .

3.5 *Reservoir Radius To Well Radius (r_e/r_w)*

This ratio have a small effect on coning behavior there for ; to evaluate its impact five cases were selected by changed re/rw from 2500/0.25 to 20000/0.25.On the other hand ,every case includes five scenarios listed as oil flow rate from 800 BPD to 5000 BPD .

Five parameters which are controlling coning problem has been taken in construction coning model ,these parameters are (Δρ, μo/μw, re/rw, kv/kh, hp/h) all these parameters affects on critical flow rate Q_o as follows ; $Q_o \alpha\ \Delta\rho$, $Q_o \alpha$ μo/μw, $Q_o\ \alpha$ re/rw , $Q_o\ \alpha$ 1/ kv/kh , $Q_o\ \alpha$ hp/h , $Q_o\ \alpha$ 1/t . Therefore the following formula has been suggested to represent the behavior of breakthrough time versus oil flow rate affected by these parameters, as in equation (1) that constructed depending on simulation results for base case as follows .

$$t = \frac{1800 \times \Delta\rho^{a} \times [ln(\frac{r_e}{r_w})]^{b} \times e^{-d \times \frac{hp}{h}}}{k_v^{e} \times \frac{\mu_o}{\mu_w}^{f} \times Q_o} \qquad (1)$$

Where a, b, c, d, e, f are constant to multiply simulator results with a ,The effect of Q_o versus Δρ. b, The effect of Q_o versus re/rw. d, The effect of Q_o versus hp/h. e, The effect of Q_o versus kv/kh. f, The effect of Q_o versus μ_o/μ_w . All the effects of these parameters has been involved in equation(1) which can be written as follows;

$$t = [\frac{1800 \times \Delta\rho \times ln(\frac{r_e}{r_w}) \times e^{-1.6 \times \frac{hp}{h}}}{K_v^{0.7} \times \frac{\mu_o}{\mu_w} \times Q_o}]^{\frac{1}{0.66}} \qquad (2)$$

Eq.(2) is created using the base case parameters which is listed in table (1) ,(2) and (3) therefore the application Eq.(2) can be expanded to any variable in these reservoir and fluid parameters this can be done by rewriting Eq.(2) as follows;

$$t = [1800 \frac{\Delta\rho^{(A)} \times ln(\frac{r_e}{r_w}) \times e^{-(1.6*C) \times \frac{hp}{h}}}{\frac{k_v}{k_h}^{(0.7*D)} \left(\frac{\mu_o}{\mu_w}\right)^{E} \times Q_o}]^{\frac{1}{0.66}} \qquad (3)$$

Where A, C, D, and E are correction factors for the effect of (Δρ, μo/μw, re/rw, kv/kh, hp/h) variation on breakthrough time respectively, these factors results by changing cases smaller and greater than the base case to have more of fluid and reservoir properties which can be determined from charts as in figures(11-14) . Eq.(3) can be used to calculate the breakthrough time of water coning in homogeneous and anisotropic reservoirs with active bottom aquifer .

The simulator has been run further cases as follows:

1- Δρ: the value of Δρ has been taken (5-7.85-10-13.85-17.85)lb/ft^3.

2- μ_o/μ_w:the value of μ_o/μ_w has been taken (1-3.33-5-10-20).

3- r_e/r_w: the value of r_e/r_w has been taken (2500/0.333-5000/0.333-7500/0.333-10000/0.333-20000/0.333).

4- k_v/k_h: the value of k_v/k_h has been taken (0.1-0.35-0.5-0.75-1.0).

5- h_p/h : the value of h_p/h has been taken (0.25-0.3-0.4-0.5-0.6).

The effect of changing these parameters on coning time has been drawn for each case to extract the parameters sensitivity, which can be shown in Figures(11-14).

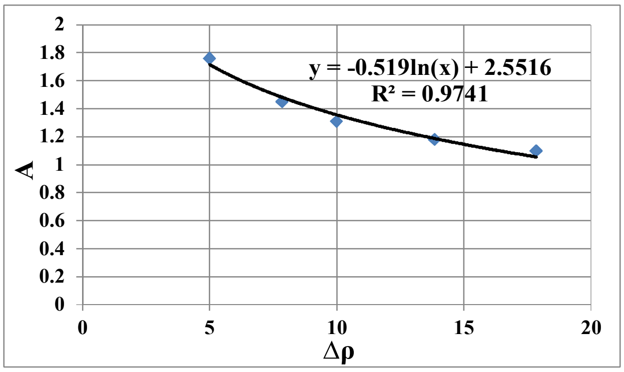

Figure 11:Correction factor for the variation of density than basic density value.

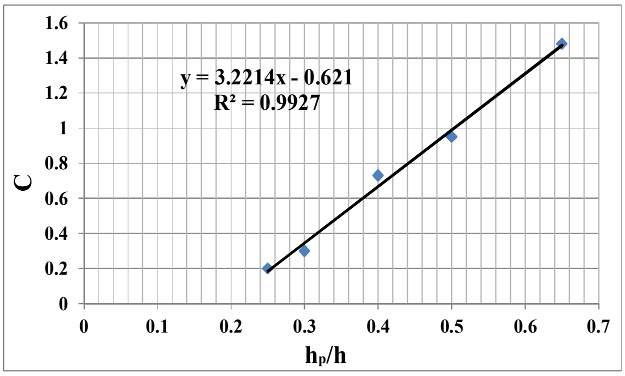

Figure 12: Correction factor for the variation of vertical to horizontal permeability ratio than basic ratio.

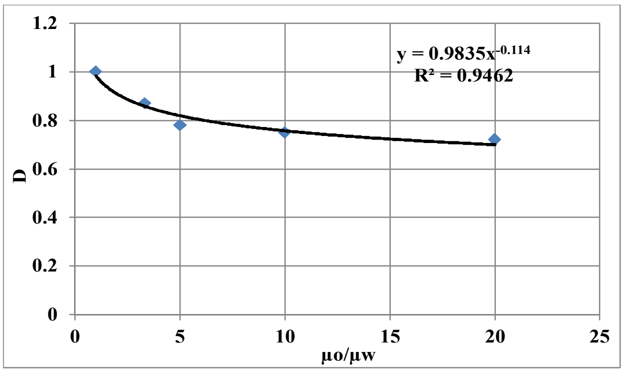

Figure 13: Correction factor for the variation of viscosity than basic viscosity ratio.

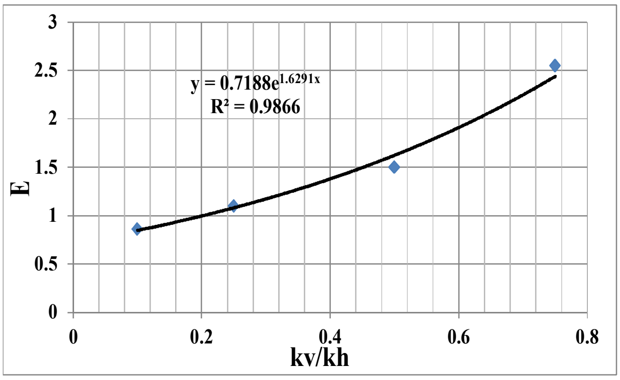

Figure 14: Correction factor for the variation of perforated thickness over reservoir thickness ratio than basic ratio.

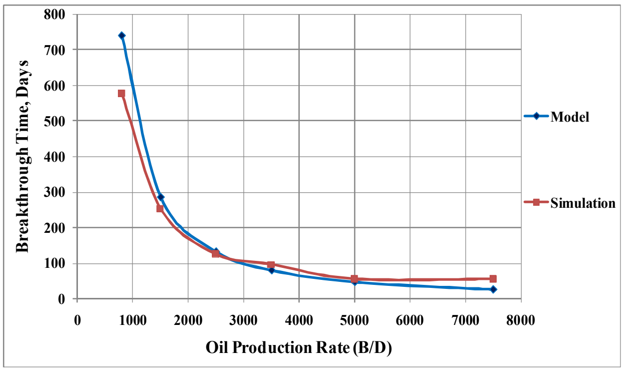

Figure 15: comparison between model's breakthrough time versus numerical simulator results for different production rates; h_p=0.45,r_e=10000ft,r_w=0.333ft ,k_v/k_h=1.0 , $\Delta\rho$=13.85 ,μ_o/μ_w=2.

However, it is found that the variation of reservoir to well radius has no traceable effect on detecting of breakthrough time, and thus it can be truly state the correction factor equals to unity.

4. Results and Discussion

Since, the model reflects the real situations of reservoir-aquifer zone systems; in which the aquifer has a specific strength to support the reservoir pressure drop depending on its characteristics and water properties.The results show that water coning is complex phenomena that depends on all reservoir and fluid properties; the dynamic critical flow rates affected simultaneously by both of the displacing fluid zones. This result shows that increase in anisotropy ratio (i.e. increase in vertical permeability,k_v) have an effect on breakthrough time decreased as anisotropy ratio increased, on the other hand as perforation ratio increased the breakthrough time decreased ,and as density difference increased the time of breakthrough is decreased , also increase the viscosity ratio lead to decreased the time of breakthrough, but the reservoir to well ratio has no effect on the breakthrough time. The results show that the breakthrough time of the presented formula provides extreme accuracy with many numerical simulator cases of same reservoir and fluid properties. Fig.15-17 show three different cases varies in perforated interval thickness, vertical to horizontal permeability ratio and reservoir to well radius ratio; it can be seen clearly high accurate results between the suggested experimental model estimated breakthrough time with that obtained from the numerical simulations. The Breakthrough time curves are depicted in these figures which explain the times(in days) every cone elevation developed from the water-oil contact(WOC) by their corresponding rates breaks into the vertical well as the peak of the cones mobile steadily to the direction of the well bore. As can show there are a difference between the simulation and model in small values of flow rates . Therefore, the suggested model can be considered as an alternative, quick and easy use tool than that of numerical simulation models, which consumes time and efforts.

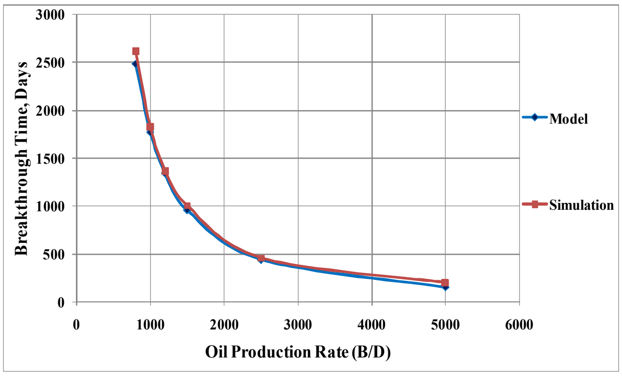

Figure 16: comparison between model's breakthrough time versus numerical simulator results for different production rates; h_p=0.3,r_e=5000ft,r_w=0.333ft ,k_v/k_h=0.3 , $\Delta\rho$=13.85 ,μ_o/μ_w=6.

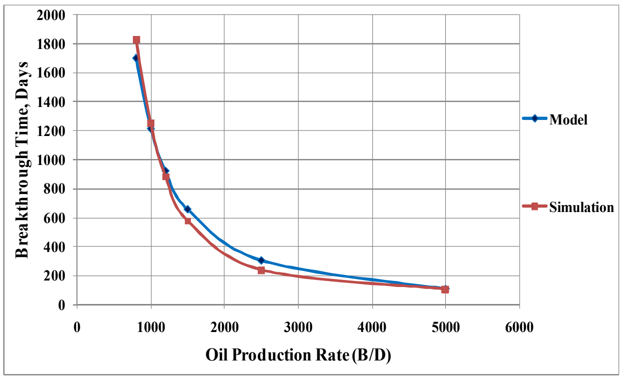

Figure 17: comparison between model's breakthrough time versus numerical simulator results for different production rates; h_p=0.4,r_e=7500ft,r_w=0.333ft ,k_v/k_h=0.25 , $\Delta\rho$=13.85 ,μ_o/μ_w=3.

5. Conclusion

It is important to study the development of two cones of water/gas with oil, and the interrelation between both; i.e. the water cone speed effects on the speed of gas cap cone**.**

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Nomenclature

T_{BT}= Breakthrough time, days.

C_f=Rock Compressibility, psi^{-}

h = Reservoir thickness,ft

Q_{oc}= Critical oil flow rate, BPD

r_e = Reservoir radius, ft

r_w = Well radius, ft

K_v= Vertical permeability,md

$\Delta\rho$ = Density difference between water and oil $(\rho_w - \rho_o), Ib/ft^3$

μ_o=Oil viscosity, Cp

μ_w=Water viscosity, Cp

Greek symbols

ϕ	Porosity
ρ	Density

Abbreviations

FOPR	Field oil production rate
FWPR	Field water production rate
FWCT	Field water cut

تقييم وقت الاختراق المائي بأستخدام المحاكاة العددية

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الخلاصة – ويعد التقمع المائي من أهم الظواهر التي تؤثر على إنتاج النفط من مكامن النفط التي تحتوي على تجمعات المياه الجوفية. وقد تم تطوير النموذج التجريبي بالاعتماد على نتائج المحاكاة العددية التحقق من اختلاف مجموعة واسعة من فرق الكثافة، نسبة اللزوجة، نسبة المنطقة المثقبة للبئر الى المنطقة المنتجة، نسبة النفاذية العمودية إلى نسبة نفاذية الأفقية وكذلك إلى نسبة نصف قطر المكمن الى نصف قطر البئر. تأثير كل هذه المتغيرات على زمن الاختراق وارتفاع المياه تم تسجيله لخمسة معدلات مختلفة من التدفق النفطي. حيث، يعكس هذا النموذج الأوضاع الحقيقية لنظام منطقة المكمن ومنطقه الخزان المائي؛ حيث تمتلك طبقة المياه الجوفية قوة محددة لدعم انخفاض ضغط المكمن اعتمادا على خصائص المكمن وخصائص الخزان المائي الذي اسفله. وعلاوة على ذلك، تم بناء النموذج العددي باستخدام شبكات دقيقة جدا بالقرب من حفرة البئر وخاصة في الاتجاه العمودي، بحيث يمكن الحصول على نتائج دقيقة جدا. و (625) تم تنفيذها لتوليد نموذج وقت الاختراق باستخدام جهاز محاكاة عددية التحقق من جميع المتغيرات او الخصائص التي تؤثر على وقت الاختراق. وأظهرت النتائج أن تقمع الماء هو من الظواهر المعقدة التي تعتمد على خصائص كل من المكمن والسوائل. فإن ديناميكية معدلات التدفق الحرجة تتأثر في وقت واحد من قبل مناطق السوائل المُزاحة. وأظهرت النتائج أن زمن الاختراق للصيغة المُقدمة يوفر دقة بالغة مع العديد من حالات محاكاة العددية من نفس المكمن وخصائص السوائل. وبالتالي، يمكن اعتبار الصيغة المقترحة كأداة بديلة وسريعة وسهلة الاستخدام اكثر من نماذج المحاكاة العددية، والتي تستهلك الوقت والجهد.

الكلمات الرئيسية – التقمع المائي ،معدل الجريان النفط الحرج ،وقت الاختراق.