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***Research paper***

# Numerical simulation of In-situ combustion and the effects of change in parameters on reservoir efficiency

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***A b s t r a c t***

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*In-situ combustion,*
*Numerical simulation,*
*Enhanced oil recovery,*
*Heavy oil,*
*Sensitivity analysis.*

In-situ combustion is a high-risk thermal recovery which usually is used for heavy oil and extra-heavy oil reservoirs. This method of EOR can be done as forward and reverse which latter has been found economically unattractive and difficult to apply. In forward combustion, dry and wet can be used. This paper focused on dry combustion. A sensitivity analysis with a compositional simulator has been done. Effect of porosity of reservoir, permeability of reservoir, anisotropy ratio, initial temperature and target total molar rate was analysed on different key parameters. Water cut, oil recovery factor, gas oil ratio, total water production, well productivity index and reaction's rate in the reservoir during combustion simulated for 600 days. It found that when permeability increased from 500 millidarcy to 1000, 3000 and 5000 millidarcy, GOR curve changed rapidly before first 90 days and shift to the lower values. Moreover, water cut decreased slightly and oil production increased from 15285 STB to 15768, 16648 and 18280 STB respectively. Furthermore, oil recovery factor and water production increased. Decreasing in porosity from 0.38 in BASE case to 0.30, 0.25 and 0.20 resulted in decreasing oil recovery factor, oil production from 15285 STB to 12180 STB, 10392 STB and 8709 STB respectively, water production and GOR. Increasing initial reservoir temperature from 200 °F to 250 °F resulted in increasing oil recovery factor from 0.85 to 0.95. In addition, it causes water start to produce sooner. Anisotropy ratio does not have any special effect on reactions, but changing initial temperature resulted in a considerable change in reactions. It proved that target total molar rate has a great effect on the oil production. In the BASE case, total molar rate of oxygen was 300 lbmol/day at 200F at 70psi and recovery factor was 0.85. By changing oxygen molar rate to 250, 100 and 70 lbmol/day at 200F at 70psi recovery factor changed to 0.95, 0.56 and 0.39 respectively. It concluded that optimum molar rate was 250 lbmol/day between these values.

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**1. Introduction**

Heavy oil and extra-heavy oil combined to constitute the second largest deposit after oil shale. In heavy oil and extra-heavy oil reservoirs, conventional production method is not working. Because viscosity is very high, and it resulted in low mobility. In fact, based on the report of IEA, the heavy and extra-heavy oils constitute around 40 % of the world oil reserves while, some resources assert that it is as high as 70 % in like Heriot Watt Institute of Petroleum Engineering [1],[ 2]. Heavy oils typically have low hydrogen in comparison to carbon, high-carbon residues, sulfur, nitrogen, and heavy-metal content and have higher acid numbers. In this type of reservoirs, recovery factor is low due to high viscosity. Thus EOR methods should be implemented in order to increase recovery factor. There are different kinds of the way to enhance oil recovery. The oil recovery methods can be categorized into two main categories based on energy source criteria. These are primary recovery methods and improved recovery methods [3], [4]. If the oil recovery is done by using only the natural energy of the reservoirs, it is known as primary recovery. The oil which cannot be displaced by primary recovery mechanisms can be produced by improved recovery methods [5]. Thermal recovery is very common for heavy and extra-heavy oil reservoirs. One of these methods are In-situ combustion.

In-situ combustion is an old and high-risk Enhance Oil Recovery (EOR) method, which it has been used since 1920 in the field. It could be a useful method to produce very heavy oils with high viscosity. Before starting this project on the field scale, it needs to accurate laboratory experiments in order to reach to a favorable result. It is observed that the sustainability of the combustion front depends upon reactivity of the crude and the initial reservoir temperature [6]. In the US, more than 230 projects were done until now. Some of them were not successful. In order to avoid failure, it is essential to have enough information about this method and effect of different parameters for this procedure. During combustion, some reactions between compositions can be occurred. The combustion reaction occurs in three stages; Thermal cracking, low temperature oxidation (LTO), high-temperature oxidation (HTO) [7].

There is two main type of combustion method, reverse and forward combustion method. Reverse combustion has been found economically unattractive and difficult to apply, but forward is practical in the field. Forward combustion derides into two methods. The first one is dry forward combustion, which in this method only air or enriched air is injected. The second one is wet forward combustion, which water in addition to air injected into injection well [8].

This paper focused on dry forward combustion and fond that what reservoir parameters can affect reservoir performance. In dry forward combustion, firstly, oil is ignited with an igniter in injection well. Then combustion front propagate by continuous flow of air. During this progress, between injection and production wells, Compositions will react with together, which their rate depends on different factors.

## 2. Model description:

The model was run in a commercial reservoir simulator in compositional method. The data that used in this model was from [9], which was based on [10]. The physical model was represented in Cartesian coordinates by grid 30 × 10 × 10 (total 3000 cells) which it can be seen in Fig. 1.

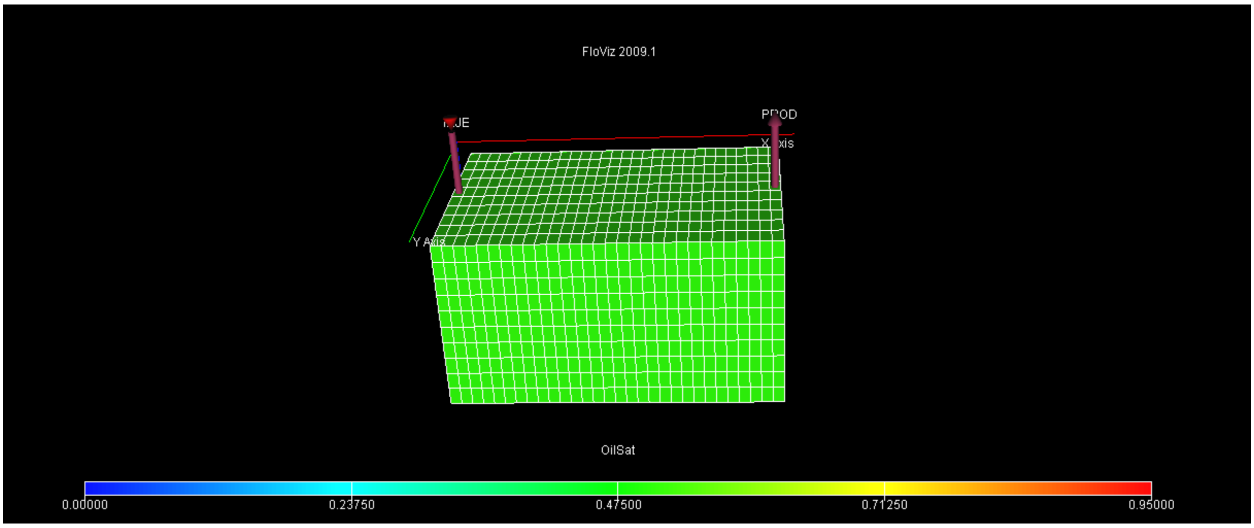



Fig. 1: 3-D model before running simulator.

Each cell in X, Y and Z direction is 5ft, 10ft and 8ft respectively. Anisotropy ratio is 0.15 and permeability in Y direction assumed equal to X direction that is 500 millidarcy averagely. Standard and initial condition brought in Table 1.

Table 1: Standard and initial condition of reservoir

| | |
|---|---|
| Standard pressure (psi) | 14.7 |
| Standard temperature (°F) | 60 |
| Initial pressure (psi) | 65 |
| Initial temperature (°F) | 200 |
| Water saturation | 0.2 |
| Gas saturation | 0.3 |
| Oil saturation | 0.5 |

Rock and fluid properties listed in Table 2 and Table 3 respectively. Relative permeability curves is shown in Figure 2.

Table 2: Rock properties

| | |
|---|---|
| Porosity (fraction) | 0.38 |
| Horizontal permeability (millidarcy) | 500 |
| Vertical permeability (millidarcy) | 0.15* horizontal permeability |
| Rock heat capacity (BTU/ft3/°F) | 35.0 |
| Thermal conductivity of rock and fluids (btu/ft/day/°F) | 38.4 |

Table 3: fluid properties

| Component | $C12H26$ | $C3H8$ | $COKE$ | $O2$ | $CO2$ |
|---|---|---|---|---|---|
| Fluid type | Liquid | Liquid | Solid | Gas | Gas |
| MW | 170 | 44 | 13 | 32 | 44 |
| Critical pressure (psi) | 264.6 | 615.9 | 673 | 730.0 | 1073 |
| Critical Temperature (°R) | 1184.9 | 665.6 | 343.08 | 343.08 | 343.08 |
| Reference density (lb/ft3) | 56.85 | 49.77 | 49.8928 | 49.8928 | 49.8928 |
| Reference pressure (psi) | 14.7 | 1000.0 | 14.7 | 14.7 | 14.7 |
| Reference temperature (°R) | 0 | 0 | 519.67 | 519.67 | 519.67 |
| Thermal expansion coefficient (1/°R) | 3.8E-4 | 7.69E-4 | 0 | 0 | 0 |
| First Oil component specific heat (BTU/lb/°R) | 0.5248 | 0.6097 | 0 | 0 | 0 |
| Second Oil component specific heat (BTU/lb/°R) | 3.547E-4 | 3.452E-3 | 0 | 0 | 0 |
| Gas component specific heat (BTU/lb/°R) | 0.25 | 0.25 | 0 | 0.24 | 0.25 |
| Solid component specific heat (BTU/lb/°R) | 0 | 0 | 0.3 | 0 | 0 |
| Heat of vaporization at standard temperature (BTU/lb) | 262.3 | 90.98 | 0 | 0 | 0 |
| Oil component K-value correlation (A) | 0 | 0 | 0 | 0 | 0 |
| Oil component K-value correlation (B) | 1.849E5 | 1.307E5 | 0 | 0 | 0 |
| Oil component K-value correlation (C) | 0 | 0 | 0 | 0 | 0 |
| Oil component K-value correlation (D) | 6.739E3 | 3.370E3 | 0 | 0 | 0 |
| Oil component K-value correlation (E) | 1.671E2 | 4.529E1 | 0 | 0 | 0 |

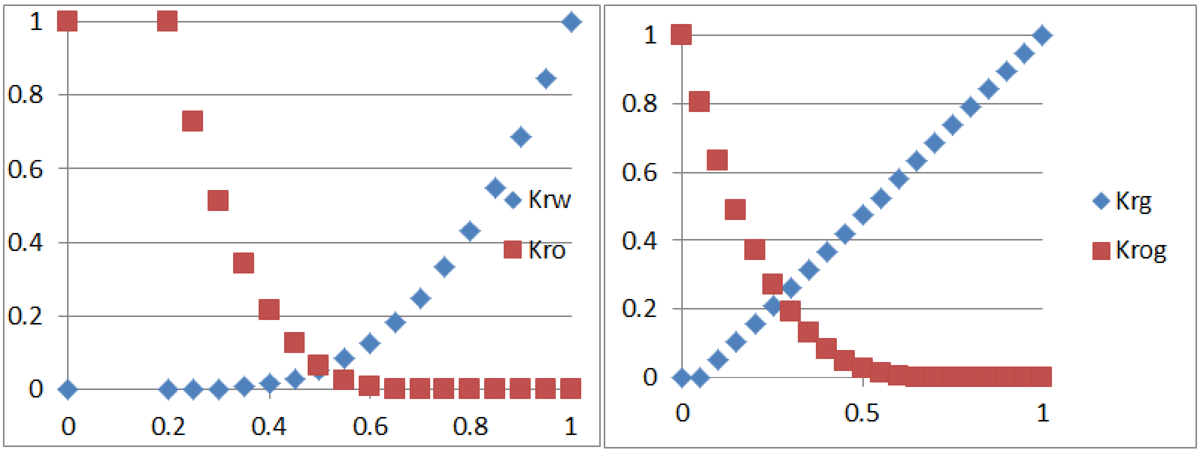



Fig. 2: Relative permeability curves

Additional information related to components brought in Tables 4, 5 and 6.

Table 4: Initial composition fraction in liquid and vapor phases

| | $C_{12}H_{26}$ | $C_3H_8$ | *COKE* | $O_2$ | $CO_2$ | Water |
|---|---|---|---|---|---|---|
| Liquid phase | 1 | 0 | 0 | 0 | 0 | 0 |
| Vapor phase | 0 | 0 | 0 | 0 | 0.806 | 0.194 |

Table 5: Oil viscosity-temperature correlation coefficients for ANDRADE formula

| | $C_{12}H_{26}$ | $C_3H_8$ | *COKE* | $O_2$ | $CO_2$ |
|---|---|---|---|---|---|
| coefficient *A* | -3.4408 | -1.681 | 1 | 1 | 1 |
| coefficient *B* | 3685.0 | 416.75 | 1 | 1 | 1 |

Table 6: Gas viscosity-temperature correlation coefficients

| | $C_{12}H_{26}$ | $C_3H_8$ | *COKE* | $O_2$ | $CO_2$ |
|---|---|---|---|---|---|
| coefficient *A* | 3.926E-6 | 2.166E-5 | 1 | 2.196E-4 | 2.127E-4 |
| coefficient *B* | 1.102 | 0.943 | 0 | 0.721 | 0.702 |

There were 5 components in this model. 5 reactions were done during combustion, which listed on Table 7.

Table 7: Reactions during In-situ combustion

| | |
|---|---|
| 1 | $C_{12}H_{26} + 18 \cdot O_2 \rightarrow 12 \cdot CO_2 + 13 \cdot H_2O$ |
| 2 | $C_3H_8 + 5 \cdot O_2 \rightarrow 3 \cdot CO_2 + 4 \cdot H_2O$ |
| 3 | $C_{12}H_{26} \rightarrow 2.C_3H_8 + 4.67.COKE + 1.33 \cdot CO_2$ |
| 4 | $COKE + 1.25 \cdot O_2 \rightarrow 1 \cdot CO_2 + 0.5 \cdot H_2O$ |

Additional information related to reactions demonstrated in Table 8.

Table 8: Reaction rate constant, Activation energy in chemical reaction rates and Reaction enthalpy

| | Reaction 1 | Reaction 2 | Reaction 3 | Reaction 4 |
|---|---|---|---|---|
| Reaction rate constant | 1.0E6 | 1.0E6 | 0.3E6 | 1.0E6 |
| Activation energy in chemical reaction rates | 33300 | 33300 | 28800 | 23400 |
| Reaction enthalpy | 3.49E6 | 0.948E6 | 2.0E4 | 0.225E6 |

There is one injection well and one production well in this model. Wells information can be seen in Table 9. Injection fluid was Oxygen with mobility ration of 10 and rate of 300 lbmol/day at 200 °F and 70 psi

Table 9: Wells information

| Wells names | X position | Y position | $K_1$ | $K_2$ | P/I | Fluid | Rate * (lbmol/day) | Diameter (ft) | Skin | Active days |
|---|---|---|---|---|---|---|---|---|---|---|
| PROD | 1 | 5 | 4 | 6 | P | Oil | --- | 1 | 0 | 600 |
| INJE | 30 | 5 | 4 | 6 | I | Oxygen | 300 | 1 | 0 | 600 |

* At 200 °F and 70 psi.

Above information was related to our BASE case. A sensitivity analysis was done on the anisotropy ratio, that has five different cases with 0.1, 0.2, 0.3, 0.4 and BASE values. After running these cases oil recovery factor, oil production rate, total oil production, gas oil ratio, water cut, total water production, well productivity index and every four reaction rate during 600 days had been analyzed. This action was done for permeability that vary between 100, 500, 1000, 30000 and 5000 millidarcy, porosity varies between 20, 25, 30, 38 and 40, initial temperature, which varies between 70, 100, 200 and 250 Fahrenheit degree and finally rate of injected oxygen varies between 50,100, 200, 300 and 500 lbmol/day.

## 3. Results and discussion

### 3.1. 3-D model

After running simulator with mentioned data 3-D model for first 200 day, 400 and the last day of simulation had been indicated if Figures 3, 4 and 5 respectively.

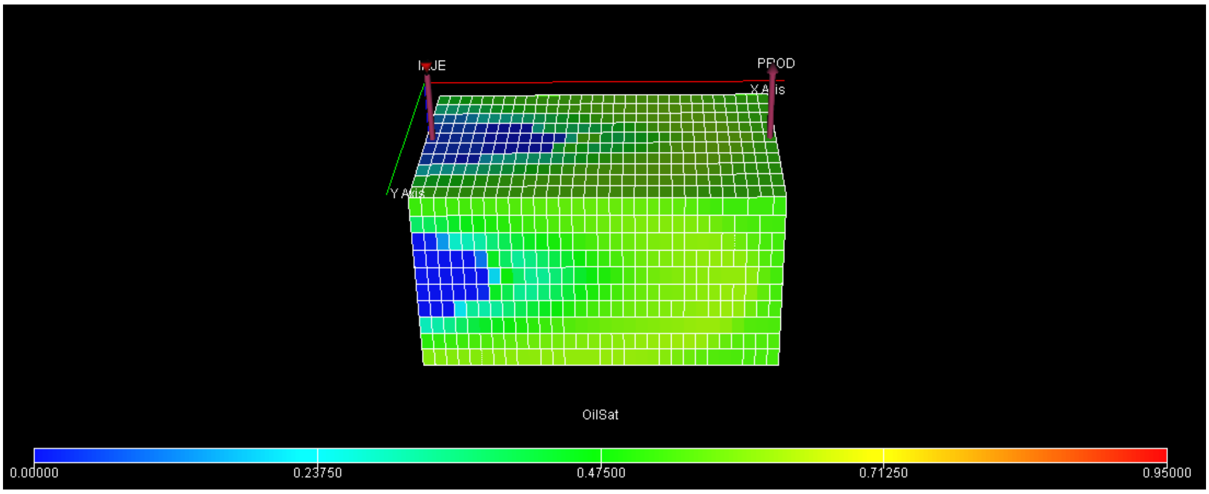



Fig. 3: 3-D model in after 200 days.

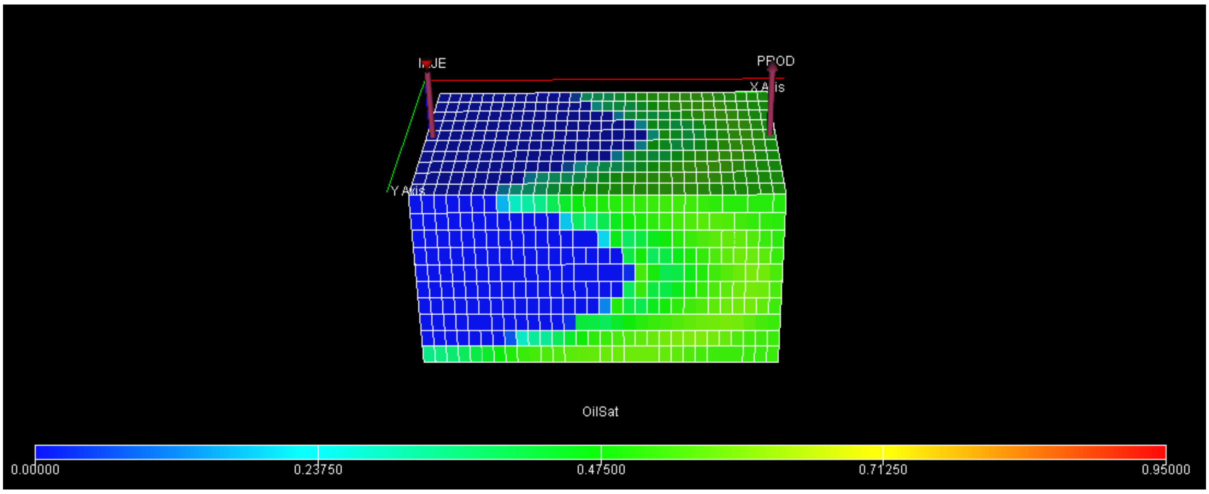



Fig. 4: 3-D model in after 400 days.

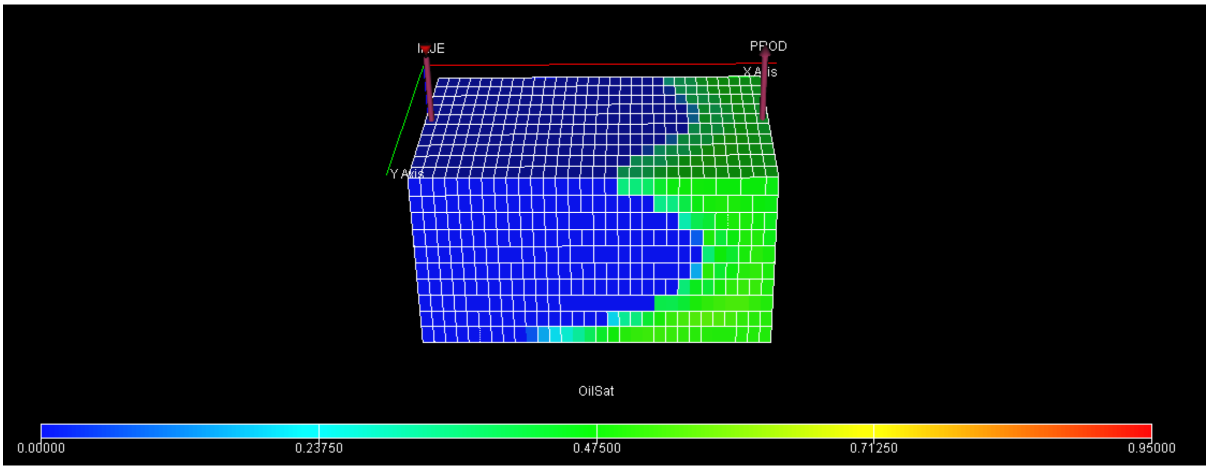



Fig. 5: 3-D model in after 600 days.

### 3.2. Anisotropy ratio effects:

After running cases that their anisotropy ratio was different it concluded that oil recovery factor decreased with increasing anisotropy ratio until 0.3, and it started to rise to higher values in this case. Its results in normal and zoom view brought in Figure 6.

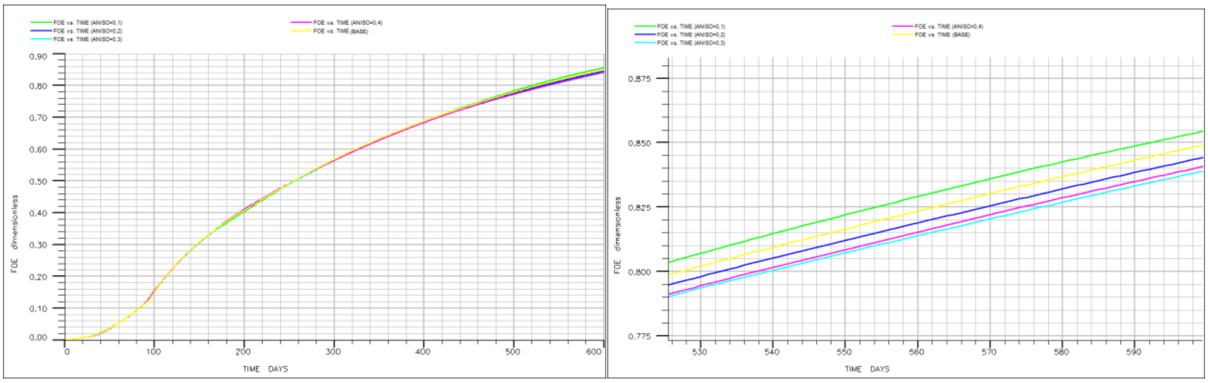


Fig. 6: Oil recovery factor for different anisotropy ratios.

In gas oil ratio analyzes, it found that increasing in the anisotropy ratio caused a small delay in reaching the peak in early time. Figure 7 shows these results.

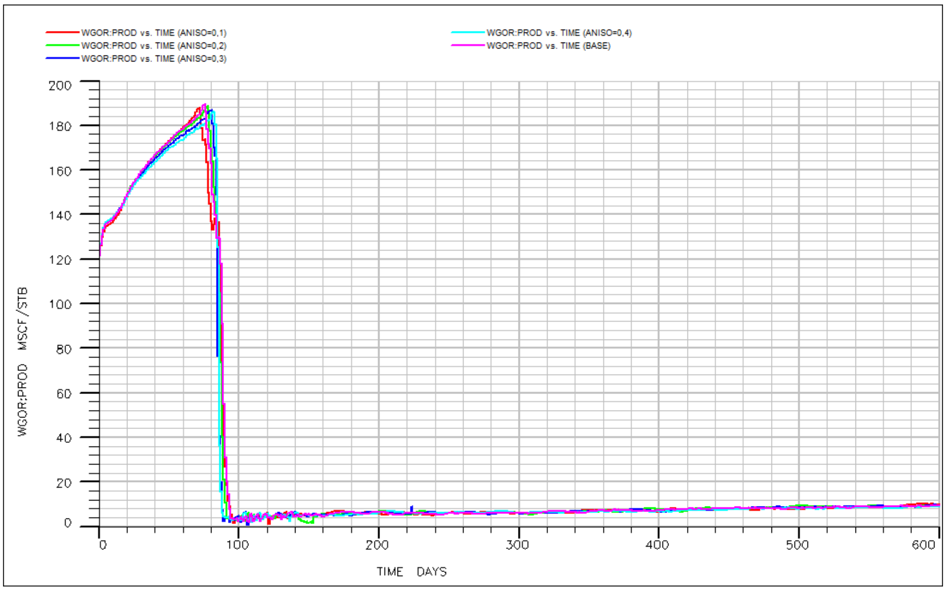



Fig. 7: Gas oil ratio for different anisotropy ratios.

Oil production rate and Total oil production vary with changing anisotropy ratio like Figures 8 and 9.

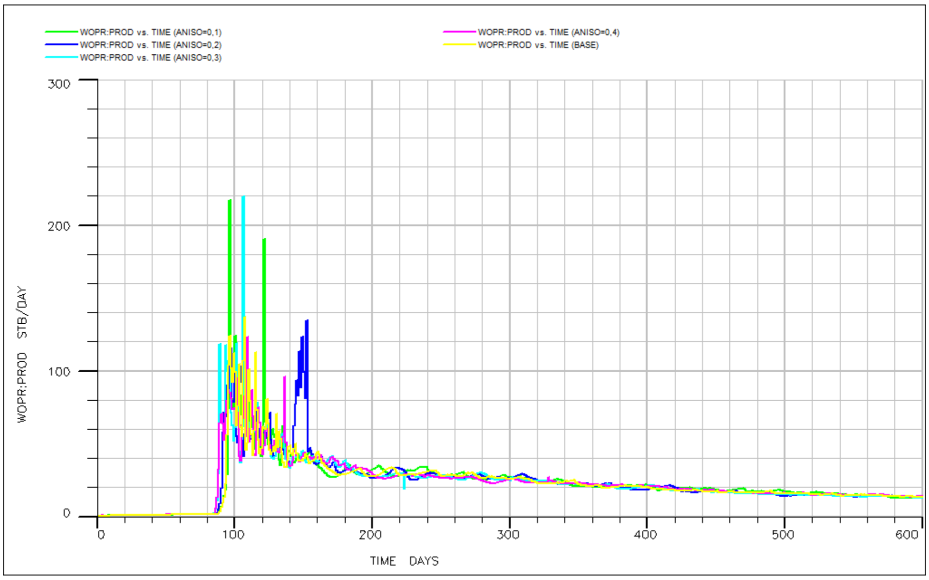



Fig. 8: Oil production rate for different anisotropy ratios.

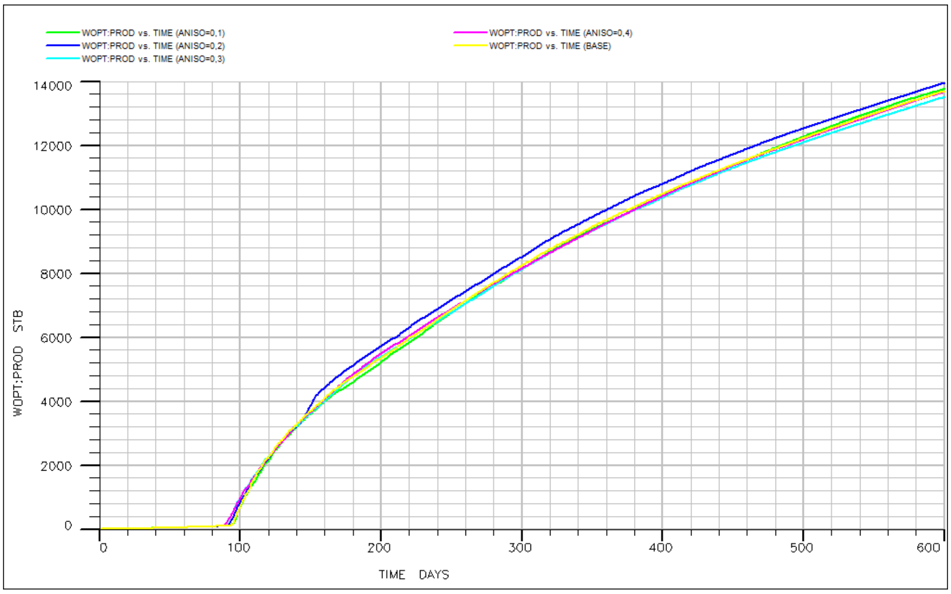
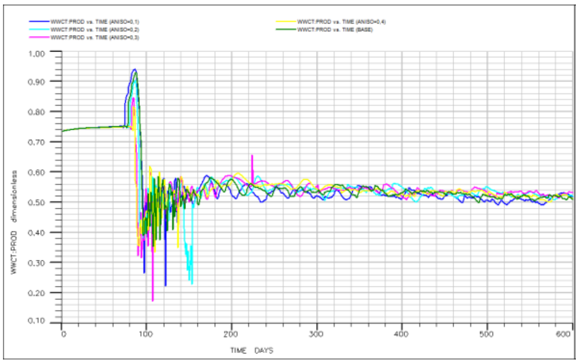



Fig. 9: Total oil production for different anisotropy ratios.

Total water production increase with rising anisotropy ration. Water cut in production well can be seen in Figure 10. Figure 11 indicates total water production during 600 days.



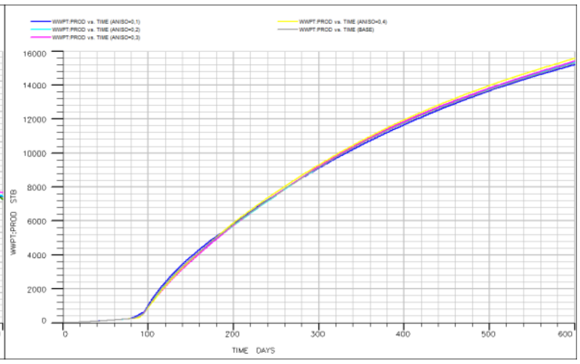


Fig. 10: Water cut for different anisotropy ratios. Fig. 11: Water production for different anisotropy ratios.

Figure 12 show production well Productivity Index (PI) for these five cases.

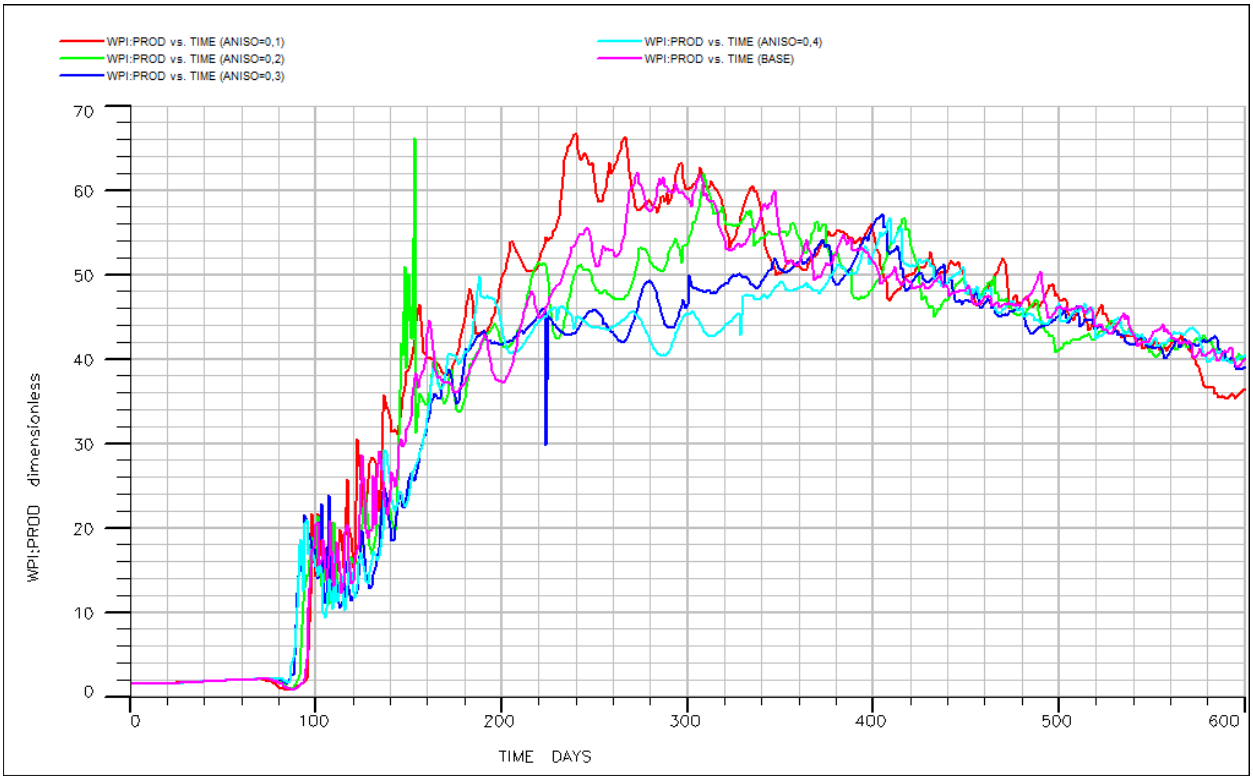



Fig. 12: Production well Productivity Index (PI) for different anisotropy ratios.

Figure 13 demonstrated data from four reactions that are available in Table 7.

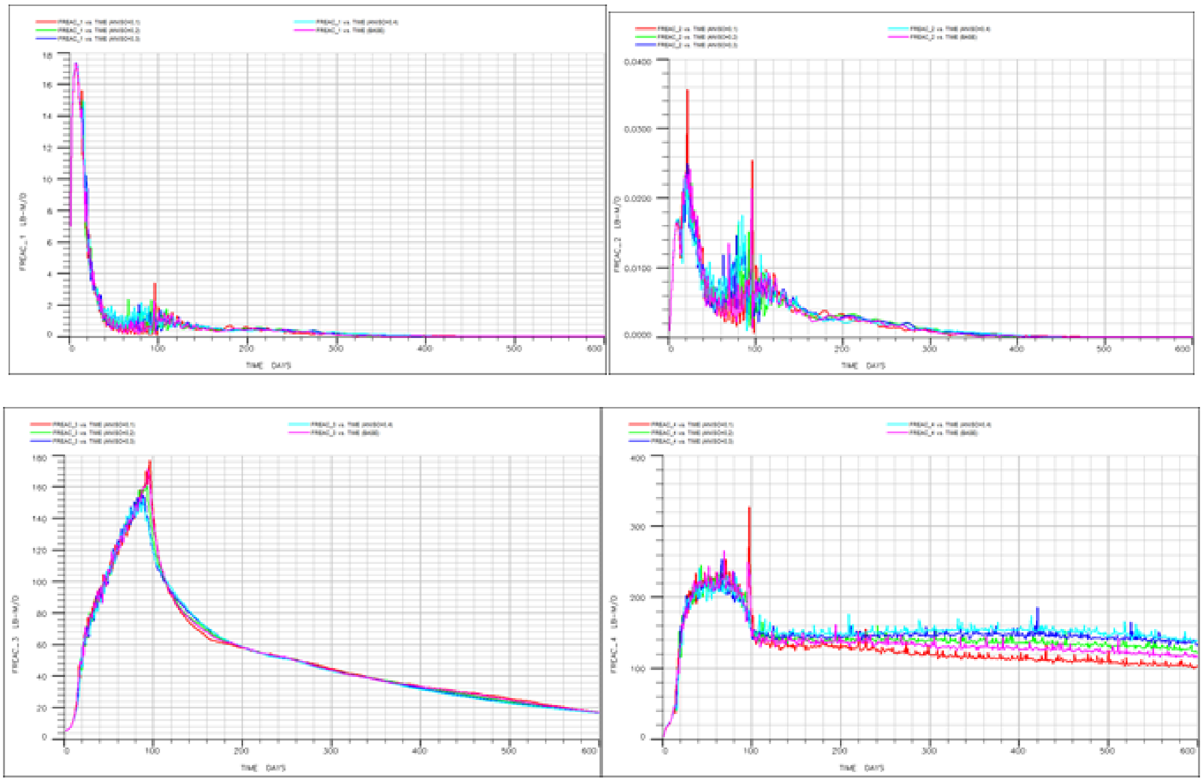


Fig. 13: Reaction's rate for different anisotropy ratios.

It can be seen that anisotropy ratio does not have powerful effect on reaction's rate.

### 3.3. Porosity effects

After running cases with changing porosity, results for recovery factor for normal and zoom view brought as Figure 14.

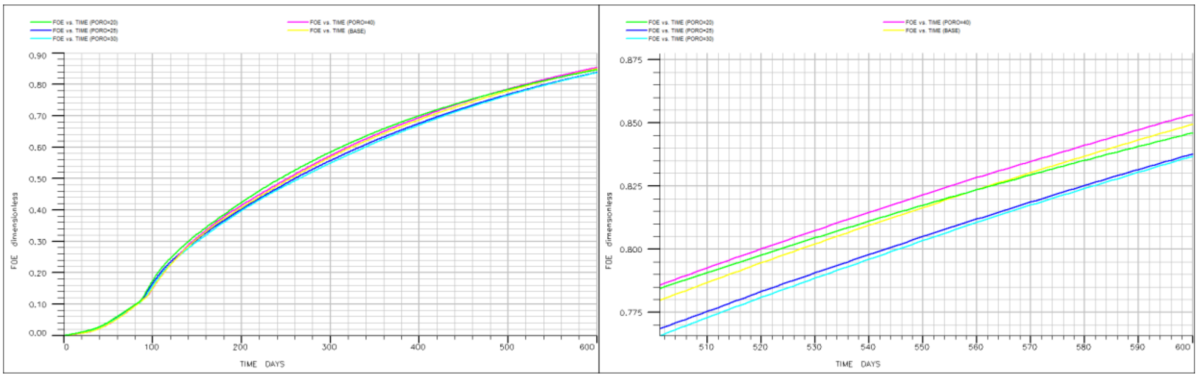


Fig. 14: Recovery factor for different porosities.

In gas oil ratio factor (GOR), it concludes that peak of GOR in early times become higher with increasing porosity. However, at the end of period, GOR became a little higher with decreasing porosity. The result showed in Figure 15.

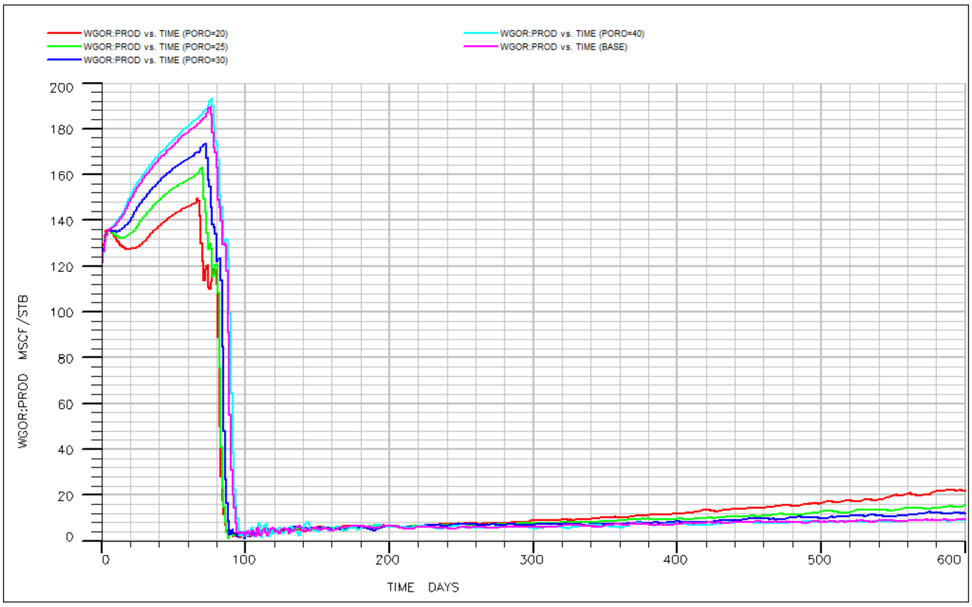



Fig. 15: Gas oil ration for different porosity.

For the oil production rate, after running our cases with changing porosity, it concludes that higher porosity cause very small delay on reaching oil rate to the peak. It is obvious in Fig. 16 and total oil production results is available in Fig. 17For the oil production rate, after running our cases with changing porosity, it concludes that higher porosity cause very small delay on reaching oil rate to the peak. It is obvious in Figure 16, and total oil production result is available in Figure 17.

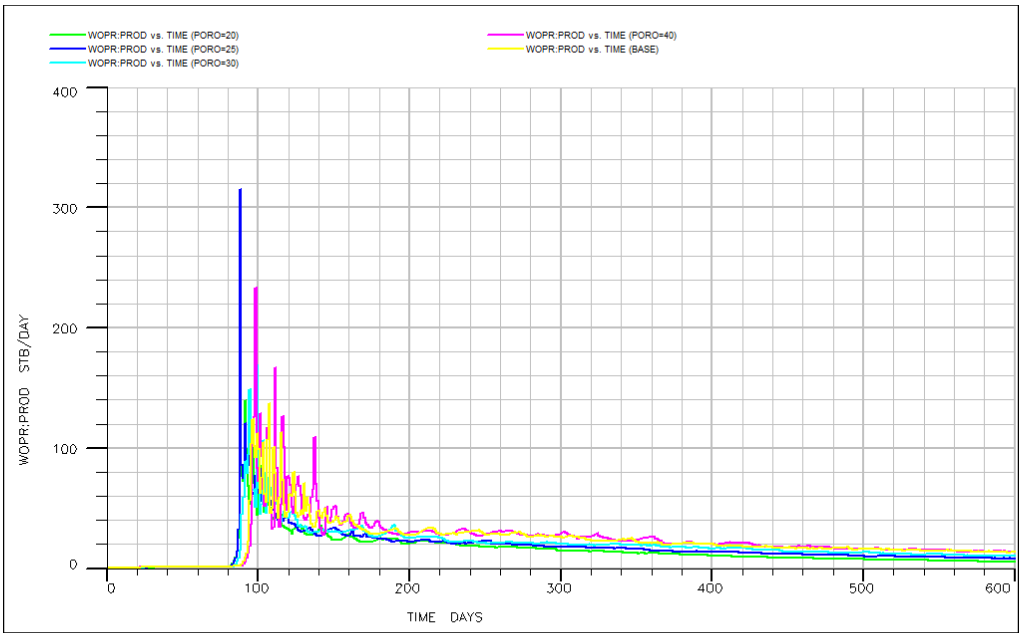



Fig. 16: Oil production rate for different porosities.

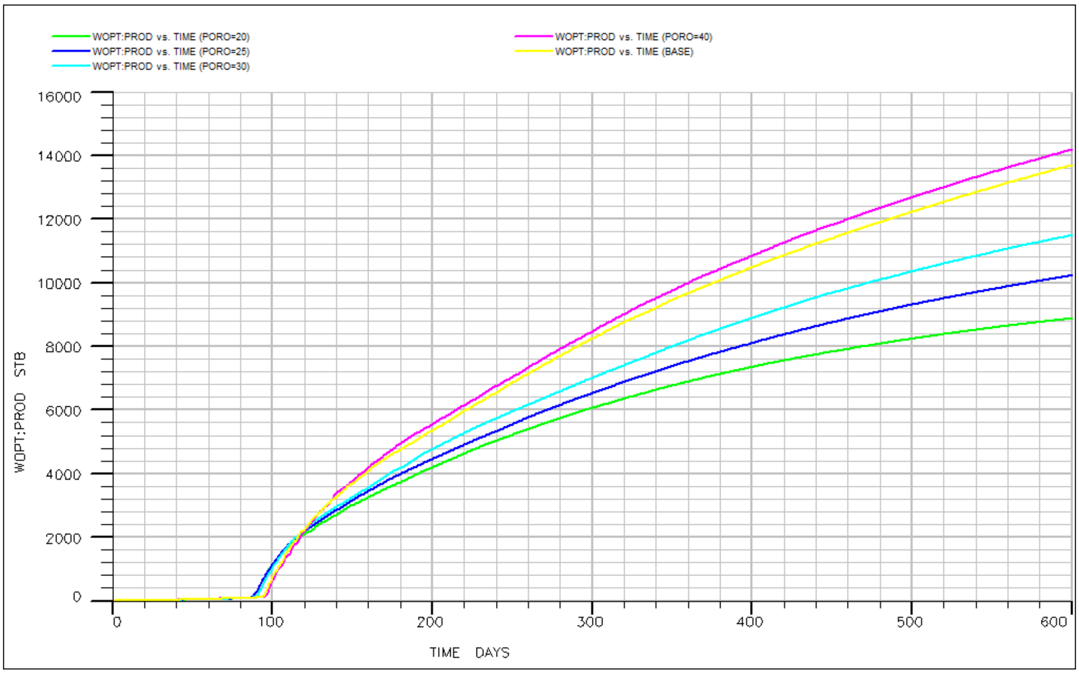



Fig. 17: Total oil production for different porosities.

Changing porosity has a considerable effect on total water production and a little effect on water cut. Figure 18 show water cut, and Figure 19 indicate total water production.

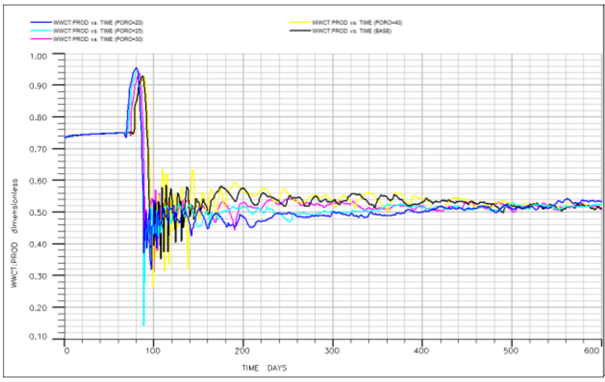


Fig. 18: Water cut for different porosities.

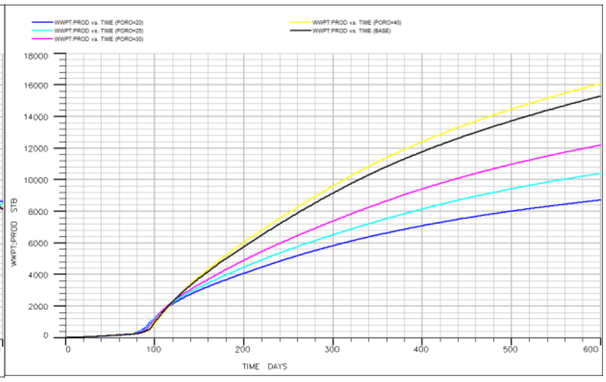


Fig. 19: Water production for different porosities.

In analyzing production well PI it was found that in early times (first 100 days) increasing of porosity has a negative effect on well PI, but this trend change after first 250 days. In another word, increasing porosity changed to a positive factor for well PI after 250th day, and it continued until the end of the period. This trend can be seen in Figure 20.

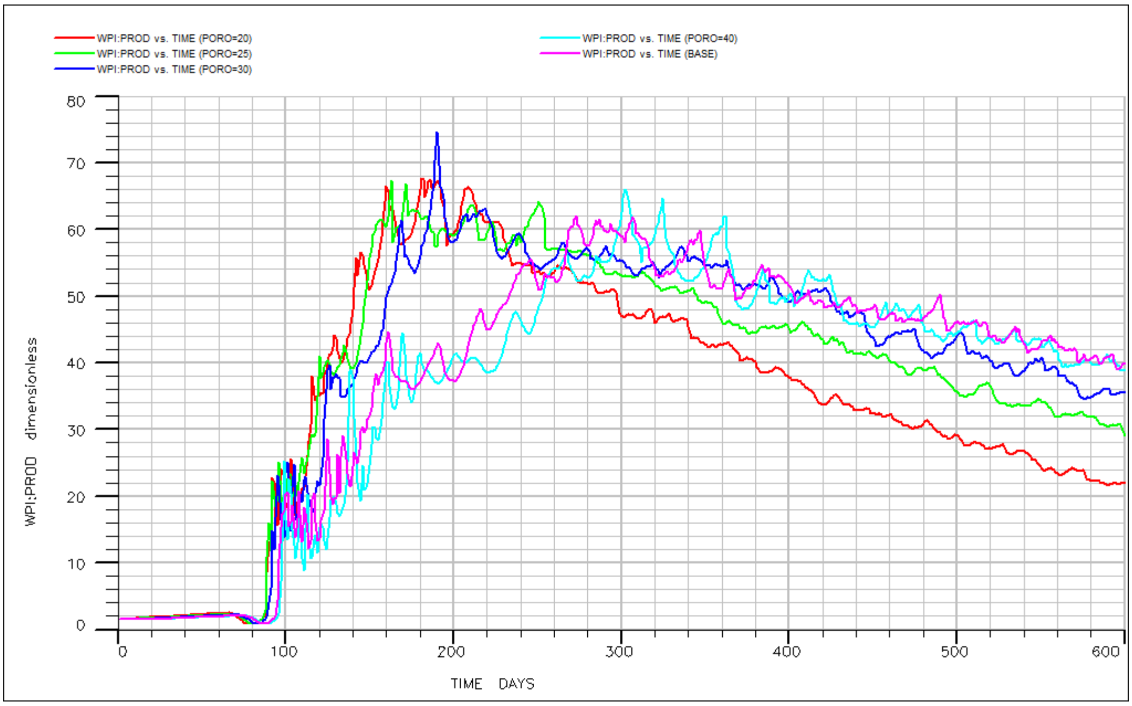



Fig. 20: Production well Productivity Index (PI) for different porosities.

With observing Figure 21 it is obvious that changing porosity can affect reaction's rate, but this effect is more considerable in third and fourth reactions.

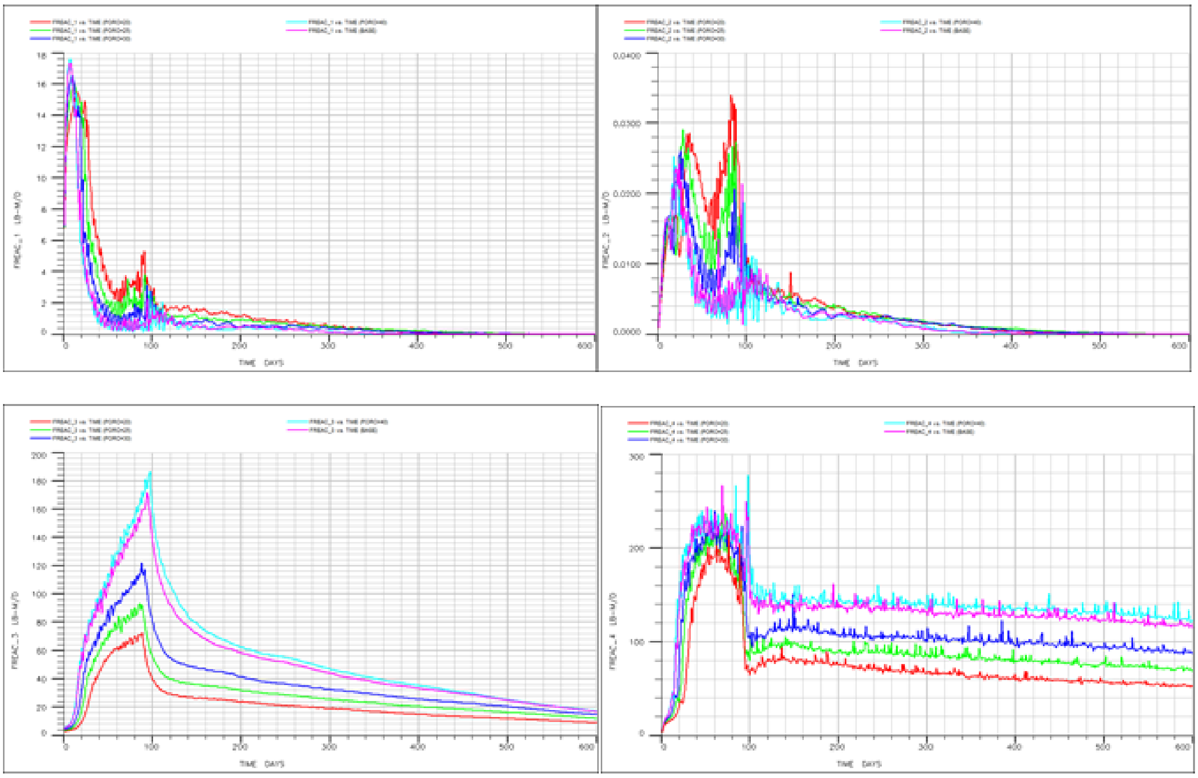


Fig. 21: Reaction’s rate for different porosities.

### 3.4. Permeability effects

After sensitivity analysis on anisotropy ratio and porosity, a sensitivity analysis was done on permeability in order to scope on effects of permeability changes on key parameters. BASE case permeability is 500 millidarcy and other cases are 100, 1000, 3000 and 5000 millidarcy. By observing Figure 22 it is clear that permeability has a great effect on the oil recovery factors. In other words, oil recovery factor increased considerably with increasing permeability.

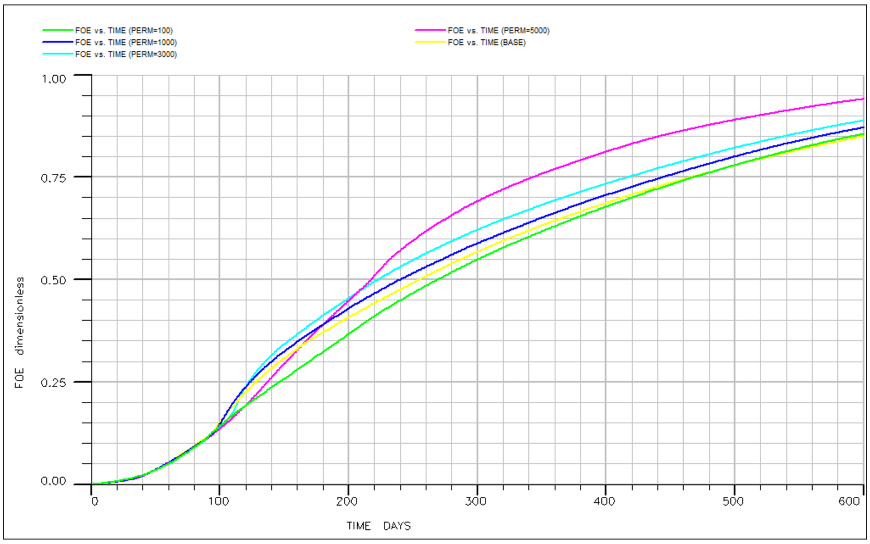



Fig. 22: Oil recovery factor for different permeability.

Oil recovery factor, GOR affected significantly by changing permeability. In low permeability, GOR is very high in its peak, but has become lower with increasing permeability. The exact trend is in Figure 23.

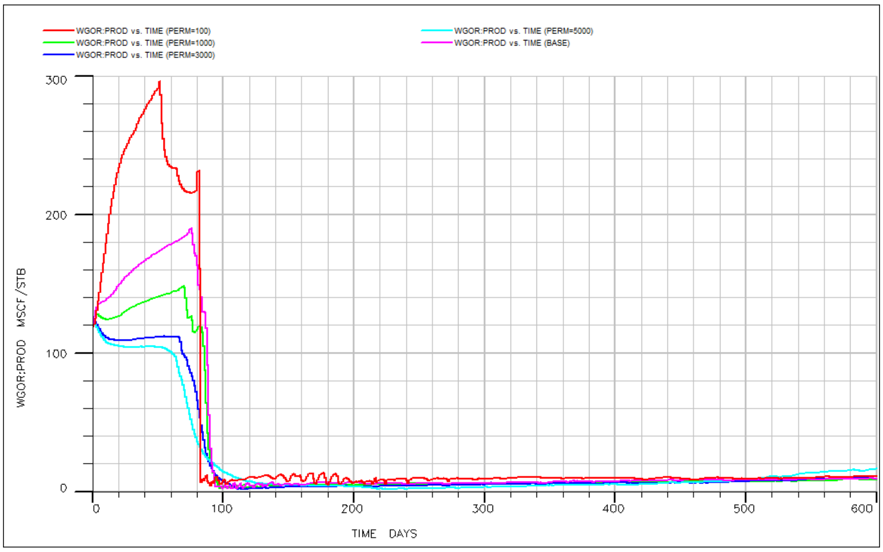



Fig. 23: Gas oil ration for different permeability.

Figure 24 indicates that oil production rate in lower permeability reach to its peak in shorter time, but it decreased rapidly rather to higher permeability cases. This trend can be seen in another aspect in the total oil production curve. In approximately 90th day, cases with lower permeability have more oil production than higher permeability cases. This trend change rapidly and noticeably in rest of the period. Total oil production detail is available is Figure 25.

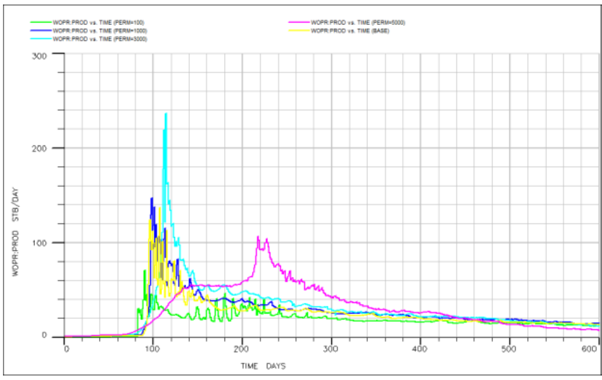



Fig. 24: oil production rate for different permeability.

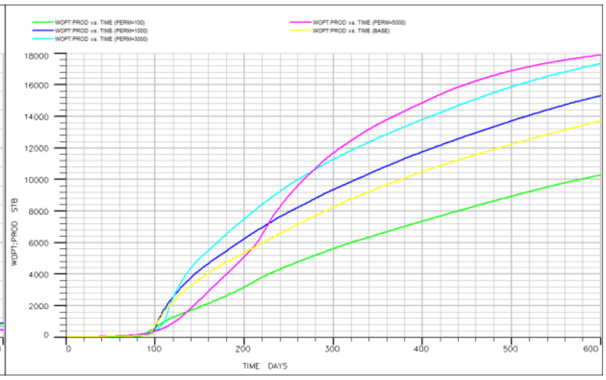



Fig. 25: total oil production for different permeability.

After analyzing water production, permeability effects on water cut and water production, Figures 26 and 27 calculated respectively. It is obvious that increasing permeability cause increasing total water production, except for BASE case that is more permeable than the case with permeability of 100 millidarcy, but it produced lower water. In analyzing water cut it found that there is no clear trend, but overall it is higher for lower permeability.

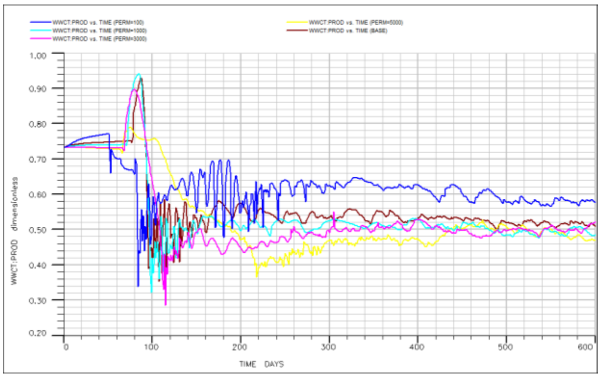



Fig. 26: Water cut for different permeability.

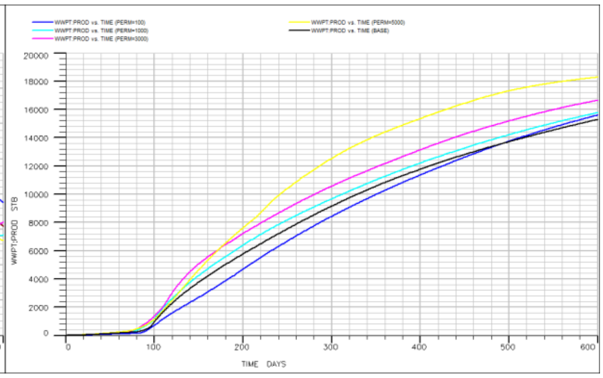



Fig. 27: water production for different permeability.

Production well PI varies rapidly during these 600 days and there is no clear trend. It has shown in Figure 28.

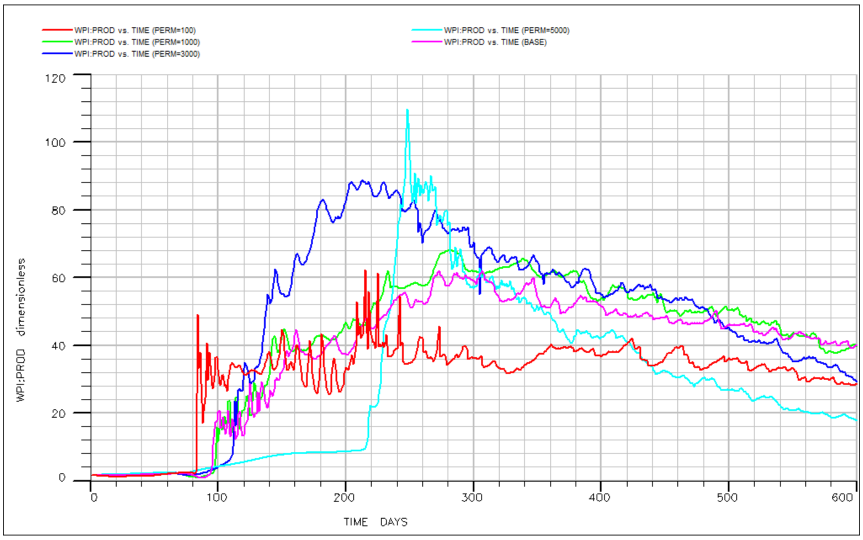



Fig. 28: Production well Productivity Index (PI) for different permeability.

Changing in permeability caused changing in reactions. Between reactions, reaction 2 was more sensible to case with lower permeability, and reaction 4 is more sensible to case with higher permeability. These four reactions showed is Figure 29.

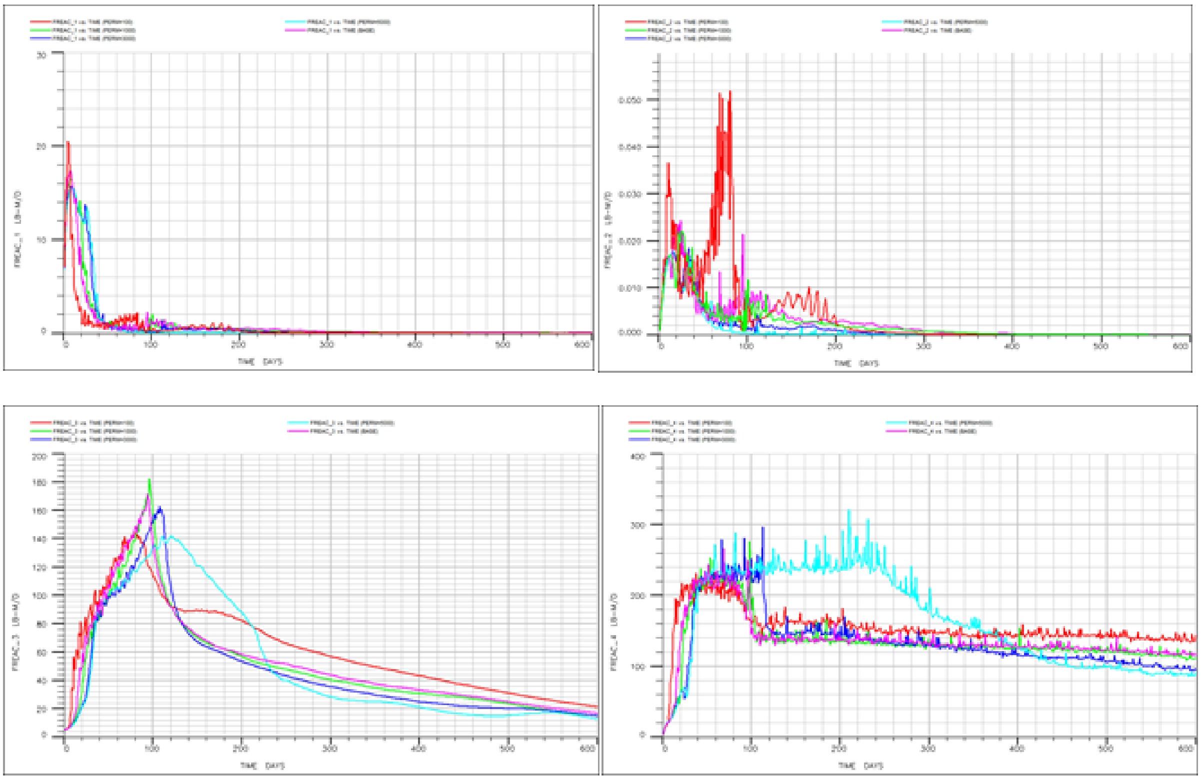


Fig. 29: Reaction's rate for different permeability.

### 3.5. Oxygen injection rate effects

In BASE case, Oxygen injected in rate of 300 lbmol/day. This rate changes between 50, 100, 200, 300 and 500 lbmol/day. Oil recovery factor affected strongly by changing in Oxygen rate. It is better to raise oxygen injection rate to have a higher oil recovery factor. Figure 30 indicates effects of this rate on the recovery factors.

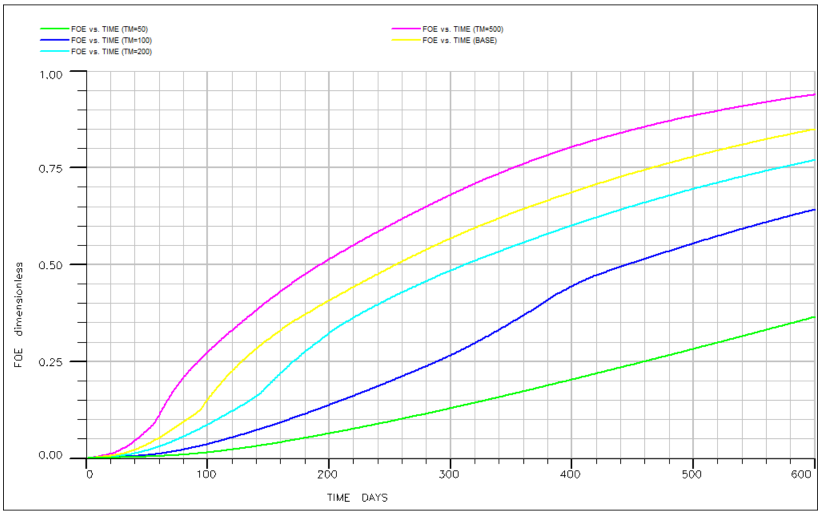



Fig. 30: Oil recovery factor for different oxygen rates.

A dramatic change can be seen in production well gas oil ration with changing in Oxygen rate. With increasing oxygen rate, sooner and narrower GOR peak can be achieved. The details are in Figure 31.

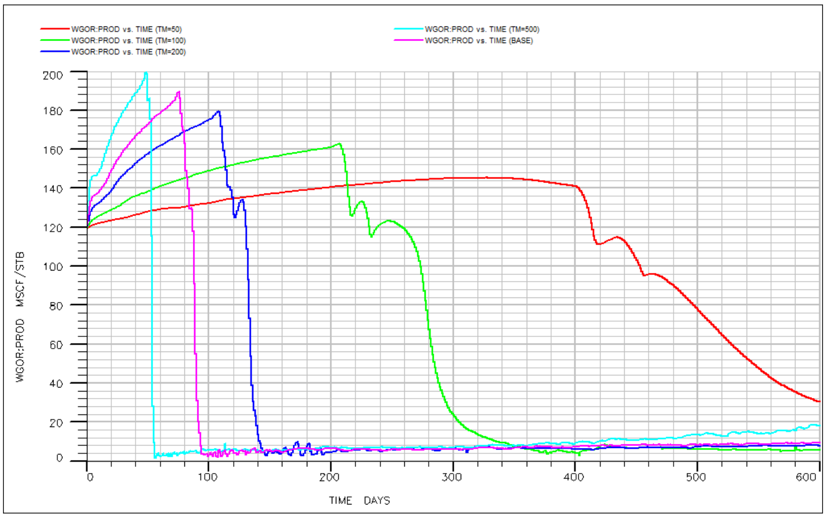



Fig. 31: Gas oil ration for different oxygen rates.

Oil production rate and total oil production varied dramatically by changing in Oxygen rate. The situation became more acceptable with high oxygen injection. In the other words, oil production became considerably high by increasing oxygen rate. Figure 32 and Figure 33 demonstrate this trend clearly.

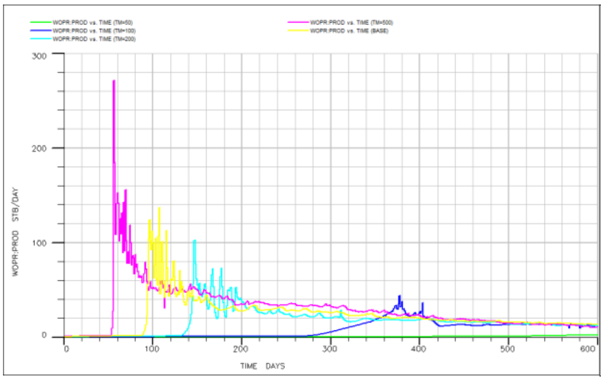



Fig. 32: Oil production rate for different oxygen rates.

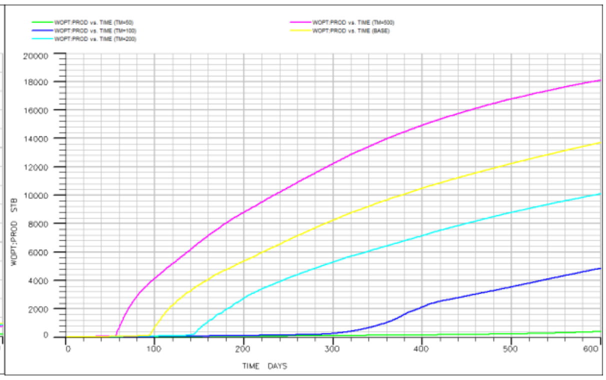



Fig. 33: Total oil production for different oxygen rates.

After analyzing water cut and water production during changing oxygen injection rate, it found that increasing oxygen injection rate result in lower water cut and higher water production. Water cut and total water production trend are obvious in figures 34 and 35 respectively.

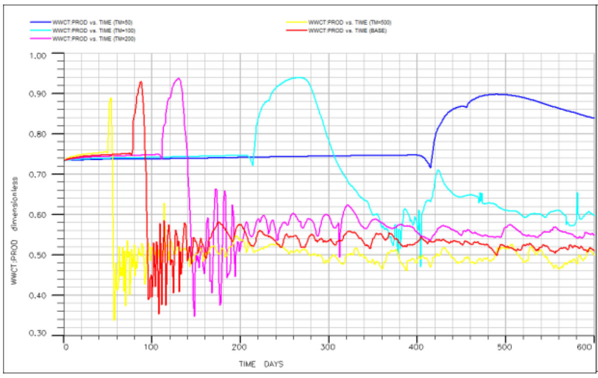



Fig. 34: Water cut for different oxygen rates.

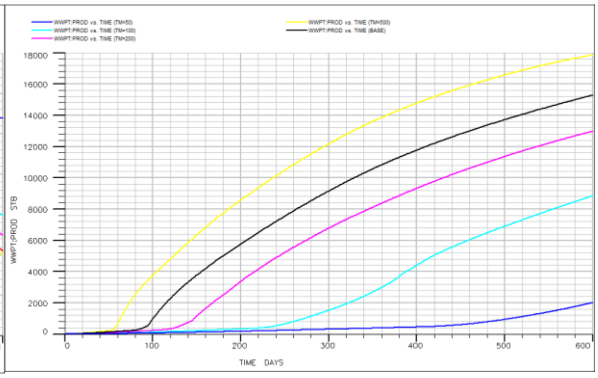



Fig. 35: Water production for different oxygen rates.

In earlier times, cases with higher oxygen injection rate had higher PI, but this trend reversed in around 400th day. More details can be seen in Figure 36.

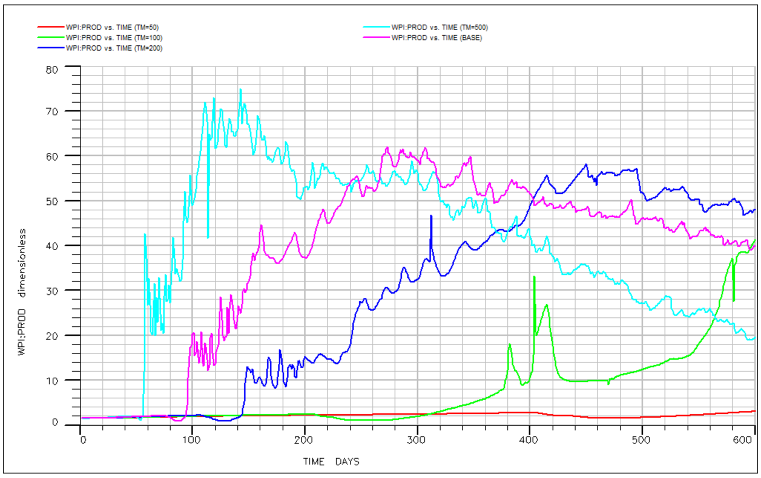



Fig. 36: Production well Productivity Index (PI) for different oxygen rates.

Changing in Oxygen injection rate affected all four reaction's rates. Figure 37 indicates effects of this change in reaction 1, 2, 3 and 4.

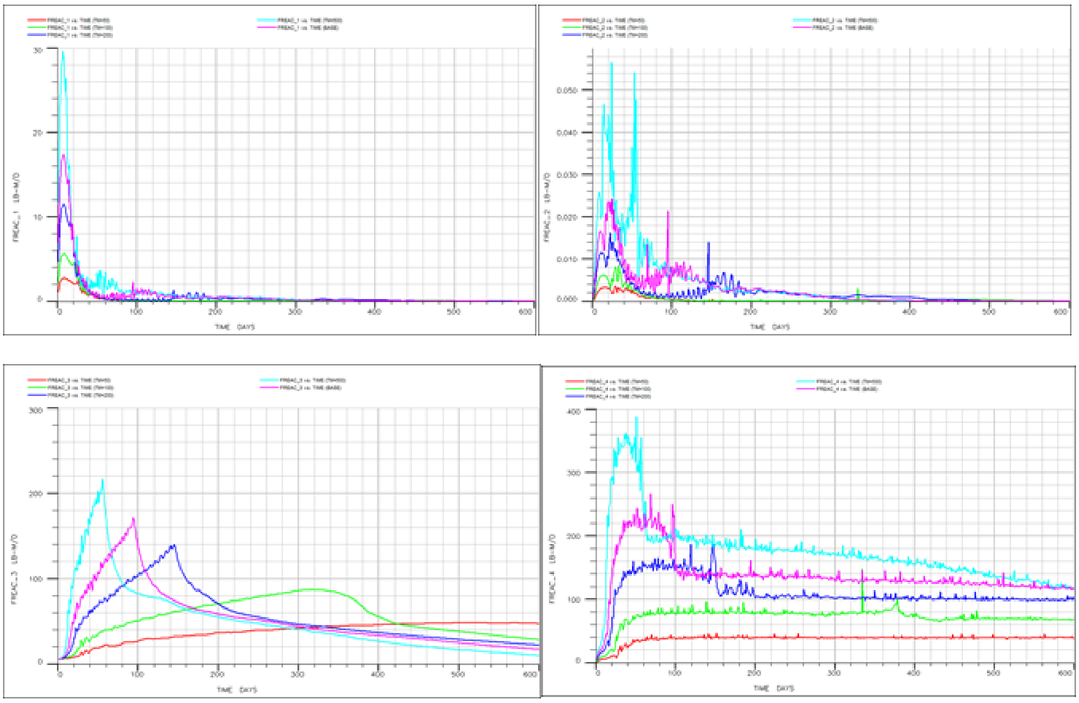


Fig. 37: Reaction's rate for different oxygen rates.

### 3.6. Initial temperature effects:

BASE case temperature is 200 Fahrenheit degree, but it changed to 70, 100 and 250 Fahrenheit degree for recognizing sensitive factors to reservoir temperature in combustion method. It is proved that high initial temperature can cause high oil recovery factor. Figure 38 shows this effect.

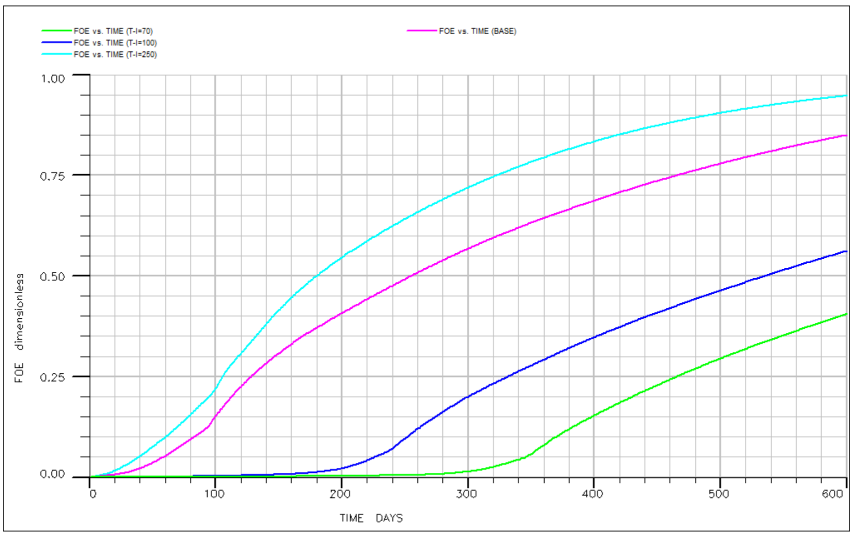



Fig. 38: Oil recovery factor for different initial temperatures.

Also it realized that initial temperature has a great effect on GOR. Between these cases, case with 70 Fahrenheit degree has extremely high GOR in compression to higher degrees. Figure 39 shows GOR in production well for different initial temperatures.

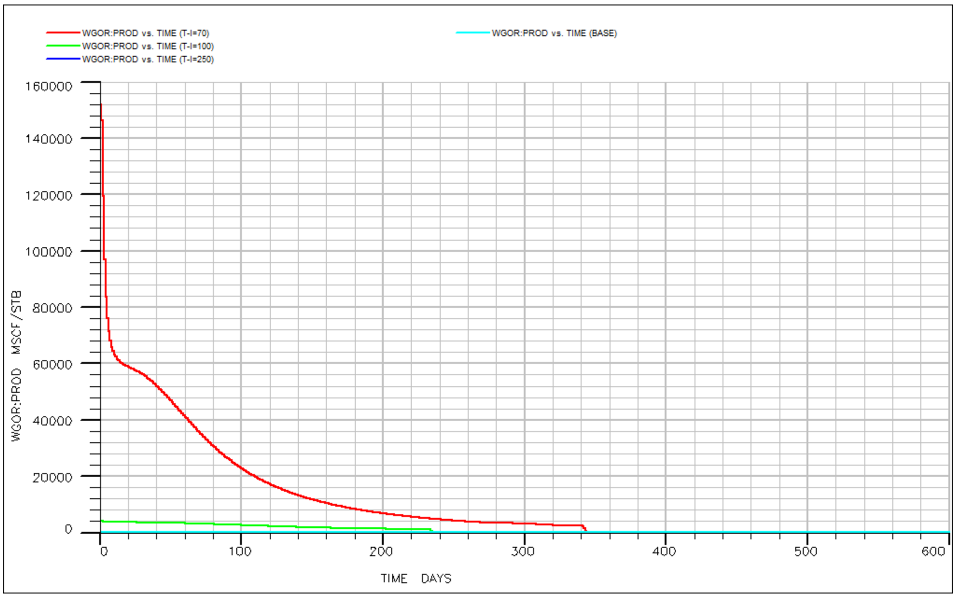
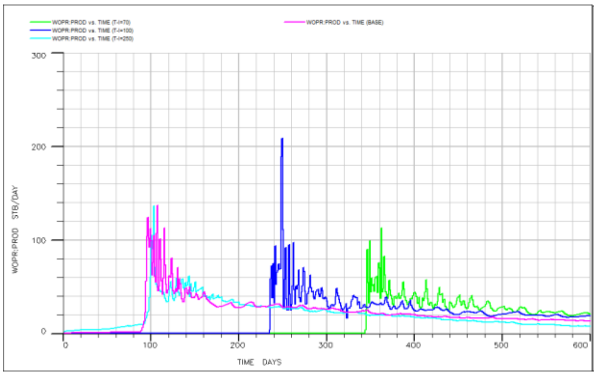



Fig. 39: Gas oil ration for different initial temperatures.

Oil production rate and total oil production, which is so important, affected by changing temperature noticeably. Cases with higher initial temperature started to production oil sooner than lower temperatures. Total oil production was higher in high-temperature cases, except our BASE case, which was 200 Fahrenheit degree, but produced more oil than the case with 250 Fahrenheit degree temperature.

These statements can be seen clearly in figures 40, which show oil production rate and Figure 41, which indicate total oil production.



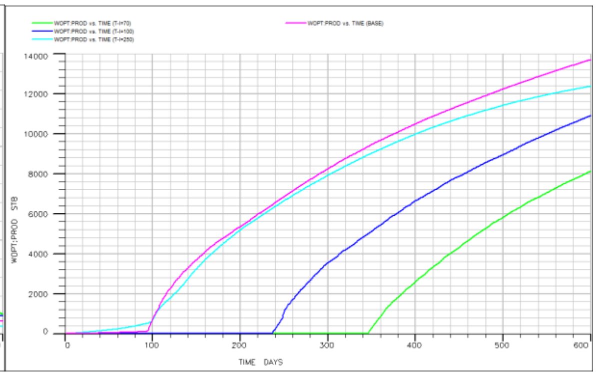




Fig. 40: Oil production rate for different initial temp. Fig. 41: Total oil production for different initial temp.

Lower initial temperature can result in late appearance of water in production well and lower water production. Water cut and total water production trend for different initial temperatures are obvious in Figure 42 and 43 respectively.

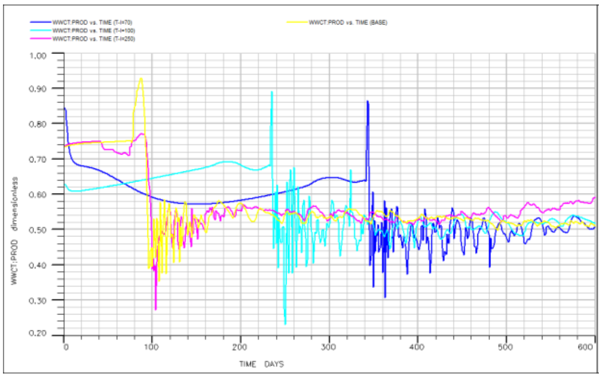


Fig. 42: Water cut for different initial temp.

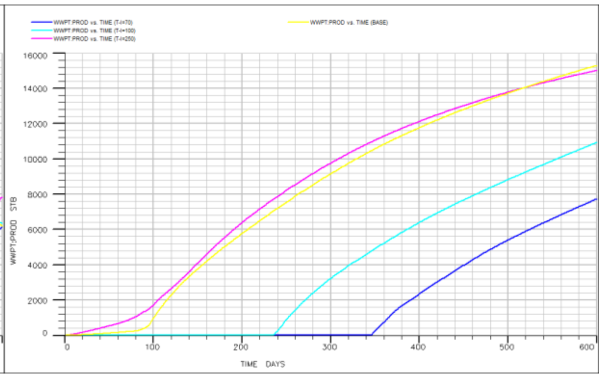


Fig. 43: Water production for different initial temp.

Production well PI does not show any clear trend for different initial temperatures. Figure 44 indicates productivity index of production well.

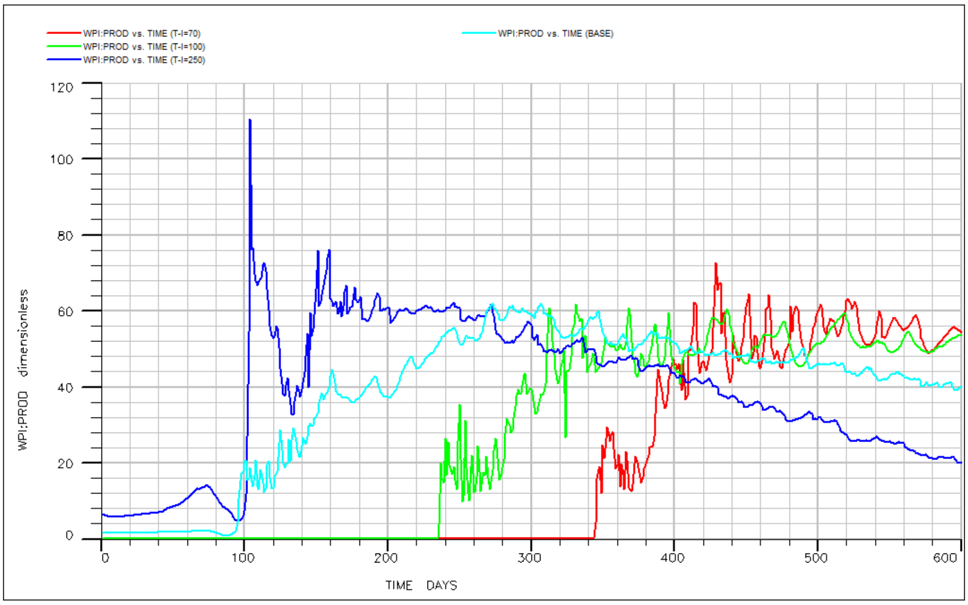



Fig. 44: Production well Productivity Index (PI) for different initial temperatures.

Initial temperature changing has a great effect on all of reaction. These considerable effects are obvious in Figure 45.

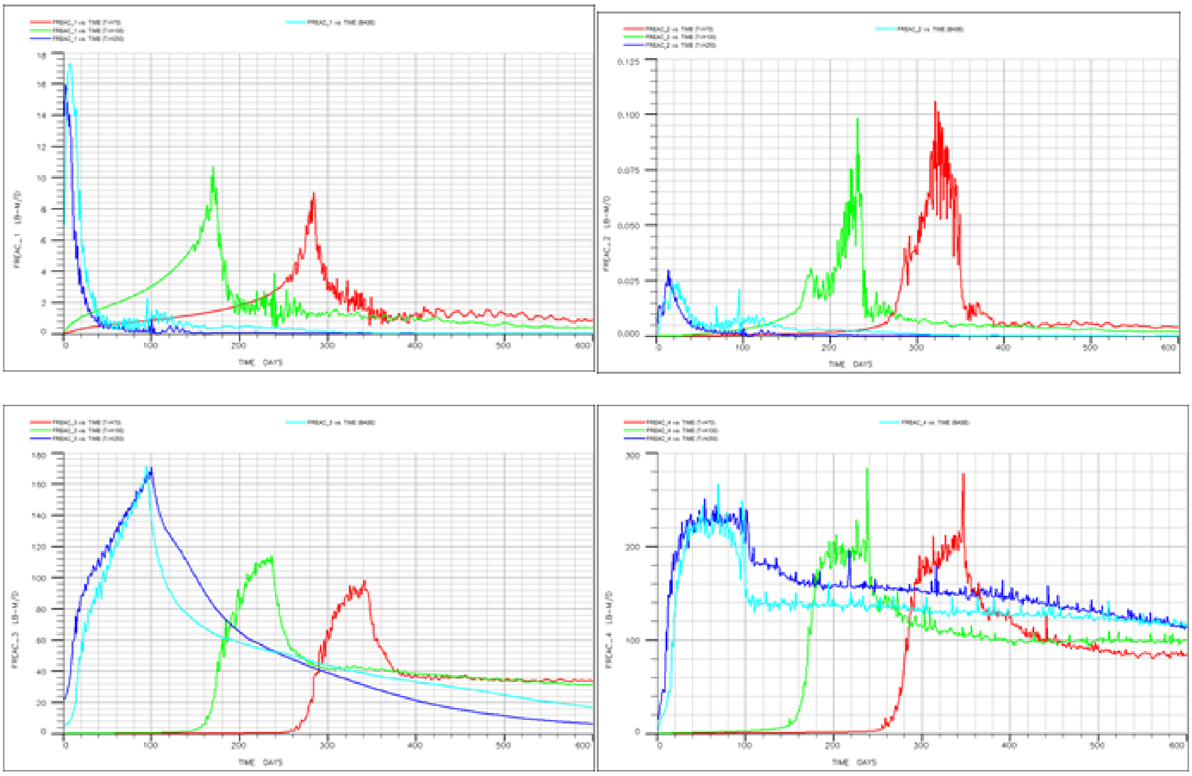


Fig. 45: Reaction's rate for different initial temperatures.

## 4. Conclusions

I. When injection well perforations and production well perforations are in the same layers, a lower anisotropic ratio resulted in more oil recovery factors.

II. Anisotropy ratio does not have any special effect on reactions.

III. Anisotropic ratio has a very small effect on water production, GOR and oil production.

IV. Increasing in porosity resulted in increasing oil recovery factor, oil production, water production, GOR and rate of reactions 3 and 4, but it caused limitation of reactions 1 and 2.

V. Increasing in Oxygen injection rate can lead to higher oil recovery factor, higher oil production, higher water production, but lower water cut.

VI. Increasing initial reservoir temperature resulted in increasing oil recovery factor and cause water start to produce sooner.

**Acknowledgments**

Dedicated to my wonderful parents, Ali and Shahin, my sister and my brothers for supporting me through my college years. Personally, I would like to thank Dr. R.Kharat and Dr. SH.Gerami for helping me in my projects.

**References**

[1] Belani, A., It's Time for an Industry Initiative on Heavy Oil, *Journal of Petroleum Technology. 2006*; 58(6): 40-42.

[2] Edwards, J. D., Crude Oil and Alternate Energy Production Forecasts for the Twenty-First Century: The End of the Hydrocarbon Era, *A.A.P.G. Bulletin, 1997; 81(8):1292-1305*.

[3] Lake, L. W., Enhanced Oil Recovery, *Prentice Hall, New Jersey*, 1989.

[4] Carcoana, A., Applied Enhanced Oil Recovery, *Prentice Hall, New Jersey*, 1992.

[5] Kumar, M., Sahni, A., Knapp, R., and Livermore, L., Electromagnetic Heating Methods for Heavy Oil Reservoirs, *presented at the 2000 SPE/AAPG Western Regional Meeting, California, SPE , 2000; 62550:19-23*.

[6] Burger J.G., Sahuquet B.C., Laboratory Research on wet combustion, *J. PetTech., Oct 1973*; 1137-1146

[7] Belgrave J.D.M., An experimental and Numerical Investigation of In-situ Combustion Tube Tests, *Ph.D. Thesis, July 1987, The University of Calgary*.

[8] SPE team, In-situ combustion, Available at*: http://petrowiki.org/In situ_combustion* (Accessed: 26th September 2014).

[9] Coats, K.H., In-Situ Combustion Model, *SPEJ, 1980;269: 533-54*.

[10] Crookstein, R.B., Culham, W.E., and Chen, W.H., Numerical Simulation Model for Thermal Recovery.