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THE IMPACT OF HETEROGENEITY EFFECT ON WATER FLOODING PERFORMANCE

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ABSTRACT

Waterflooding is one of the cheapest oil recovery methods and the most popular secondary method to increase oil recovery by injecting water into the reservoir. This study aim to examine the effect degree of heterogeneity on the main forces that governing the water flooding performance in stratified reservoirs. These forces such as capillary Forces which arise when water is injected into a layered reservoir, movement of the flood front are more rapid in the more permeable layers. The different flood front positions create sharp saturation gradients between layers. The second important force is the viscous forces, due to similar viscosities between the displacing and the displaced phase, the injection front advances almost as a piston. This means that in general a large fraction of the porous medium was perfectly swept by water and only residual oil is left behind in a microscopic from as isolated ganglia. Last but not least gravity force, when water displaces oil linearly in an inclined, it is necessary to include the contribution of gravity forces to the fractional-flow, because the oil density is less than the water density, gravity forces reduce the fractional flow of water when water is moving updip.This work is being conducted to study the Water flooding performance of layered reservoirs with permeability variation in vertical direction being characterized by log-normal distribution function with cross flow between layers. The permeability distribution function is defined by controlling the degree of variation by setting the Dykstra-Parsons (DP) variation coefficient VDP and the standard deviation of the distribution σk. The study indicates that performance of the water flooding is getting worse as the degree of heterogeneity increased and the contrast in permeability between the adjacent layers become bigger.

KEYWORDS: Water flooding, heterogeneity, variation coefficient, oil recovery.

الملخص

يعتبر الحقن المائي من أرخص طرق استخلاص النفط وأكثر الطرق الثانوية شيوعاً لزيادة استخلاص النفط عن طريق حقن الماء في المكمن. تهدف هذه الدراسة إلى فحص مدى تأثير درجة عدم التجانس على القوى الرئيسية التي تحكم أداء الحقن المائي في الخزانات الطبقية . هناك عدة قوى تؤثر على هذه العملية وهذه القوى مثل القوى الشعرية التي تنشأ عندما يتم حقن الماء في المكمن متعدد الطبقات، وتكون حركة مقدمة الازاحة أكثر سرعة في الطبقات الأكثر نفاذية. القوة الثانية المهمة هي القوى اللزجة، بسبب اللزوجة المتشابهة بين مراحل الإزاحة، تتقدم جبهة الحقن تقريبًا مثل المكبس. وهذا يعني أنه بشكل عام، تم اجتياح جزء كبير من الوسط المسامي تمامًا

بواسطة الماء ولم يتم ترك سوى الزيت المتبقي في العقد المجهرية المعزولة. وأخيرًا وليس آخرًا قوة الجاذبية، يتم وضع بعض الخزانات بزاوية مع الأفقي. تم إجراء هذا العمل لدراسة أداء غمر المياه في المكامن ذات الطبقات مع اختلاف النفاذية في الاتجاه الرأسي الذي يتميز بوظيفة التوزيع اللوغاريتمي الطبيعي مع التدفق المتقاطع بين الطبقات. يتم تعريف وظيفة توزيع النفاذية عن طريق التحكم في درجة التباين عن طريق تحديد معامل التباين Dykstra-Parsons (DP) VDP والانحراف المعياري للتوزيع σk وتشير الدراسة إلى أن أداء الحقن المائي يزداد سوءاً مع زيادة درجة عدم التجانس وزيادة التباين في النفاذية بين الطبقات المتجاورة.

الكلمات الرئيسية: حقن المياه،عدم التجانس،معامل الاختلاف،استخلاص النفط.

1. INTRODUCTION

Over the years, waterflooding has been most widely used secondary oil recovery method after the exhaustion of the primary depletion energy of the reservoir. Water flooding is a secondary-recovery method by which water is injected into a reservoir to recover more petroleum from it through movement of reservoir oil to a producing well, after the reservoir has approached its economically productive limit by primary-recovery methods [1]. Water flooding – usually the first secondary method applied to a reservoir, because Capital costs, mainly for surface facilities to handle the injection and production water, are relatively in expensive compared with those of most other EOR methods. Operating costs for a water flood are typically lower than for other EOR techniques. The first recognition of the benefits that can be obtained from water injection came as a results of accidental flooding when water was inadvertently admitted to producing oil sands through abandonment wells. In 1880 Carl reported increased oil production following accidental flooding in the Pit hole city and suggested the use of intentional flooding Increased production was noted in 1907 in Pennsylvania's Bradford field and in 1912 in New York. The line drive pattern was introduced in 1922 and the five-spot pattern in 1924 .The first waterflood was initiated in Oklahoma in 1931 in shallow Bartlesville sand in Nowata County [2, 3].

It was pointed out that in determining the suitability of a candidate reservoir for waterflooding, the following reservoir characteristics must be considered: reservoir geometry, fluid properties, reservoir depth, lithology & rock properties, fluid saturations, primary reservoir driving mechanisms, reservoir uniformity and pay continuity [4].

Buckley – leveret theory established for immiscible displacement calculation. The theory for linear one dimensional displacement and incompressible flow .The theory determines the velocity of a plane of constant water saturation moving through a linear system [5, 6]. The degree of heterogeneity in an oil reservoir plays a crucial role in determining the effectiveness of water flooding. Understanding and modeling this heterogeneity is essential for optimizing water flooding strategies and maximizing oil recovery. Enhanced predictive techniques and adaptive management strategies can help address the challenges presented by heterogeneous reservoirs.

Reservoir heterogeneity refers to the variation in reservoir properties—such as permeability, porosity, thickness, and rock characteristics—across different spatial locations within the reservoir. This variability can significantly influence oil production efficiency and recovery rates [7, 8]. Dykstra–Parsons coefficient is used to present the reservoir heterogeneity. The Dykstra–Parsons coefficient is widely applied in the reservoir characteristics [7, 8]. Heterogeneity is a very significant factor in reservoir static modeling, reservoir simulation, and determining hydrocarbon recovery of petroleum reservoirs. Dykstra Parsons is a straight forward method to calculate heterogeneity efficiently and accurately [9, 10].

2. METHODOLOGY

Three dimensional numerical simulation model water flooding will be performed using input relative permeability and capillary pressure, PVT lab and reservoir rock properties data. After running the simulation, the data will be collected to study the effect of many factors on performance of water flooding.

3. NUMERICAL SIMULATION RESULTS AND DISCUSSION

Three dimensions numerical reservoir simulation studies were conducted on a model with dimensions of 1350*1350*600 feet as shown in the figure (1). These dimensions were divided to generate 13*13*10 simulation cells. The model is constructed to be composed of 10 discrete layers. Each layer has its own absolute horizontal and vertical permeability. The permeability variation is characterized by Log-Normal distribution, as shown in the figure (2) with VDP=0.4 and the geometric permeability is equal to 500 md. The general rock and fluid properties and model specifications are demonstrated in the table (1). PVT properties for oil and water which used in the model are presented in the tables (2). The oil and gas viscosity are shown in figure (3), Rock-fluid interaction properties oil-water capillary pressure, oil-water relative permeability and oil and gas relative permeability curves are shown in figures (4), (5) and (6) respectively.

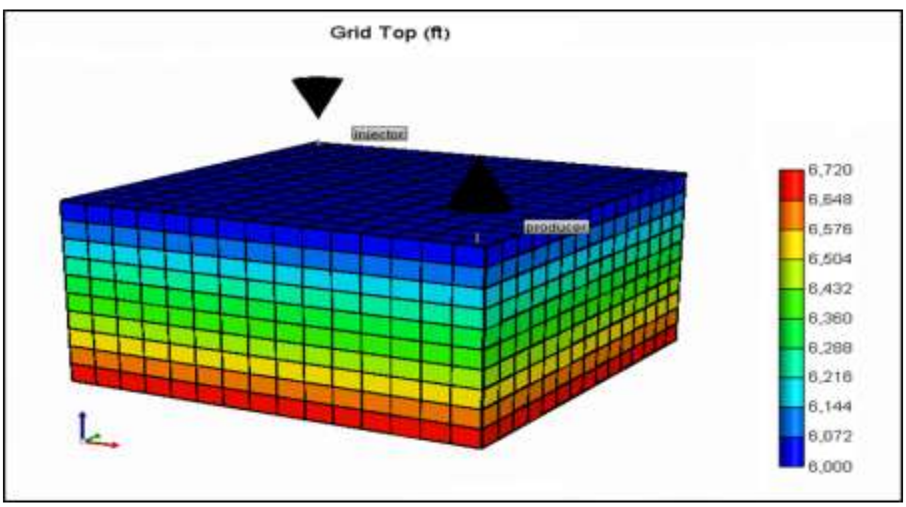

Figure 1: reservoir model

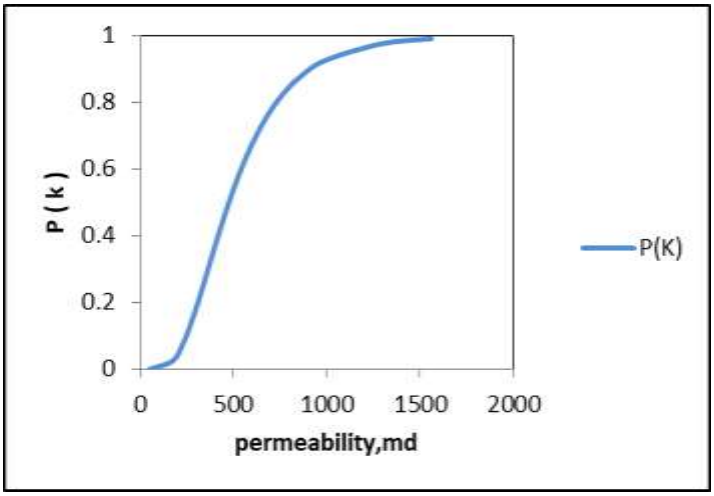

Figure 2: distribution of permeability

Table 1: reservoir data

Ø Porosity , fraction	0.25
h Total reservoir thickness , feet	600
P_{in} Initial reservoir pressure , psia	4000
S_{wi} Irreducible water saturation , fraction	0.23
C_f Rock compressibility , psi^{-1}	4.89E-6
ρ_o Oil density , lb/ft^3	53.7
ρ_w water density , lb/ft^3	61.8
ρ_g gas density , lb/ft^3	0.037061
P_b Bubble point pressure , psia	1910
B_w Water formation volume factor , rb/stb	1.01
Rsi Initial solution gas oil ratio , Mscf/stb	0.289
μ_o Oil viscosity , cp	2.096
μ_w Water viscosity , cp	0.34
T Reservoir temperature , ^oF	158
C_w Water compressibility	2.78E-6

Table 2: PVT data

Pressure ,psi	Bo, rb/stb	Rs, mscf/stb	Visc, cp	Bg bbl/scf	Viscosity Cp
1300.2	1.1107	0.19333	1.7821	0.003964915	0.0149
1700.3	1.1351	0.25546	1.6103	0.002981656	0.0159
1950.1	1.1464	0.28675	1.5352	0.002632769	0.0165
2111.3	1.1616	0.31827	1.4644	0.002378985	0.0172
2450.2	1.1783	0.36203	1.374	0.0021252	0.0181
2700.1	1.1955	0.40641	1.291	0.001903117	0.0191
3000.2	1.2128	0.4515	1.2147	0.001744595	0.0201
3300.9	1.2302	0.49738	1.1446	0.001586002	0.0211
3580.2	1.2477	0.54415	1.08	0.001490846	0.0222
3600.8	1.2655	0.59188	1.0205	0.001395672	0.0233
3690.9	1.2835	0.64066	0.9654	0.001332235	0.0243
3860.1	1.3017	0.69058	0.9144	0.001268798	0.0253
4000	1.3392	0.79416	0.823	0.001141923	0.0274

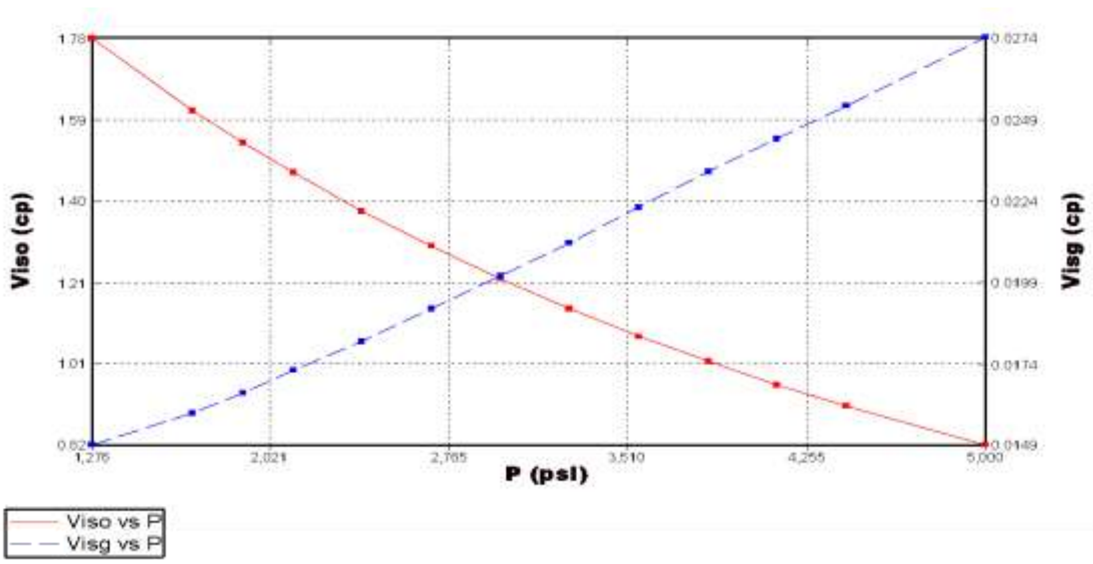

Figure 3: oil and gas viscosity

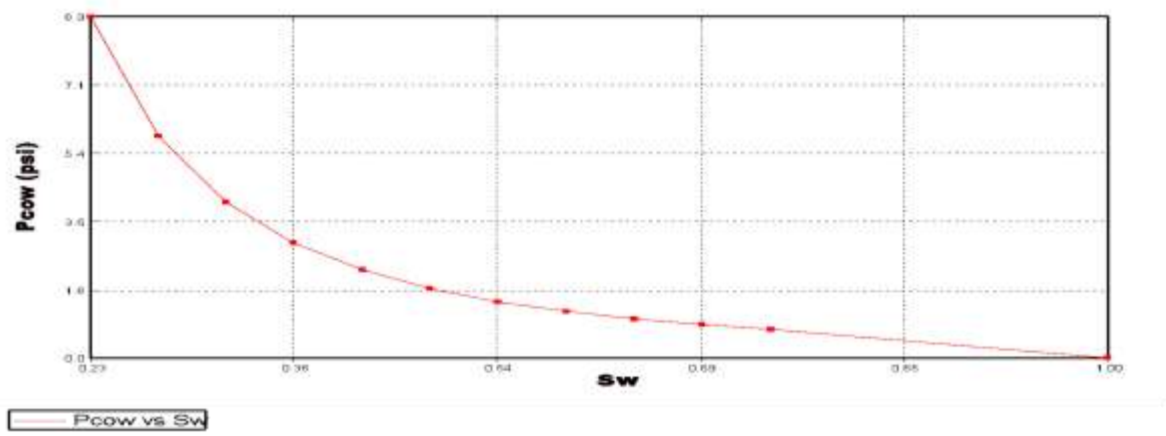

Figure 4: capillary pressure

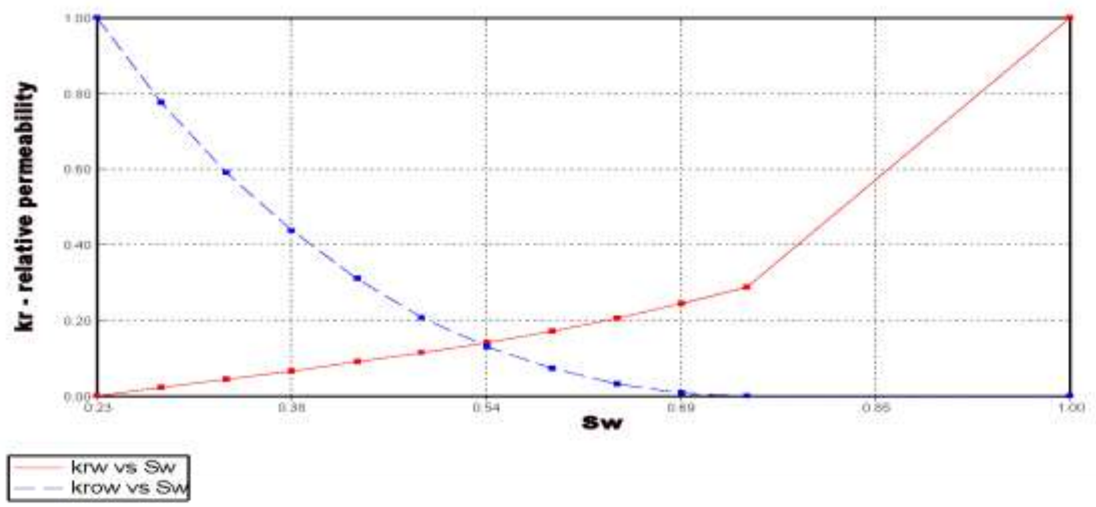

Figure 5: oil & water relative permeability

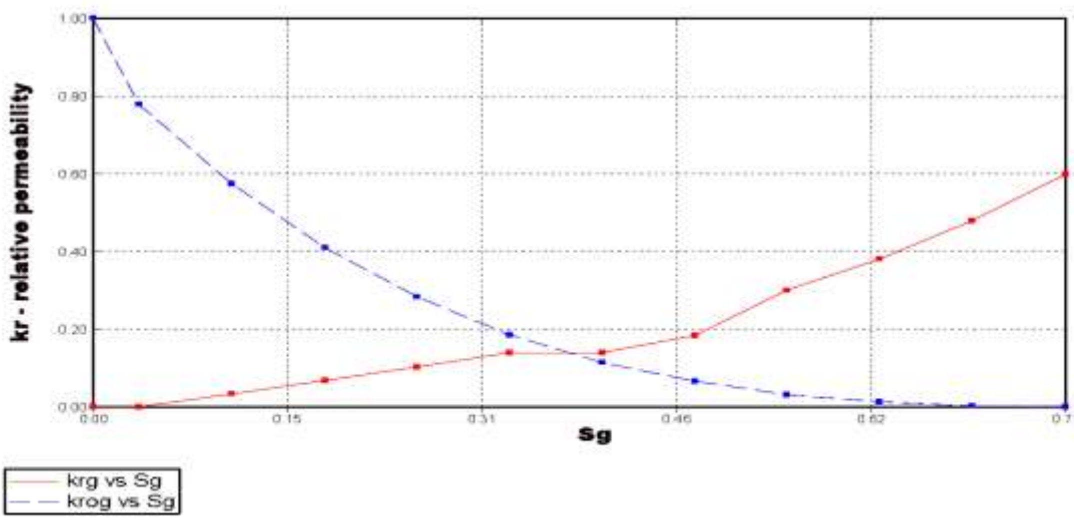

Figure 6: oil gas relative permeability

The reservoir model contain one well to inject the water and another one to produce the oil. The same internal diameter was used for both injection and production wells and it is set to be 0.6488 ft.

The injection well (I) was located in the cell (1, 1) to inject the water up dip direction in the cases where the reservoir is inclined and the production well (P) was located at cell (13,13). The perforation thickness for the both wells was equal to the reservoir thickness. The production was started simultaneously with the injection operation at 1 JAN 2024. The reservoir was depleted at maximum fluid production rate equal to 5000 stb/day and water was injected at 5000 stb/day of water. These operation constrains were applied to keep depleting the reservoir above its saturation pressure. The model was running for 20 years. The top of reservoir is located at 6000 ft in term of reservoir depth and the initial pressure is set to be 4000 psi. The shallowest depth with 100% water saturation being at 7800 ft.

Five simulation studies were conducted to examine the effects of vertical heterogeneity, the factors which control the gravity dimensionless number, cross flow between the adjacent layers, the layers permeability order and the mobility ratio on the performance of the water flooding is such reservoirs which exhibited the stratification.

4. CASE STUDIES FOR SENSITIVITY ANALYSIS

Case 1:

The first case is designed to study the impact of the mobility ratios on the water flooding performance. The models have the same base case (the dipping angle is equal to zero) dimensions, reservoir rock, the rock-fluid interaction data and fluid properties except the water viscosity which varied in systemic manner to produce the mobility ratios that shown in table 3 . Even the production and the injection constrains are the same as the ones used in the case where the reservoir is horizontal.

Table 3: mobility ratio cases.

Case number	Mobility Ratio
1	0.5
2	1
3	6.25

Case2

The purpose of this study is to examine the gravity cross flow which depend on the actual ordering of the layers in the reservoir. The evaluation of the bouncy effect can be achieved by randomly assigning the layers permeability without any order.

In addition to the base case where permeability was assigned in decreasing order five random permeability orders with fining upward shown in table 4were investigated for horizontal models with mobility ratio equal 1.

Table 4: permeability ordering cases

Permeability Md	Fining upward	Fining downward	Random 1	Random 2	Random 3	Random 4	Random 5
990.950284	174.5331996	990.950284	174.533	263.930	322.928	376.727	431.258
765.651389	263.930778	765.6513899	990.950	174.533	263.930	322.928	376.727
644.623221	322.9280206	644.6232214	765.651	990.950	174.533	263.930	322.928
558.963377	376.7272498	558.963377	644.623	765.651	990.950	174.533	263.930
490.461621	431.2587534	490.4616218	558.963	644.623	765.651	990.950	174.533
431.258753	490.4616218	431.2587534	490.461	558.963	644.623	765.651	990.950
376.727249	558.963377	376.7272498	431.258	490.461	558.963	644.623	765.651
322.928020	644.6232214	322.9280206	376.727	431.258	490.461	558.963	644.623
263.930778	765.6513899	263.930778	322.928	376.727	431.258	490.461	558.963
174.533199	990.950284	174.5331996	263.930	322.928	376.727	431.258	490.461

Case3

The injection rate considered as one of the main factors which control the water flooding performance and have huge effect on the gravity forces. However generally any incremental in the injection lead to increase oil recovery factor within critical limit of injection rate that flood become unstable at it. The values of injection rates used in this study are varied in manner of ± 17% of first case model.

Case4

The main sensitivity variable in this case is the density different between the driving and the driven fluid. The density different factor have marked effects on the gravity force which is one of the main forces that control flooding performance especially in inclination communicating reservoirs. The simulation study was conducted on horizontal communicating models with density difference equal to 5.7, 6.8and 7.2.

Case5

This study described the impact of the cross flow between the adjacent layers on the oil recovery. The vertical permeability for the layers is set to zero to prevent the cross flow. This isolation technique was used to all inclined and horizontal models for different mobility ratios to compare the result with communicating system result.

The horizontal permeability variation in the vertical direction has significant effect on the performance of the water flooding. To investigate the effect of the degree of the reservoir heterogeneity and since the permeability is represented by log-normal distribution. The layers permeability were generated using log-normal distribution with VDP equal to 0.2 and 0.6 in addition to the base case. The reservoir dipping 35 degree from the horizontal with M=6.25 was used to examine the effect of the permeability variation degree. The permeability distribution functions are demonstrated in Figure (7).

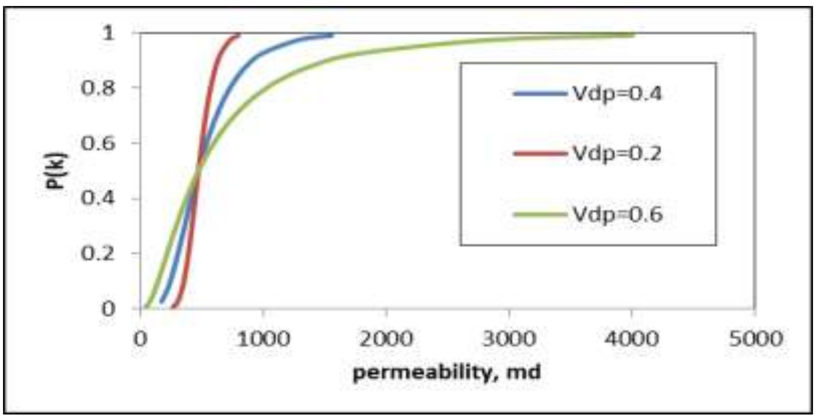

Figure 7: permeability distribution with different VDP

5. SIMULATION STUDIES ANALYSIS

Oil recovery increases as the mobility ratio decreases. This improvement in the oil recovery is due to the reduction of the velocity of the water which clearly represented by the decreasing in the water mobility in compare to hydrocarbon mobility, see the figure (8). In very unfavourable condition when the mobility ration equal to 6.25 which refer to the mobility of water is greater than the mobility of oil by six times and quarter, the water will reach faster the producing wells and end with lowest breakthrough time and higher water cut as shown in figure (9).

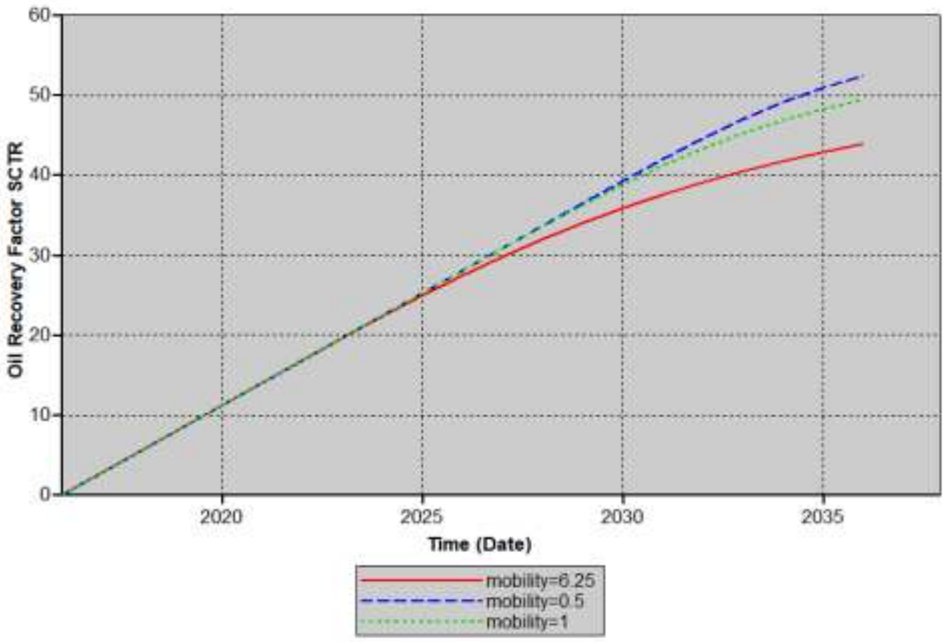

Figure 8: oil recovery for different mobility ratio

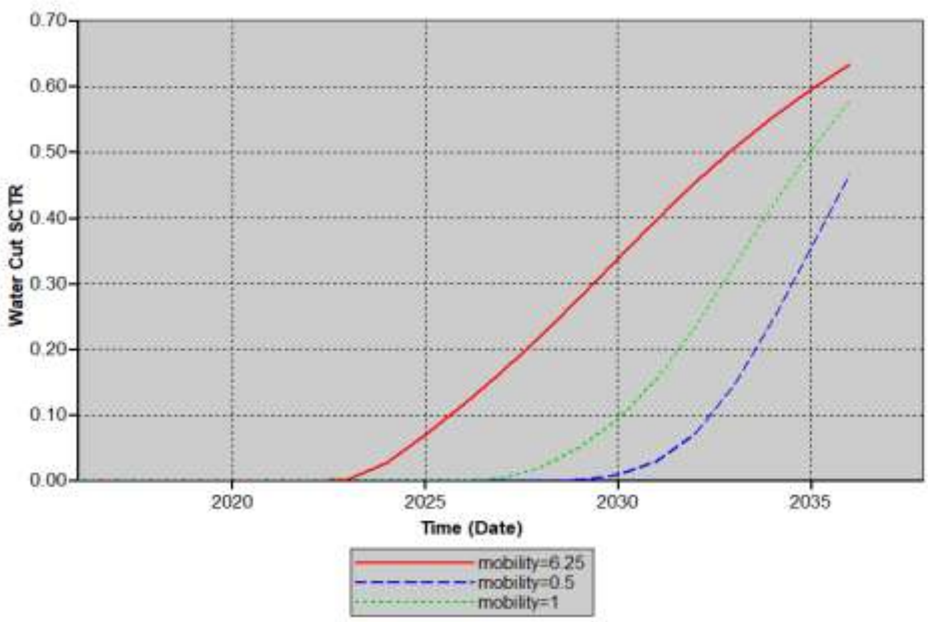

Figure 9: water cut for different mobility ratios cases

The improvement in the recovery factor can be clearly seen between cases different permeability-depth configuration. It is obvious from the figure (10) that the best case which leads to highest oil recovery is the fining downward case.

The gravity force always acts to increase the water saturation in the bottom layers by withdraw the water from the top layers toward bottom. The domination of the gravity force is dependent on permeability-depth configuration and Kv/Kh ratio. In the case where the permeability is kept decreasing with depth the front advance slower in the top layers due to drainage the water down. This effect will sharpen the front and enhance the performance, see the figure(10).For the opposite permeability configuration the performance will get worse since the gravity effect will improve the water velocity in bottom layers which will accelerate the water breakthrough. In the case where the permeability is randomly distributed with depth (i.e. permeability alternately increase and decrease with depth) the cross flow between the layers due to the bouncy effect may be greater than in the fining downward case. The bouncy drives the oil to flow upward while the water segregates downward which delay the front advance. The magnitude of the bouncy effect on the performance significantly relies on the area which opens to the gravity segregation. The extension of this area depends on the permeability contrast between the adjacent layers. Since the gravity improves the recovery as permeability decreases with depth and vies versa. The incremental oil recovery as permeability decreases with depth tend to compensate the reduction in the recovery which is caused by the opposite permeability configuration. As the result of this compensation the random permeability distribution tend to have minor effect on the performance. The fining upward case is the worst case since it accelerates the water breakthrough and increase the water cut, figure (11)

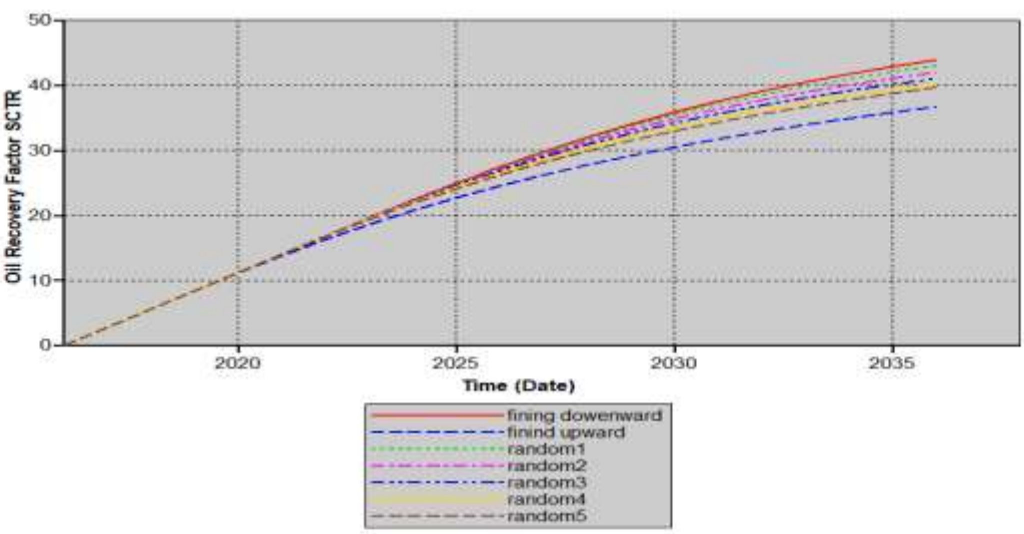

Figure 10: recovery factor for the permeability ordering

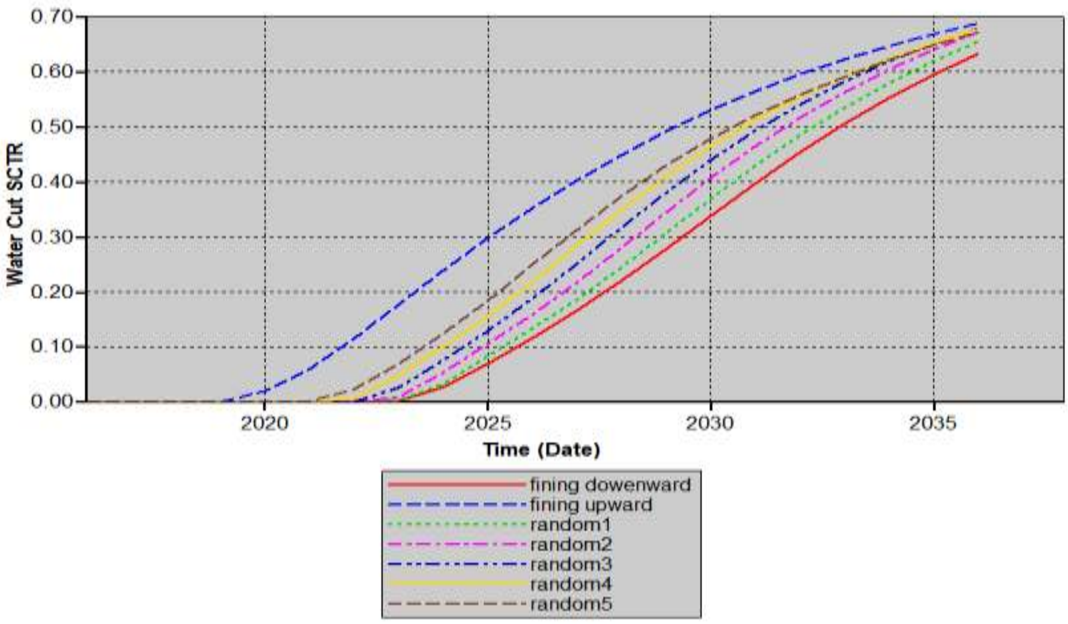

Figure 11: water cut for the permeability ordering

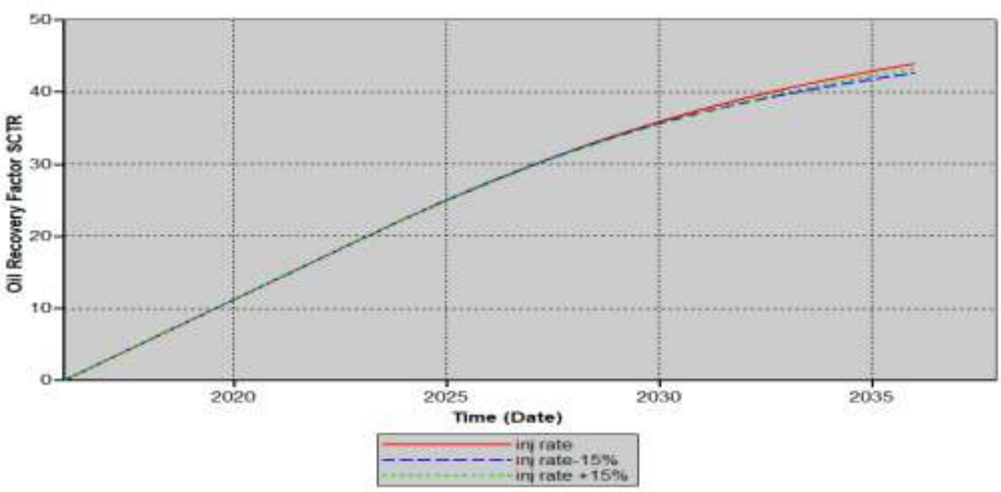

Figure 12: recovery factor for different injection rates

The improvement in the recovery factor can be clearly noticed at higher water injection rates until meet the critical injection rate which lead to poor unstable performance. The three studied cases state that the recovery will be enhanced as the water injection rate is increased as demonstrated in figure (12). The increase in density difference between the displaced and displacing fluid enhances the oil recovery, figure (13). The term which represents the density difference appears in the fractional flow equation for inclined reservoirs, As this difference increase it lower the water cut and increase the oil recovery, figure(14)

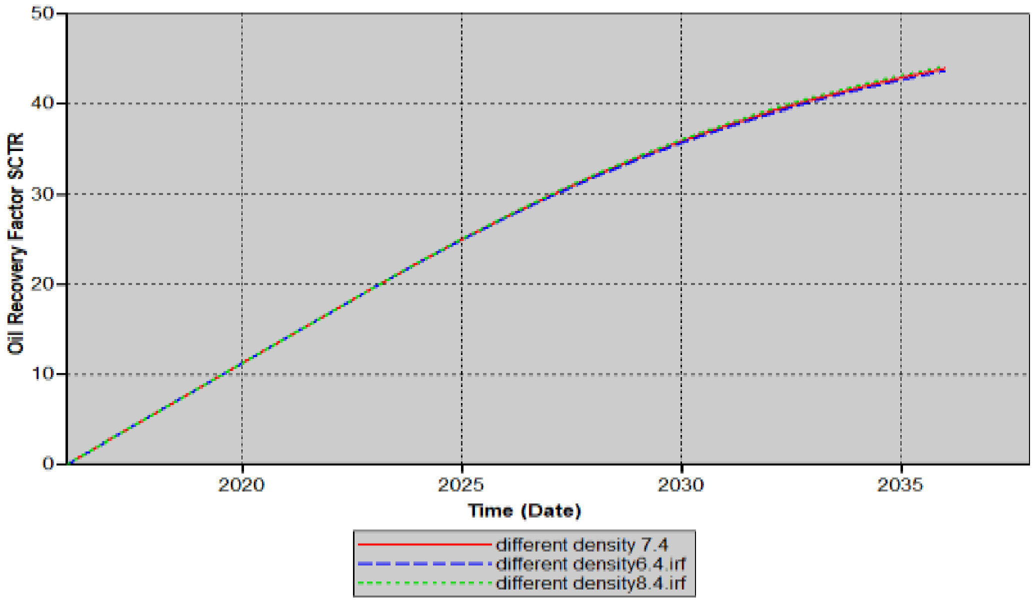

Figure 13: recovery factor for density difference

The performance of the flood gets worse as the Dykstra-Parson coefficient increased because the reservoir became more heterogeneous as the permeability variation increases, figure (15). Obviously, As the reservoir get more heterogeneous the water breakthrough happens earlier and make the water cut higher as shown in figure (16).

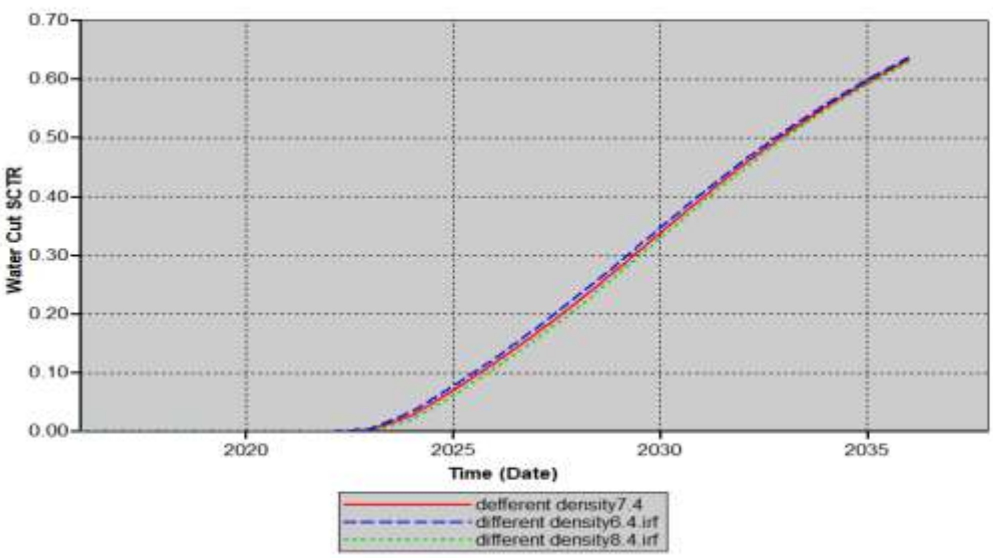

Figure 14: water cut for density difference

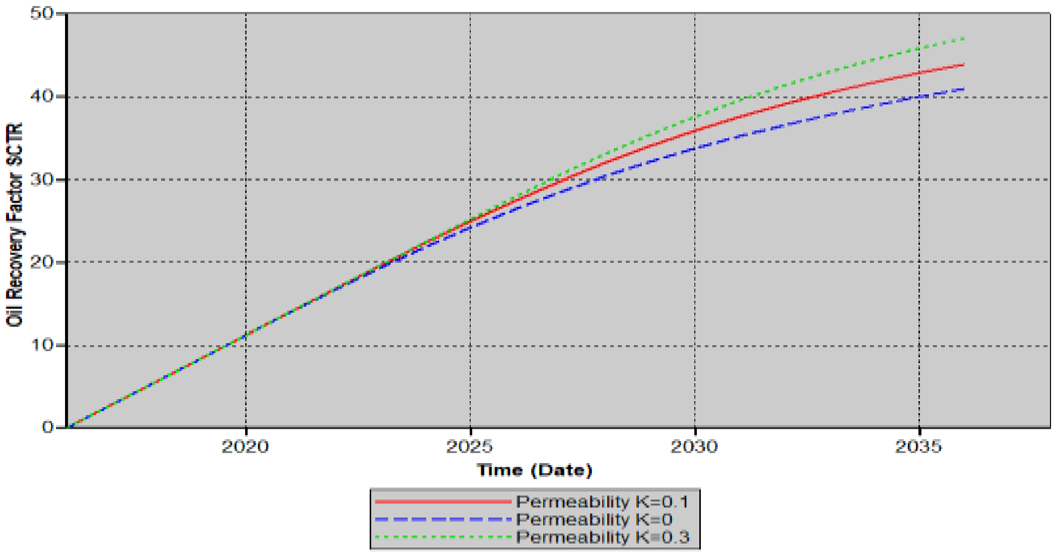

Figure 15: recovery factor for the effect of the degree of heterogeneity

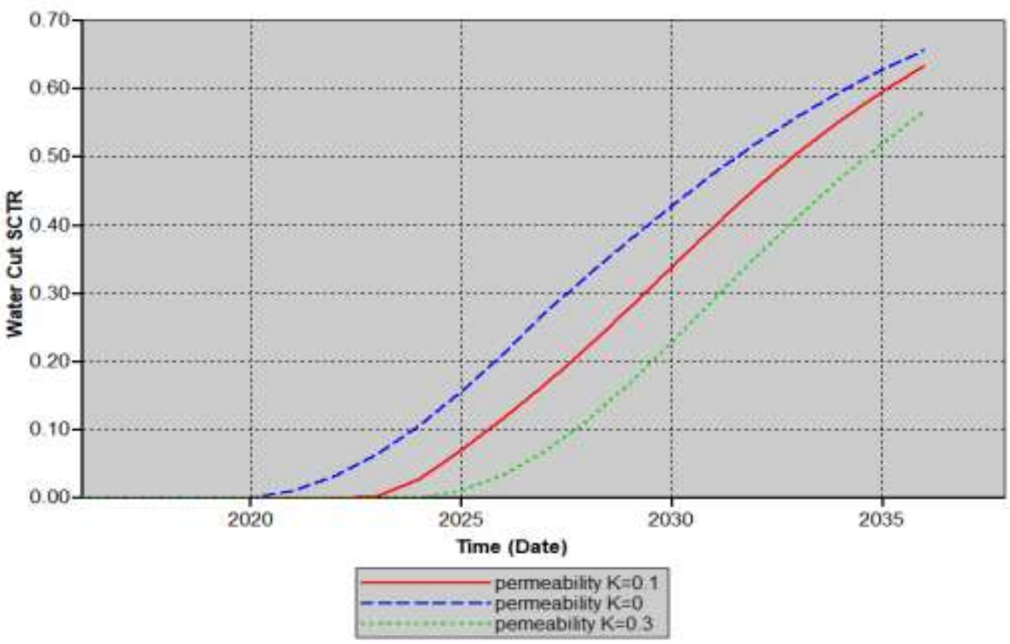

Figure 16: water cut for the effect of the degree of heterogeneity

6. CONCLUSION AND RECOMMENDATIONS

Water flooding performance in stratified system, in which layer are arranged systematically, can be greatly affected by gravity segregation depending on injection rates. The improvement in the oil recovery due to the decreasing in the degree of the reservoir heterogeneity will be more evident in the case with favourable mobility ratio than for unfavourable mobility ratio case. At low enough flooding rates the water flooding performance of a systematically ordered system in which the most permeable layer is on top can be vastly different from an identical one with opposite permeability ordering.The increase in the density difference between the displacing and the displaced fluid or decreasing in the injection rate will enhance the oil recovery due to its effect on the gravity number. The study recommended that the Effect of cross flow due to the capillary pressure, also porosity and saturation change and their variation can be represented by normal distribution function. Sensitize the location of injection and production wells and examine the effect of different flood pattern on the flooding performance.

LIST OF SYMBOLS

k_{ro} ⇒ Relative permeability
μ_o ⇒ Oil viscosity
ρ_o ⇒ Oil density
k_{rw} ⇒ Relative permeability to water
μ_w ⇒ Water viscosity
P_O ⇒ Oil pressure
ϕ ⇒ Porosity
S_w ⇒ Water saturation
S_{or} ⇒ Residual oil saturation
S_{wi} ⇒ Initial water saturation
β_o ⇒ Formation volume factor of oil
β_w ⇒ Formation volume factor of water
M ⇒ Mobility
λ_{wi} ⇒ Mobility of water
λ_{oi} ⇒ Mobility of oil
ϕ ⇒ porosity
WC ⇒ Water cut

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