CERTIFICATION OF APPROVAL

Comparison of Methods to Reduce Grid Orientation Effect in Miscible Flood Simulation

by

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

Numerical dispersion is an artefact of current numerical analysis techniques that can cause severe distortions in simulations of processes in which relatively rapid saturation changes occur. Grid Orientation Effect (GOE) is a phenomenon in simulation caused by numerical dispersion, in which calculated performance is influenced by the orientation of the grid relative to the locations of injection and production wells. Pressures as well as saturations are distorted by grid orientation. This effect can cause serious problems in simulation of steam flooding or miscible-gas displacements. Therefore it is the objectives of this project to investigate the seriousness of this problem and the means in reducing the effect, using a numerical simulation. Carbon dioxide (CO_2) miscible flooding process is being simulated on a homogeneous conceptual model, utilizing both parallel and diagonal grid configurations. Three methods of reducing GOE were studies; namely the two point upstream weightage method, nine-point scheme and increment of grid block (refining grid). Results were analysed and compared to evaluate the effectiveness of each method used. Results showed that the nine-point scheme gives the highest incremental recovery. However, in overall, combination of the three methods in parallel orientation yields the highest increment (9.15%). The average result for comparing the highest in parallel orientation and the lowest in diagonal orientation is 6.906%. Since the result is around 7%, it can be concluded that the results are converging.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Numerical dispersion is an artefact of current numerical analysis techniques that can cause severe distortions in simulations of processes in which relatively rapid saturation changes occur. In multidimensional model, numerical dispersion leads to an interesting and troublesome phenomenon in which calculated performance is influenced by the orientation of the grid relative to the locations of injection and production wells. In other words, when the mobility of the displacing fluid is greater than the mobility of the resident fluid, instability occurs [1]. This phenomenon is called the Grid Orientation Effect (GOE). It is a serious problem in numerical simulation and at times it can cause serious problem in simulation of steam-flooding or miscible gas displacements. Grid Orientation Effect (GOE) is important in simulations in which the displacing phase is much more mobile than the displaced phase (as in steam-floods of heavy oil).

There are severe differences in the numerical solutions on the parallel and diagonal grid lines when the mobility ration is high. These differences do not vanish when finer grids are used. Since even for examples with simple geometry, such as radial or five-spot displacement, fronts may be distorted on finite grids in a physically unreasonable way, it is difficult to have confidence in the simulations of the field-scale displacements. A front is table if it retains the shape of the interface between displaced and displacing fluids as the front moves through the medium. Use of a fine grid, higher order mobility weighting and various nine-point (oppose to five-point) finite difference schemes has been proposed by Brand, C.W., Heinemann, J.E., and Aziz, K. in their paperwork [2].

1.2 PROBLEM STATEMENT

Yanosik and McCracken, [9], studied the GOE by comparing the nine-point scheme with five-point scheme in diagonal and parallel grid orientation, giving result advantage on nine-point method. In other similar work on GOE is paperwork written by Todd, M.R., O'Dell, P.M., and Hiraski, G.J, [3], by comparing two-point weighting with one-point weighting, also in diagonal and parallel grid orientation, showing result advantage on two-point method. However, Brand, C.W., Heinemann, J.E., and Aziz, K. in their work , [2], using combination of nine-point and two-point, into a technique to estimating reasonable block size for displacement problem.

In oil and gas industry, economic analysis plays important roles in determining total revenue and expenses will be generated by a proposed reservoir management plan. Economic performance of the project depends on the relationship between revenue and expenses. In a way, the reservoir model determines how much money will be available to pay for wells, compressors, pipelines, platforms, processing facilities and any other items that are needed. For this reason, from reservoir modelling, it is expected to generate better recoveries if a less optimistic set of parameters had been used. However, one of the problems encounter in modelling reservoir is GOE.

GOE is a phenomenon in simulation caused by numerical dispersion, in which calculated performance is influenced by the orientation of the grid relative to the locations of injection and production wells. Pressures as well as saturations are distorted by grid orientation. This effect can cause serious problems in simulation of steam flooding or miscible-gas displacements. An initiative has been taken, where; comparison is being made using two point upstream weighting, nine-point scheme and increase grid block (refining grid). Hopefully, with the proposed study will help in determining the optimum recovery in modelling simulation.

1.3 OBJECTIVES

The objectives for this project are;

1. To determine the Grid Orientation Effect (GOE) on simulation of miscible displacement.
2. To determine the most effective method in reducing Grid Orientation Effect (GOE) for miscible displacement.

1.4 SCOPE OF STUDY

This project is focused on the effect of the grid orientation on miscible flood simulation and the means of reducing the effect. The scopes of study for this project are;

1. To study the concept of Grid Orientation Effect (GOE).
2. To study the mean of reducing the Grid Orientation Effect (GOE).
3. To stimulate miscible flooding on a conceptual model (homogeneous) – both parallel and diagonal grid orientations.
4. To incorporate methods to reduce Grid Orientation Effect (GOE) in simulating miscible displacements.
5. To evaluate the effectiveness of those methods in reducing Grid Orientation Effect (GOE).

CHAPTER 2
LITERATURE REVIEW

2.1 GRID ORIENTATION EFFECT (GOE)

Numerical simulation in oil and gas industry plays an important role in predicting performance of an oil field. The general working of a reservoir numerical simulation is to first divide the reservoir into a number of cells. Then basic data is provided for each of the cells. Production wells and if there are any injection wells are position within the cells. The required well production rates are specified as a function of time. The equations are then solved to give the pressure and saturation of each block as well as the production of each phase from each well. Each cell is solved simultaneously.

In general, the partial differential equations that describe fluid flow in reservoir can not be solved analytically. Fluid flow equations are a set of nonlinear partial differential equations that must be solved by computer. Formulate fluid flow equation, such as,

$$\frac{\partial}{\partial x}\left[\frac{Kk_r}{\mu B}\left(\frac{\partial P}{\partial x}\right)\right] + q_s\partial(x - x_o) = \frac{\partial}{\partial t}\left(\frac{\emptyset s}{B}\right)$$

The partial derivatives are replaced with finite differences, which are in turn derived by Taylor's series. The spatial finite difference interval Δx along the x-axis is called grid block length, and the temporal finite difference interval Δt is called time step. Index n labels the present time level, so that n + 1 represent future time level. Approximate derivatives with finite differences, discretize region into grid blocks Δx:

$$\frac{\partial P}{\partial x} \approx \frac{P_{i+1} - P_i}{x_{i+1} - x_i} = \frac{\Delta P}{\Delta x}$$

And discretize region into grid blocks Δt:

$$\frac{\partial S}{\partial t} \approx \frac{S^{n+1} - S^{n}}{t^{n+1} - t^{n}} \equiv \frac{\Delta S}{\Delta t}$$

If the finite difference representations of the partial derivatives are substituted into the original flow equations, the result is a set of equations that can be arranged into set of equations that can be solved numerically. The conceptual reservoir volume elements are referred to as grid blocks and the time intervals as time steps.

Numerical dispersion is an artefact of current numerical analysis techniques that can cause severe distortions in simulations of processes in which relatively rapid saturation changes occur. In multidimensional model, numerical dispersion leads to an interesting and troublesome phenomenon in which calculated performance is influenced by the orientation of the grid relative to the locations of injection and production wells. In other words, when the mobility of the displacing fluid is greater than the mobility of the resident fluid, instability occurs. This phenomenon is called the Grid Orientation Effect (GOE). It is a serious problem in numerical simulation and at times it can oppose serious problem in simulation of steam-flooding or miscible gas displacements. GOE is important in simulations in which the displacing phase is much more mobile than the displaced phase (as in steam-floods of heavy oil).

Figure 2.1 illustrates the problem. It is a sketch of part of the Cartesian grid system of a model for simulating water flooding in an oil reservoir. This part of the model contains one production well and two injection wells. In the simulator, water from Well A will move in a direct path to the producer. However, water from Well B will follow a zig-zag path to the producer. Not only is the flow path from Well B longer, but water from Well B will sweep the reservoir “more efficiently” than water from Well A. However, if the grid is rotated 45°, the performances calculated for the two wells would be reversed.

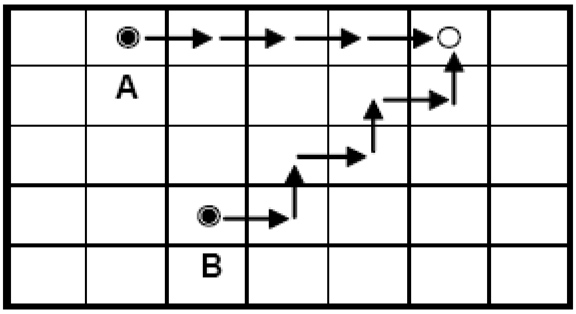

Figure 2.1: Flow paths for parallel and diagonal flow in a Cartesian grid [4]

Grid orientation may distort and affect the accuracy of calculated pressures and saturations. Thus, the grid orientation effect has become one of the important factors in evaluating different types of grid.

For simulation of displacements at mobility ratios that are favourable, neutral or slightly unfavourable, the Grid Orientation Effect can be reduced by refining the grid. Diagonal orientation is prone to introduce distortion by grid orientation than is parallel orientation. The Grid Orientation Effect is more pronounced for unfavourable mobility ratios. Mobility ratio, M can be defined as the ratio of the mobility of the displaced phase to the mobility of the displacing phase across the saturation front. It can also be defined as the ratio of the initial reservoir fluid mobility to the injected fluid mobility.

Despite the fact that the reservoir is isotropic and homogeneous, Grid Orientation Effect was still observed when rectangular Cartesian grid models are run at mobility ratio, M = 1.0. Grid refinement can help to reduce the grid orientation effect in rectangular Cartesian grid models when there are favourable mobility ratios, i.e. M = 1.0 or less.

However, at an unfavourable mobility ratio of M = 10.0, it is found that neither parallel nor diagonal orientation can be used reliably for the displacement problems run in this study. This is because as the number of grid blocks is increased (grids are refined), the performance of diagonal and parallel models actually diverges for the grid spacings investigated here.

2.2 METHODS TO REDUCE GRID ORIENTATION EFFECT (GOE)

Generally, neither parallel nor diagonal orientation can be used reliably for displacements at highly adverse mobility ratios. There are possible alternative methods include nine-point formulations and the application of two-point upstream mobility. The nine-point formulation is possibly the most reliable current solution to the grid orientation problem. This formulation allows flow between a grid block and all eight surrounding blocks, and in simulations, the performances of diagonal and parallel models tends to converge as the spacing is refined. However, increased reliability is obtained for a cost. The nine-point formulation couples diagonal as well as parallel blocks thus increases the required work to solve the flow equations.

Two-point upstream mobility weighting is uses information from the two blocks immediately upstream from the flow boundary in order to develop estimated mobility at the interface of two blocks. Specifically, the method estimated relative permeabilities at the flow boundary by extrapolation of the relative permeabilities evaluated at the two upstream blocks. This two-point upstream method leads to better solutions at displacement fronts than single-point upstream weighting.

Using of a large number of grid blocks, which normally control dispersion, will also reduce the effect of the grid orientation. However the cost of a single time step will increase because the amount of computation will be a function of the number of grid blocks, regardless of the solution used. In addition, because a larger number of grid blocks imply decrease in block size, time step must be shorter to satisfy tolerance criteria. In other words, if some maximum is imposed on saturation change, smaller blocks cannot tolerate as much as larger blocks during a single time step; hence, the number of time steps must be increased.

2.3 STUDY ON METHODS TO REDUCE GRID ORIENTATION EFFECT (GOE)

2.3.1 NINE-POINT FINITE DIFFERENCE FORMULATION

Nine-point scheme is a weighted-interpolation between the two five-point grids with a common centre point and its diagonal transmissibilities. In other words, a weighted nine-point scheme is a linear combination of two five-point finite-difference solutions with grid coordinates rotated at 45° to each other, as defined and illustrated in Figure 2.2.

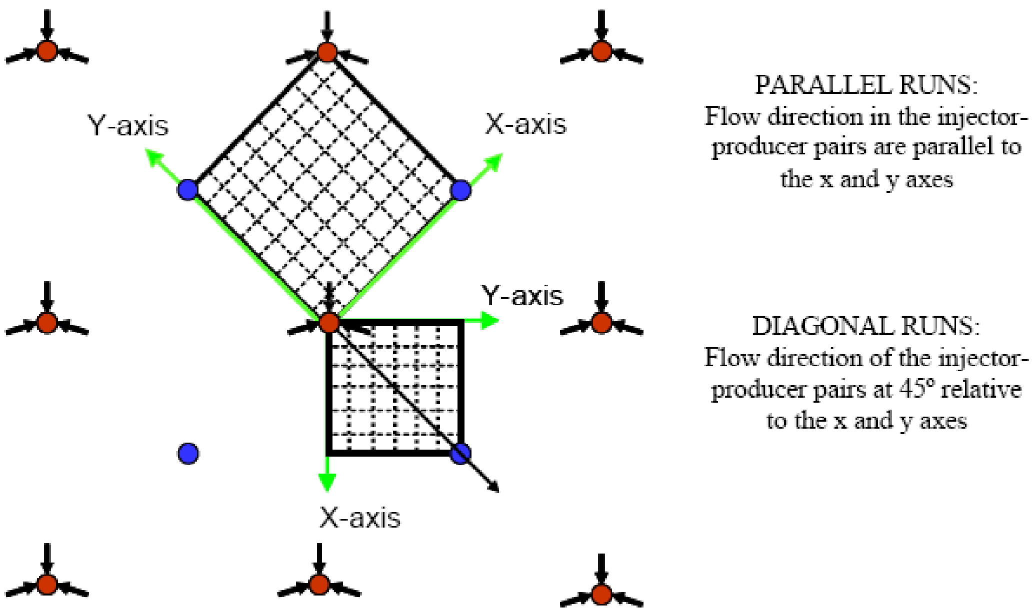

Figure 2.2: Parallel and diagonal orientation for simulations for water flooding in five-spot symmetry elements [4]

It was first introduced by Yanosik, J.L. and McCracken, T.A. [9], the application of a nine-point finite-difference approximation showed some improvements over the previous five-point finite-difference methods for reducing grid orientation effects in adverse mobility ratio (Ms less than 20) piston-like displacement problems.

This formulation allows flow between a grid block and all eight surrounding blocks, including those diagonally adjacent, as illustrated in Figure 2.3 and Figure 2.4. The nine-point formulation is possibly the most reliable current solution to the grid orientation problem. The nine-point formulation couples diagonal as well as parallel blocks.

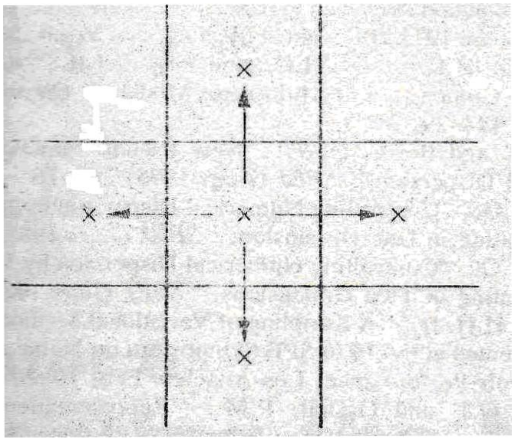

Figure 2.3: Five-point formulation [1]

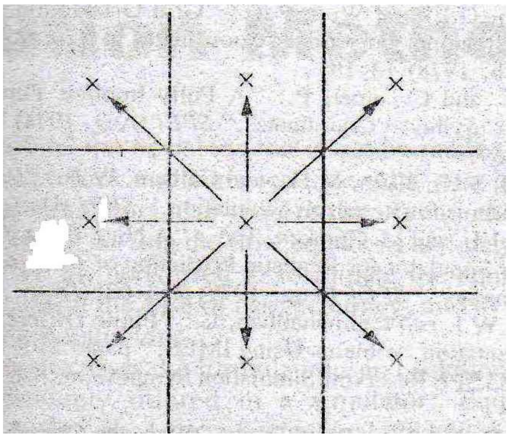

Figure 2.4: Nine-point formulation [1]

The standard five-point formulation can be used to generate acceptable results by initializing the model with injection fluid in a circle surrounding the injection well. In this example, an initial radius of 20% of distance from injector to producer and a saturation corresponding to residual oil behind the front were used. For more precision, a theoretical radial distribution of saturation could be used as input. Results from this approach for a 10:1 unfavourable mobility ratio flood in the one-quarter five-spot model discussed shown in Figure 2.5.

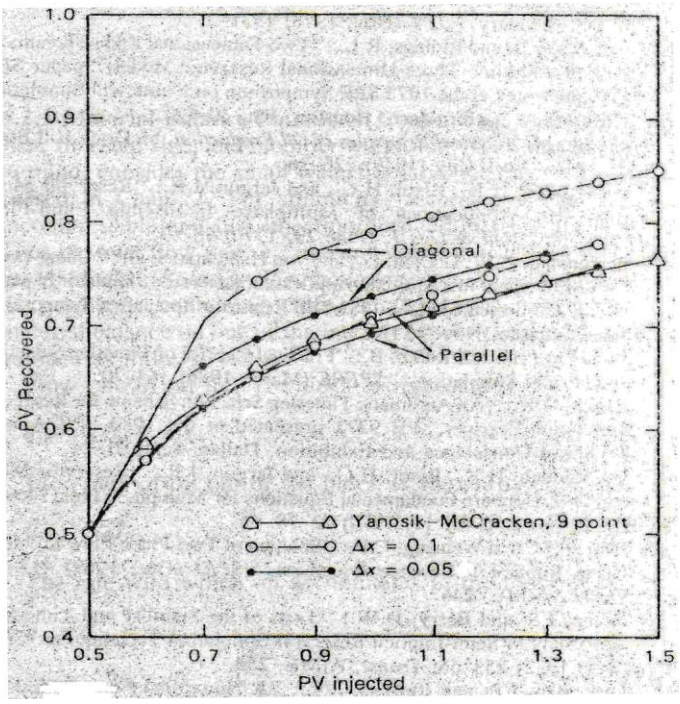

Figure 2.5: Calculated performance of unfavourable mobility ratio displacement [1]

As the grid is refined, recovery tends to approach that the predicted nine point formulation. The parallel model appears to be somewhat more reliable than the diagonal model. In simulations with the nine-point formulation, the performances of diagonal and parallel models tend to converge as the spacing is refined.

2.3.2 TWO-POINT UPSTREAM MOBILITY WEIGHTING

Two-point upstream mobility weighting is uses information from the two blocks immediately upstream from the flow boundary in order to develop estimated mobility at the interface of two blocks. Specifically, the method estimated relative permeabilities at the flow boundary by extrapolation of the relative permeabilities evaluated at the two upstream blocks. This two-point upstream method leads to better solutions at displacement fronts than single-point upstream weighting.

As described by Todd, M.R., O’Dell, P.M., and Hiraski, G.J [3], the techniques appear to be the most useful in mobility weighting is the two-point mobility weighting scheme. In this approach, the relative permeability for flow across the boundary between two grid blocks is calculated by extrapolating the relative permeabilities of the two upstream blocks to a point on the boundary.

This technique reduces numerical dispersion and is widely used. However, be cautioned, that for some combinations of saturations in the two upstream blocks, the result of extrapolation can give unrealistic (negative or very large) value of relative permeability. Realistic bounds must be placed on the acceptable range of values. Another limitation of this approach is the implicit assumption that the two upstream grid locations lie on a flow streamline and hence that saturations can be extrapolated with the value in those two blocks.

2.3.3 INCREASE GRID BLOCKS

The resolution of the model depends on the resolution of the grid. A fine grid divides the reservoir into many small grid blocks. It gives the most accurate numerical representation, but has the greatest computational expense. A coarse grid has fewer grid blocks, but the coarse grid blocks must be larger than the fine grid blocks to cover the same model volume. As a result, the coarse grid is less expensive to run than a fine grid, but it is also less accurate numerically. The loss of accuracy is the most evident when a coarse grid is used to model the interface between phases such a fluid contacts and displacement fronts. Thus, fine grid modelling is often the preferred choice to achieve maximum numerical accuracy. Sensitivity studies can help quantify the uncertainty associated with the model study.

As written by Staggs, H.M., and Herbeck, E.F. [6], their studied the effect of grid block size on predicted flow rate. They used several two-phase black-oil models of a 5-arce [2-ha] one-quarter five spot to model a 1:1 mobility-ratio water flood in which constant bottom hole pressure was maintained at both wells. The only difference between the models was the number of area grid blocks – 3 × 3, 4 × 4, 5 × 5, and 6 × 6 grids. Results summarized in Figure 2.6 shows the relationship between grid size and calculated performance. They conclude that at least two blocks should be used between offsetting production and injection wells. Others experience suggests that more than two blocks between offsetting wells are needed for most problems [1].

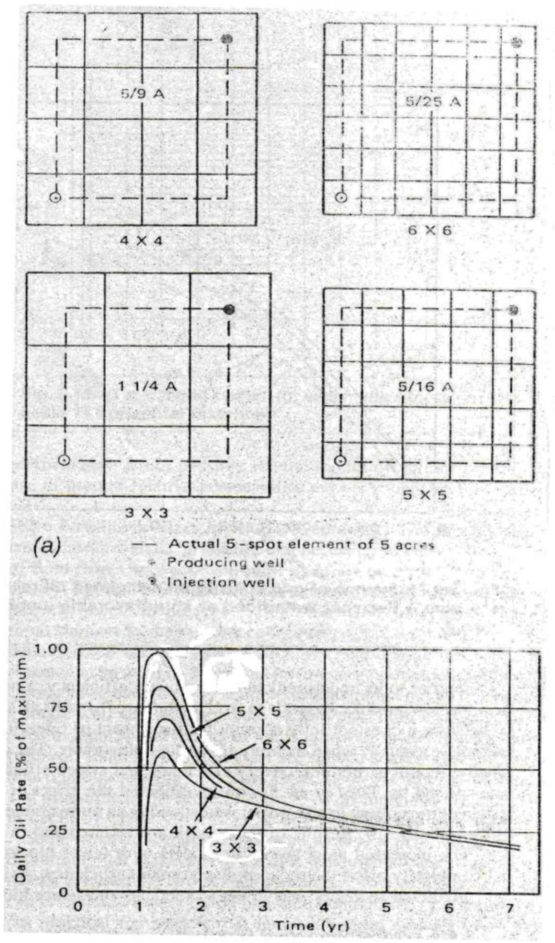

Figure 2.6: a) Models used to study the effect of spacing and b) oil predicted by the model [6]

In a work conducted by students at Texas A&M University [5], water flood simulations were performed for oil/water mobility ratios (M) of 0.5, 1.0 and 10. Since the distance of injector to producer is the same, it is expected to get similar recovery performance from both grid systems. However, when compared the recovery performance of parallel grid blocks of 8 × 8 and diagonal of 6 × 6 (Figure 2.7), the recovery performances from both grid blocks are different because rotation of the coordinate axes results in differing amounts of truncation error [1]. To eliminate the truncation error, they increased the number of grid blocks individually, in diagonal and parallel grid blocks model. In this study, they found that recovery performance is not very sensitive to the number of grid blocks in the diagonal model. However, as the number of the parallel grid blocks is increased, the recovery performance changes gradually until it converge to a single recovery curve (Figure 2.8).

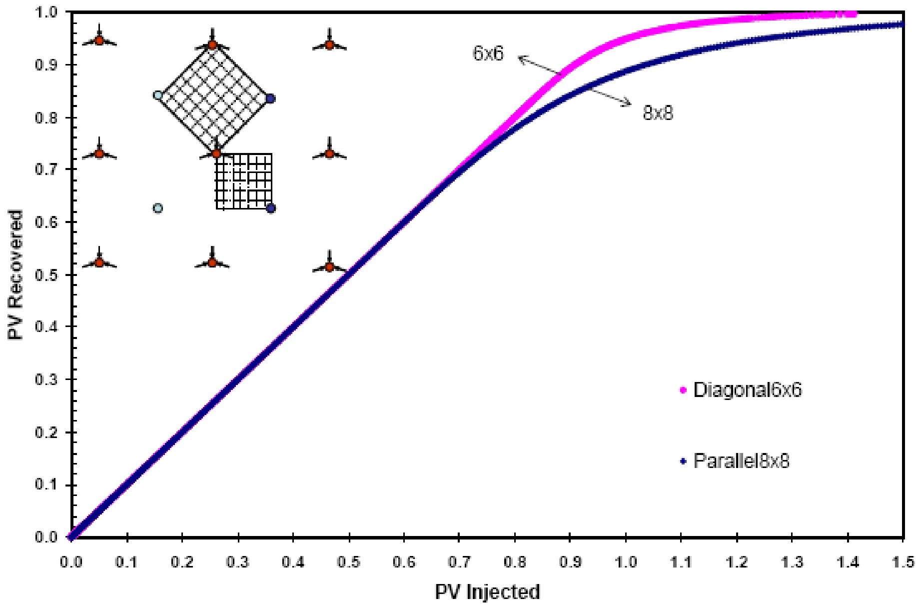

Figure 2.7: Predicted performance at M=0.5 for parallel (8 × 8) and diagonal (6 × 6) grid blocks [5]

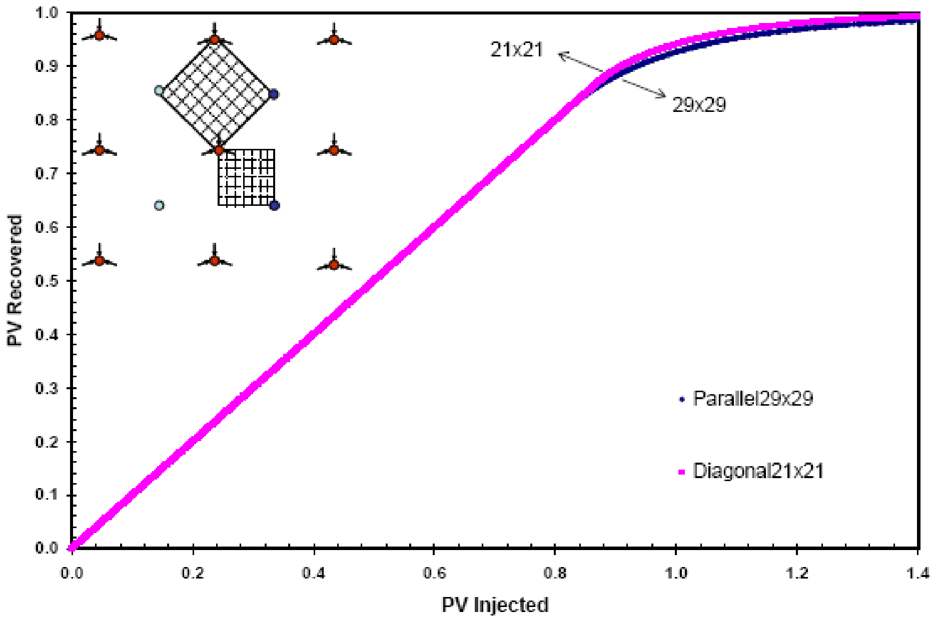

Figure 2.8: Predicted performance at M=0.5 for parallel (29 × 29) and diagonal (21 × 21) grid blocks [5]

The grid orientation effect can be reduced by increasing the resolution of the grid blocks for cases with favourable mobility ratio ($M \leq 1.0$) [3], where they refined grid blocks in both models (diagonal 21 × 21 vs. parallel 29 × 29) and found out that the grid orientation effect reduces as expected. When the mobility ratio is increased to 10, the performance of the diagonal does not follow a certain trend. On the other hand, for the parallel grid, the solution does not seem to converge to a single curve even when a large number of grid blocks were used. Thus, as the grid spacing increases, the performance of diagonal and parallel models actually diverges. The saturation map for diagonal grid model shows "viscous fingering" at the saturation front while the parallel model also shows a distorted front.

2.4 CO_2 MISCIBLE DISPLACEMENT

Improved recovery technology includes traditional secondary recovery processes such as water flooding and immiscible gas injection, as well as enhanced oil recovery (EOR) processes. EOR processes are usually classified as one of the following processes; chemical, miscible, thermal, and microbial.

In miscible section, miscible flooding methods include carbon dioxide injection, natural gas injection and nitrogen injection. Miscible gas injection must be performed at high enough pressure to ensure miscibility between the injected gas and in situ oil. Miscible flooding forms a single phase solution with the hydrocarbon reservoir when injected and in contact with the hydrocarbon. Miscibility is achieved when interfacial tension (IFT) between the aqueous and oleic phases is significantly reduced. Any reduction in IFT can improve displacement efficiency, and a near miscible process can yield much of the incremental oil that might be obtained from a miscible process. If reservoir pressure is not maintained above the minimum miscibility pressure (MMP) of the system, the gas flood will be an immiscible gas injection process. Immiscible flooding occurs when carbon dioxide does not form a single phase solution with the hydrocarbons in the reservoir. Immiscible flooding is usually used to recover heavy crude oil.

CO_2 is not miscible on first contact with reservoir oils. However, past research shows that at sufficiently high pressure CO_2 achieves dynamic miscibility with many reservoir oils. According to this concept, CO_2 vaporizes or extracts hydrocarbon from crude as heavy as the gasoline and gas/oil fractions. For a reservoir to use a CO_2 miscible flooding, miscibility pressure must be attainable, over a volume of reservoir. The miscibility pressure of CO_2 often lower than pressure required for miscibility of other gases such as natural gas, flue gas or nitrogen, which gives CO_2 a big advantage to compare with others. Opportunity with other gases is limited since high pressure is required for dynamic miscibility is unattainable in many reservoirs. Oil viscosity and reservoir heterogeneity also determine suitability of a reservoir for flooding. Since CO_2 has low viscosity, the viscosity ratio with reservoir oils will be unfavourable, and then mobility ratio also becomes unfavourable unless CO_2 relative permeability is sufficiently reduced to keep mobility favourable.

2.4.1 CO_2 MISCIBLE DISPLACEMENT MECHANISM

Carbon dioxide (CO_2) mixes with oil by dissolution. The displacement mechanism involved the vaporization of ethane, propane and butane from the crude oil by CO_2 to generate an oil-miscible front to displace residual oil. Within the porous medium, there is a large contact area between the gas and oil during the displacement. Rapid mass transfer occurs between carbon dioxide (CO_2) and the oil by fractionation of the oil.

The frontal part of the mixing zone becomes progressively richer in light hydrocarbon fractions as the light hydrocarbons are extracted by the displacing gas which is CO_2. If the oil contains high methane content, it may be extracted from the oil and travel just ahead of the carbon dioxide (CO_2) front. The formation of methane bank between the oil and the carbon dioxide saturated zone when the injection pressure is lower than the miscibility pressure of methane.

In the mixing zone, the intermediates and carbon dioxide make the oil significantly lighter. Behind the front oil, due to the extraction of the lighter hydrocarbon, the oil progressively becomes heavier. Although it is saturated with carbon dioxide (CO_2), it has relatively low mobility. The density of CO_2 – saturated oil increases with increment of its content in light oils. Low gravity oils however experience a different effect and decrease by increment of CO_2 content.

In miscible flooding using carbon dioxide (CO_2), the IFT as well as the related capillary forces between the fluids are absent. Theoretically, all the driving fluid will displace all of the oil in place in the rock entered by the driving fluid.

CHAPTER 3
METHODOLOGY

3.1 METHODOLOGY

The methodology for this project is illustrated by the following flow chart;

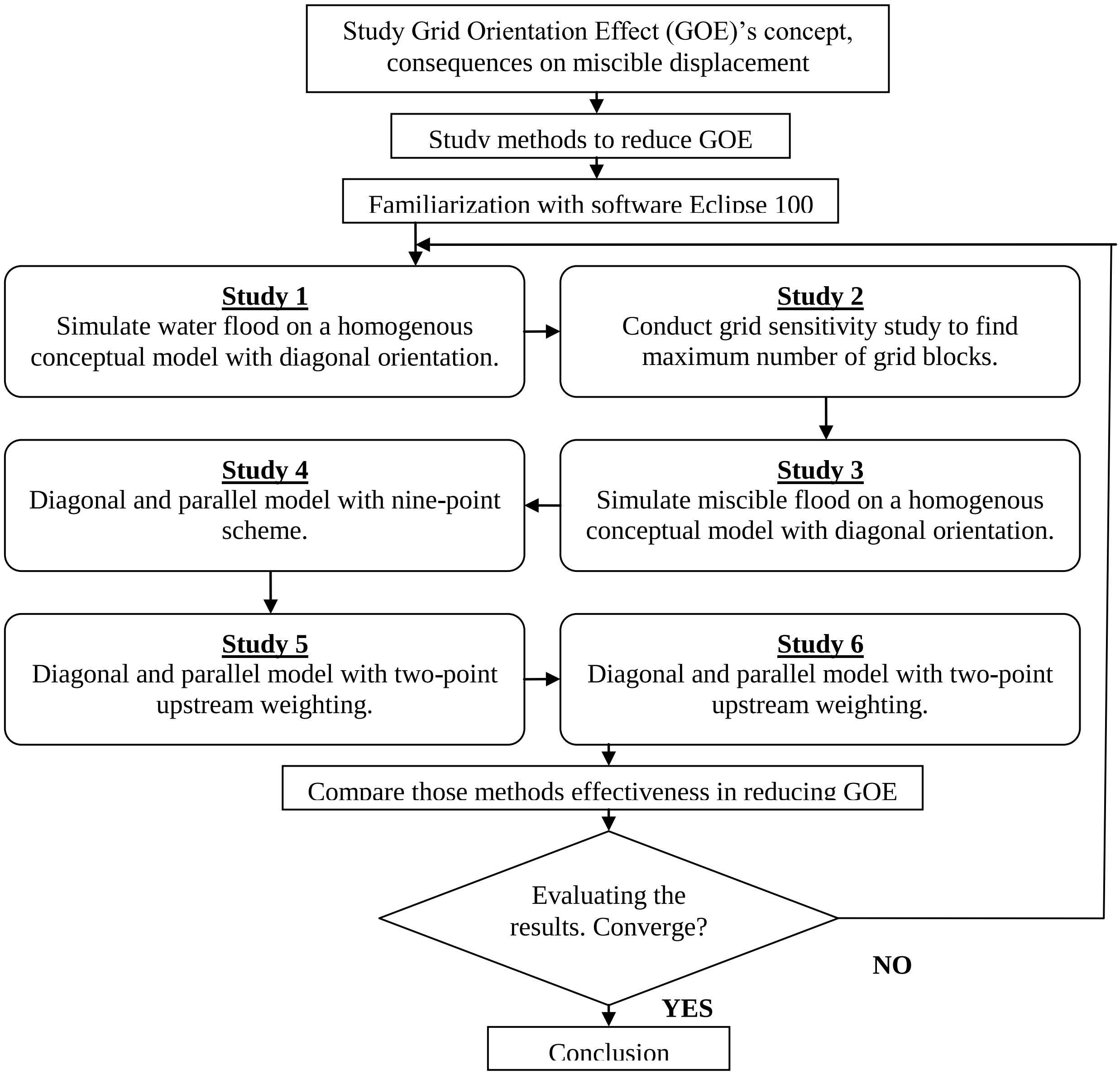

Figure 3.1: Flowchart of methodology

3.2 SIMULATION ON CONCEPTUAL MODEL

3.2.1 WATER-FLOODING SIMULATION

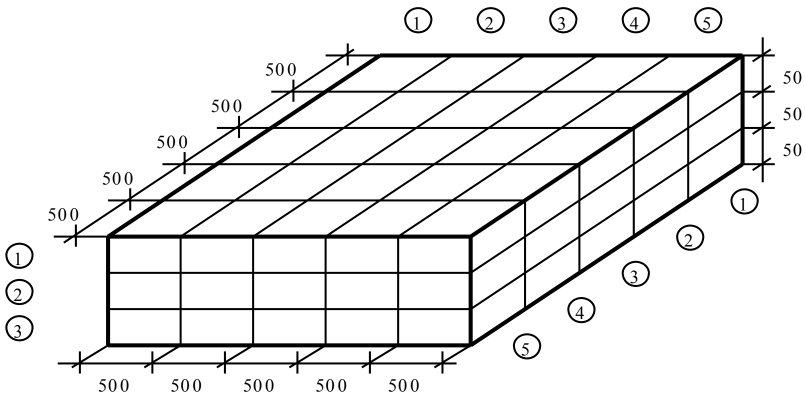

Figure 3.2: Schematic of diagonal model

Input data file is prepared for simulating the performance of a two phase (water/oil) three dimensional reservoir of size 2500ft. × 2500ft. × 150ft. The reservoir is divided into three layers of equal thickness and the number of cells in the x and y directions are 5 and 5 respectively. The reservoir characteristics are as follow;

Depth of reservoir top	:	8000 ft
Initial pressure at 8075'	:	4500 psia
Porosity	:	0.20
Permeability in x direction	:	200 mD (1st and 3rd layers)
	:	1000 mD (2nd layer)
Permeability in y direction	:	150 mD (1st and 3rd layers)
	:	800 mD (2nd layer)
Permeability in z direction	:	20 mD (1st and 3rd layers)
	:	100 mD (2nd layer)

The following data shows the saturation, PVT and density of water and oil together with rock compressibility.

Table 3.1: Water and oil relative permeability and capillary pressure functions

Water Saturation	k_{rw}	k_{ro}	P_{cow} (psi)
0.25*	0.0	0.9	4.0
0.5	0.2	0.3	0.8
0.7	0.4	0.1	0.2
0.8	0.55	0.0	0.1

* Initial saturation throughout.

Table 3.2: Water PVT data at reservoir pressure and temperature

Pressure (psia)	B_w (rb/stb)	C_w (psi^{-1})	μ_w (cp)	Viscosibility (psi^{-1})
4500	1.02	3.0E-06	0.8	0.0

Table 3.3: Oil PVT data, bubble point pressure (Pb) = 300 psia

Pressure (psia)	B_o (rb/stb)	Viscosity (cp)
300	1.25	1.0
800	1.20	1.1
6000	1.15	2.0

Rock compressibility at 4500 psia	:	4E-06 psi^{-1}
Oil density at surface conditions	:	49 lbs/cf
Water density at surface conditions	:	63 lbs/cf
Gas density at surface conditions	:	0.01 lbs/cf

The oil-water contact is below the reservoir (8,200 ft), with zero capillary pressure at the contact.

A producer PROD, belonging to group G1, in Block No. (1,1) and an injector INJ, belonging to group G2, in Block No. (5,5) are drilled. Both the injector and producer are perforated in all 3 layers and the producer is controlled by liquid flow rate mode of

10,000 stb liquid/day whereas the injector is controlled by water flow rate mode of 11,000 stb water/day. Simulation is run with 21 time steps of 200 days starting from 1 January 2007.

3.2.2 GRID SENSITIVITY STUDY

After generating the base model, a finer grid model will be simulated. The objective is to get optimum number of grid block to be used subsequently. This is done by reducing the size of each of the cells and increasing the number of cells, such that the reservoir volumes of both the fine and coarse grid models are the same.

There are 4 cases to be simulated for this study.

Case A : $15 \times 15 \times 9$

Case B : $25 \times 25 \times 15$

Case C : $45 \times 45 \times 27$

Case D : $50 \times 50 \times 30$

Table 3.4: Coarse grid block size for each case

Case	Coarse Grid Block Size		
	DX (ft)	DY (ft)	DZ (ft)
A	166.7	166.7	16.7
B	100	100	10
C	55.6	55.6	5.6
D	50	50	5

The new coordinate also being change, but location of both injector and producer for all tested models are the same.

Results from simulation focusing on the oil production flow rate stated in Field Oil Production Rate (FOPR) and recovery factors stated in Field Oil Recovery Efficiency (FOE) are compared.

3.2.3 MISCIBLE FLOODING SIMULATION

In simulating the carbon dioxide miscible flooding, the reservoir properties of the model remain the same as the base case. To run a miscible flooding, the miscible function is to be entered in the RUNSPEC section. The saturation, PVT and density of water, oil and gas together with rock compressibility are defined in the PROPS section is altered as follows.

Rock compressibility at 4500 psia	:	4E-06 psi^{-1}
Oil density at surface conditions	:	49 lbs/cf
Water density at surface conditions	:	63 lbs/cf
Gas density at surface conditions	:	0.01 lbs/cf
Carbon dioxide density at surface condition	:	0.1159 lbs/cf

Table 3.5: Gas PVT Data at Reservoir Pressure and Temperature

Pressure (psia)	B_g (rb/Mscf)	Viscosity (cp)
200	17.08380866	0.018
2000	1.145811194	0.026
3000	0.690046089	0.04
4000	0.547804063	0.051

The phase of the injector is then changed from water to gas with a controlled flow rate of 9000 Mscf/day. The simulation is run with a 6 time steps of 100 days, 7 time steps of 200 days, 11 time steps for 300 days and 7 time steps of 500 days.

3.2.4 MISCIBLE FLOODING IN PARALLEL ORIENTATION

In this study, preceding model will be used. However, the grid orientation is changed from diagonal to parallel orientation.

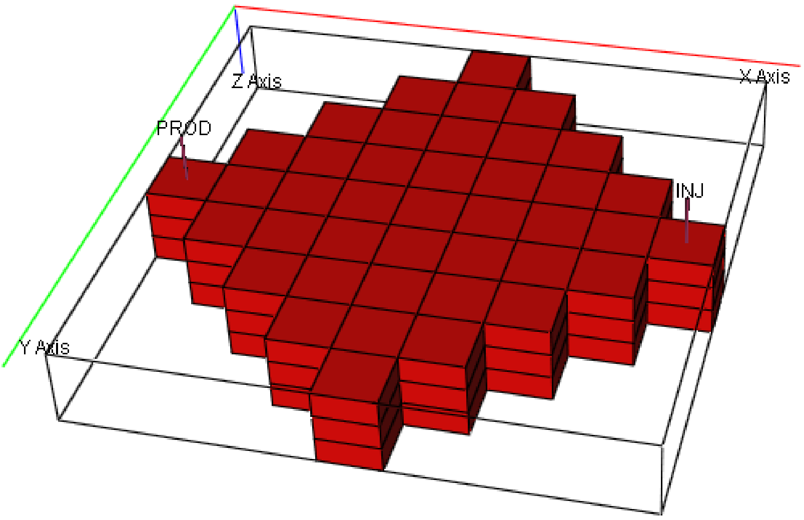

Figure 3.3: Schematic of model (parallel orientation)

3.2.5 CASES

Cases for the whole study have been arranged as below.

Table 3.6: Description for cases

Case	Description
Base Case D	Diagonal grid (15 × 15 × 9)
DA	Diagonal grid (15 × 15 × 9) with two-point method
DB	Diagonal grid (15 × 15 × 9) with nine-point method
DC	Diagonal grid (25 × 25 × 15)
DD	Diagonal grid (15 × 15 × 9) with two-point and nine-point method
DE	Diagonal grid (25 × 25 × 15) with two-point and nine-point method
Base Case P	Parallel grid (15 × 15 × 9)
PA	Parallel grid (15 × 15 × 9) with two-point method
PB	Parallel grid (15 × 15 × 9) with nine-point method
PC	Parallel grid (25 × 25 × 15)
PD	Parallel grid (15 × 15 × 9) with two-point and nine-point method
PE	Parallel grid (25 × 25 × 15) with two-point and nine-point method

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 WATER FLOODING MODEL

Figure 4.1 shows the simulation results of a displacement water flooded on 5 × 5 × 3 grid blocks model.

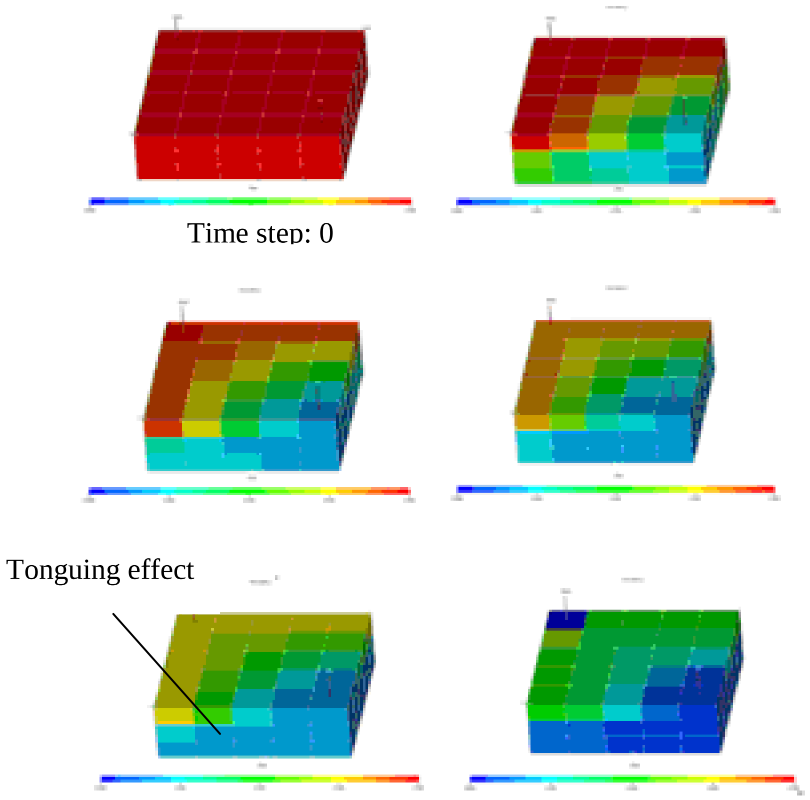

Figure 4.1: Water flooding simulation on 5 × 5 × 3 grid blocks

From the FloViz simulation, the tonguing effect can be hardly seen. As water is injected into the reservoir, the oil saturation changes is quite fast since the number of grid blocks is small, causing the saturation process sweeping fast.

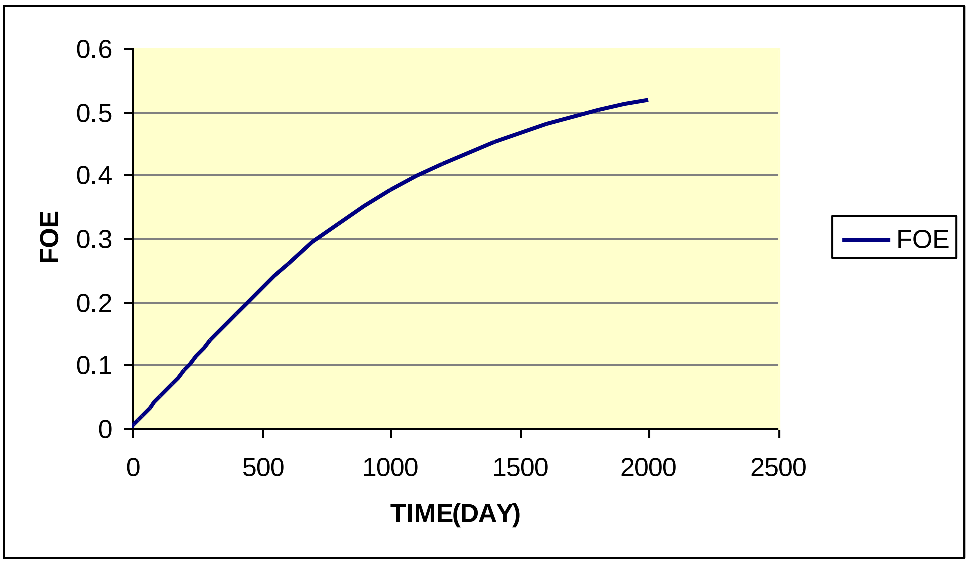

Figure 4.2: Field Oil Recovery Efficiency (FOE) for water flood model

Figure 4.2 shows the recovery factor for the water flooded model. The recovery is increasing as the amount of oil recovered in the model increased. The highest FOE for the model is 0.519.

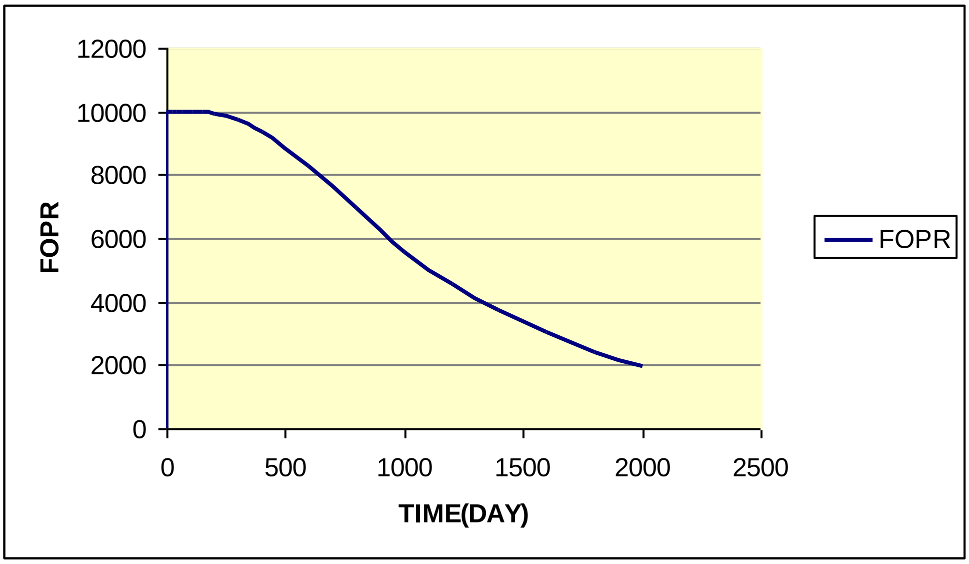

Figure 4.3: Field Oil Production Rate (FOPR) for water flood model

Figure 4.3 shows the recovery rate for the water flooded model. The 10 000 stb/day is set as maximum water rate injected for the model. The decline line showing the injector has sweep and recovered most of the oil in the model.

4.2 GRID SENSITIVITY STUDY

Figure 4.4 shows the simulation results of a displacement water flooded on 15 × 15 × 9 grid blocks model.

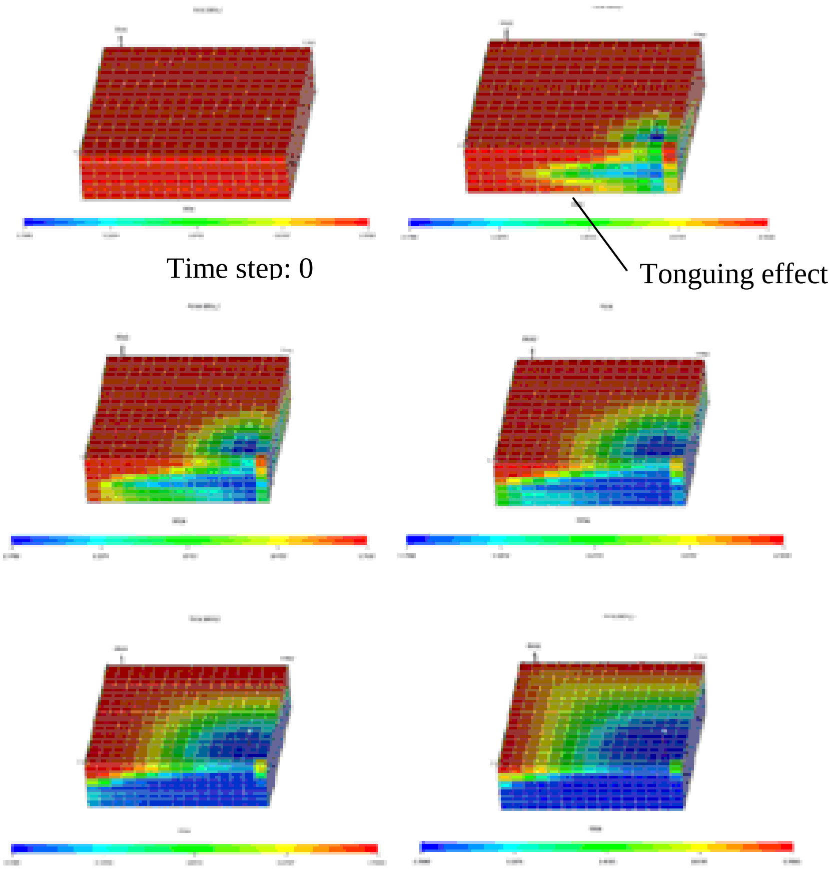

Figure 4.4: Grid sensitivity simulation on 15 × 15 × 9 grid blocks

From the FloViz simulation shown, differences can be seen between the water flooded modelling for coarse grid case (5 × 5 × 3) and finer grid case (15 × 15 × 9). For the water modelling, the tonguing effect is observed in both models. However, for finer grid blocks the oil saturation changes as water is injected into the reservoir is more reliable compared to the coarse grid model giving same time step simulation.

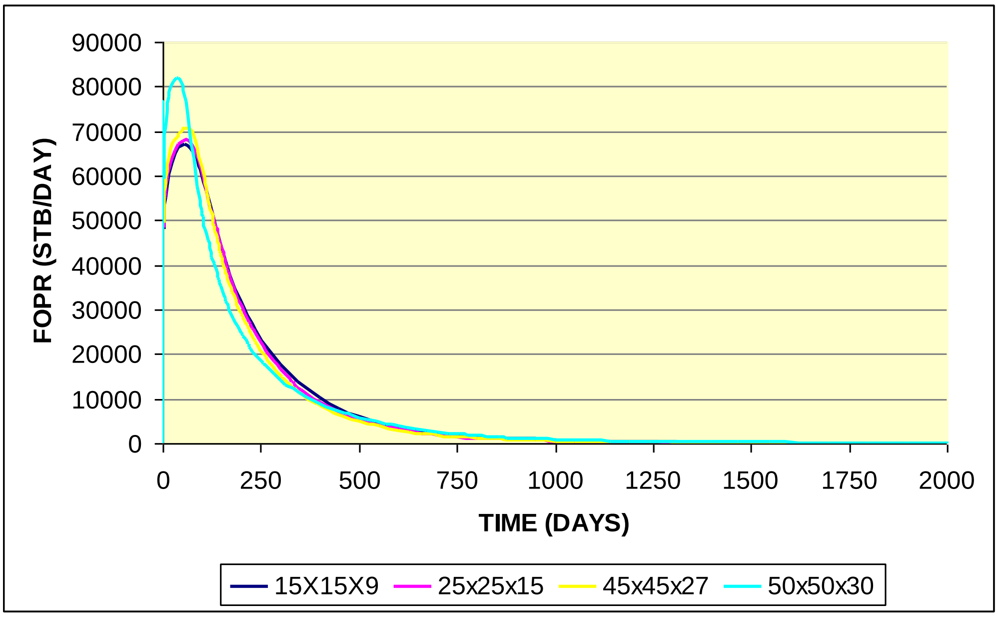

Figure 4.5: Field Oil Production Rate (FOPR) for all water flood model

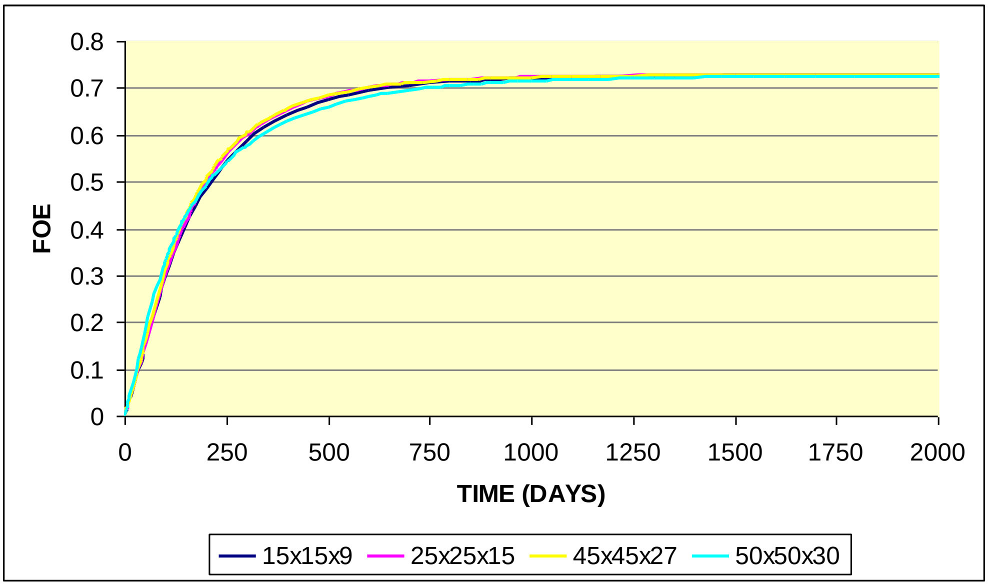

Figure 4.6: Field Oil Production Efficiency (FOE) for all water flood model

To compare the effect of the grid sensitivity, few water flooding models were simulated. The main objective is to find optimum number of grid block to be used as base case. The dimensions of the entire reservoir blocks are the same. The difference between models is as the number of grid block increase, the finer the grid cells are. From the results obtained (Figure 4.5 and Figure 4.6), slight variations in the plots are observed. The model with the finer gridding exhibits a higher initial oil production rate (Figure 4.5) and hence a higher field oil production total (Figure 4.6). From the FloViz simulation, the oil saturation changes as water is injected into the reservoir is more reliable for the finer grid model as compared to the coarse grid model given the same time step simulation.

The grid geometry in this water flooding simulation is specified in block centered format which is commonly termed as a Cartesian model. Block centered models are rectangular and have horizontal upper and lower surfaces and vertical sides. The location of all property information such as the porosity, permeability and net to gross is at the cell center. Depending on the size of the cell, the values are normally some average of finer scale properties. In this case, the model with coarse gridding has a larger grid cell and the values assigned to the cells represent a larger volume of the reservoir as compared to the finer grid cell in the fine gridding model. The number of processing required to simulate the model is more for the model with fine grids as more grid cells are present. Hence, the model with finer grids yields a more refined and reliable results.

However, it is not necessary to have such refined grid cells throughout the block. Usually, more refined grid cells will be placed near the injection and the producer well where the observation of bottom hole pressure and the production rate is crucial. Furthermore having finer grids requires more grid cells to represent the block and thus requires more computations or processing which requires more memory and is prone to errors or problems.

In this project, $50 \times 50 \times 30$ grid block gives the best option for the simulation. However, when conducting the further FloViz simulation in comparison study, there are more problem and error encountered in the simulation, thus leaving to second option in picking other grid blocks and replacing it. In comparison, there are slightly different shown in the result (Figure 4.5 and Figure 4.6). Since the result does not vary much, explaining the simulator is insensitive to the grid block and grid orientation regarding the number of grid block used. But computational time increase, also giving load to computer, as the number of grid block increased, showing that by increasing grid block does not effecting much in reducing the dispersion.

However, $15 \times 15 \times 9$ grid block is used as base case model, since the result does not vary too much indicating the simulators insensitive to number of grid blocks used.

4.3 MISCIBLE FLOODING (BASE CASE)

Figure 4.7 shows the simulation results of a miscible flooding on parallel orientation grid block.

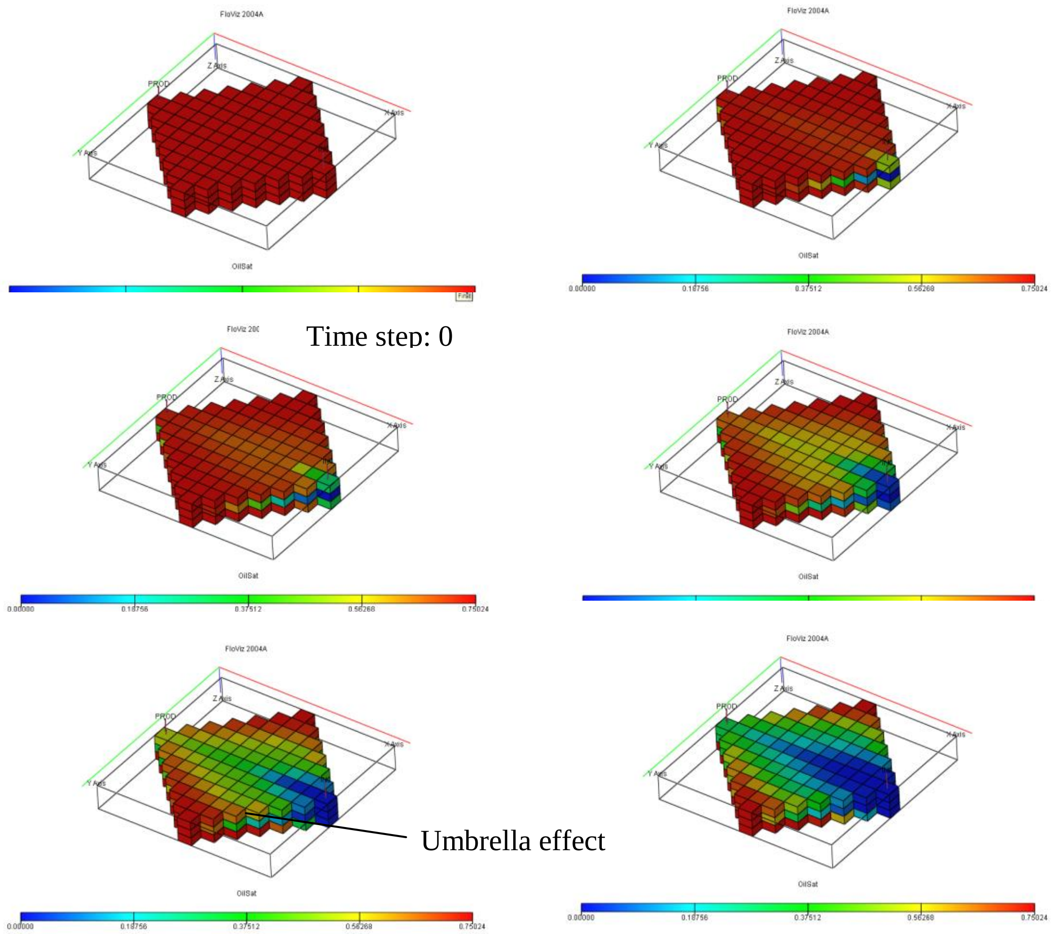

Figure 4.7: Miscible flooding simulation on parallel grid orientation

From the FloViz simulation, some differences can be seen between the water flooded modelling and the miscible flooded modelling. For the water flooded modelling, the tonguing effect is observed based on low oil saturation at the bottom of the reservoir compared to low oil saturation at the top of the reservoir as oil is displaced. The miscible flooded flooding on the other hand, as the density of the carbon dioxide is lower, the umbrella effect is observed based on low oil saturation at the top of the reservoir compared to bottom of the reservoir when oil is displaced by the reservoir.

The miscible carbon dioxide flooding that is simulated in this project is a 3 phase simulation where the reservoir consists of reservoir oil, injection gas which is carbon dioxide and water. The reservoir oil component consists of stock tank oil together with their associated solution gas. The solvent and the reservoir oil component are assumed to be miscible at all proportions and consequently only one hydrocarbon phase exists in the reservoir.

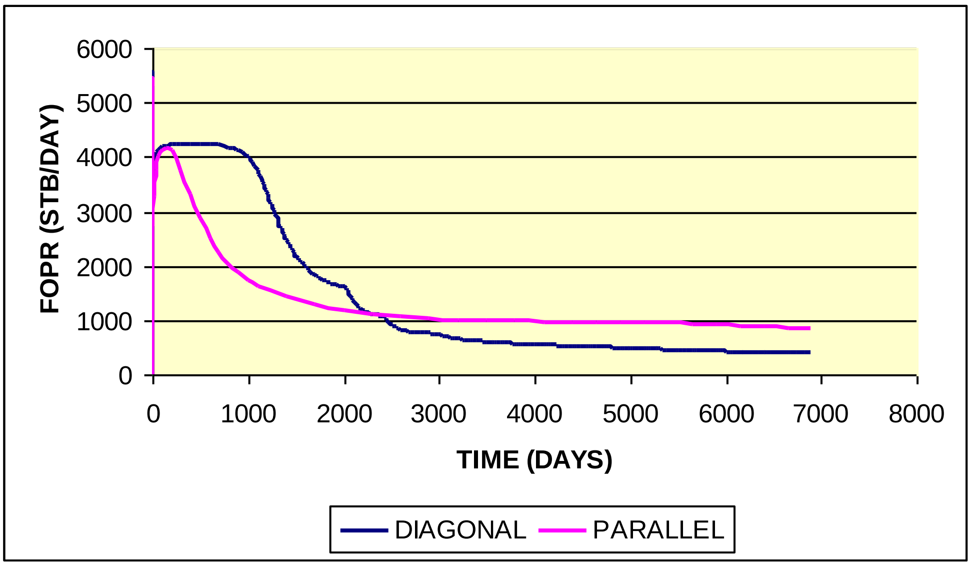

Figure 4.8: Field Oil Production Rate (FOPR) for miscible flooding model

Figure 4.8 explained the difference result for both cases. Since the diagonal sweep more blocks than parallel orientation, shown on the diagonal line, where it stay longer at around 4000 stb/day compare to parallel line, where it dropped faster.

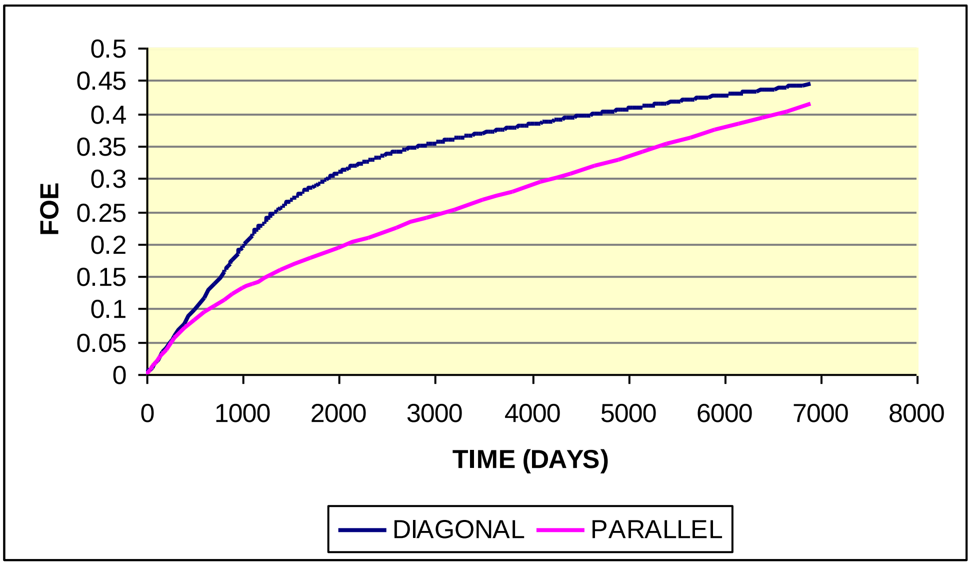

Figure 4.9: Field Oil Production Efficiency (FOE) for miscible flooding model

Figure 4.9 show that the recovery factor for diagonal line is higher compare to parallel line. Diagonal orientation cover more blocks compare to parallel orientation, which allow it to recover more oil than parallel orientation.

4.4 COMPARISON OF METHODS

This Figure 4.10 shows the recovery factor for all parallel orientation cases, where Base Case P is selected as reference line.

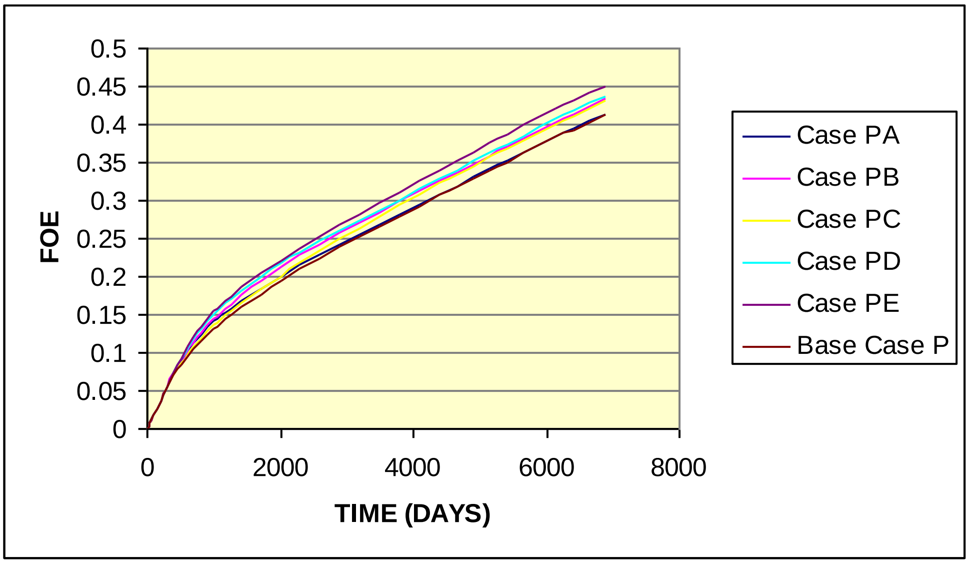

Figure 4.10: Field Oil Production Efficiency (FOE) for all parallel orientation cases

Case PE has the highest line compare to other cases. It show that every case exceeding the reference line, Base Case P. Comparing three methods used, Case PB, representing nine-point scheme has the highest line. This probably, the method sweeps the reservoir more efficient since it covers more area than other methods. Percentage increment for each case is shown in Table 4.1 below.

This Figure 4.11 shows the recovery factor for all diagonal orientation cases, where Base Case D is selected as reference line.

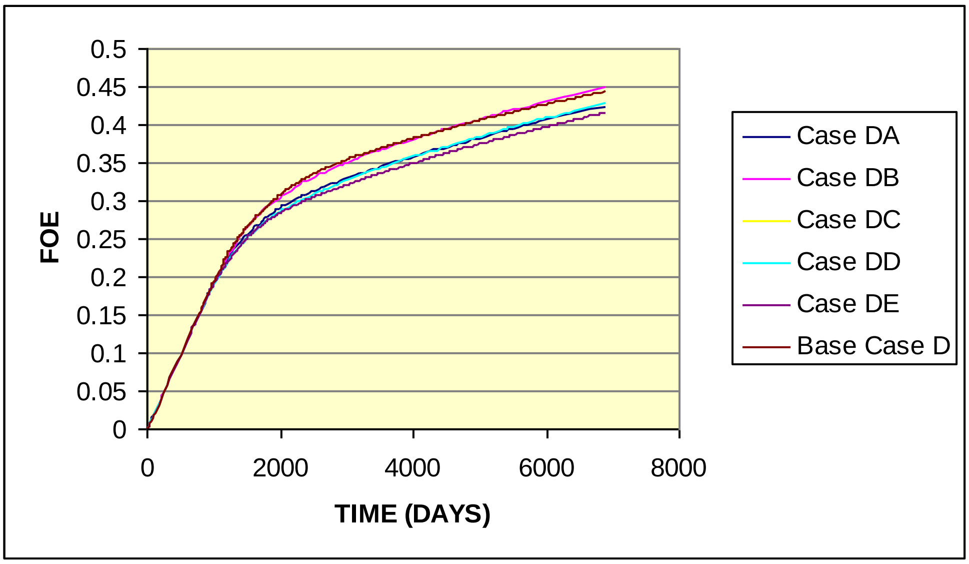

Figure 4.11: Field Oil Production Efficiency (FOE) for all diagonal orientation cases

Case DB has the highest line compare to other cases. Case DE, combination of three methods has the lowest line. Comparing three methods used, Case DB, representing nine-point scheme has the highest line. This probably, the method sweeps the reservoir more efficient since it covers more area than other methods. Percentage increment for each case is shown in Table 4.1 below.

Table 4.1: Percentage increment in recovery factor for all methods

Case	Final Value	% Increment
Base Case P	0.413	0
PA	0.414	0.149
PB	0.433	4.961
PC	0.431	4.245
PD	0.438	5.969
PE	0.451	9.153
Base Case D	0.444	0
DA	0.425	-4.319
DB	0.449	1.130
DC	0.444	0
DD	0.429	-3.395
DE	0.416	-6.281

For percentage increment for each method, the following calculation is used.

$$\% \text{ increment} = \frac{\underline{(\text{Final value for case}) - (\text{Base value})}}{\text{Base value}} \times 100$$

From the simulation, the nine point scheme showed effective result, comparing three methods simulated, for both diagonal (1.13% increment) and parallel (4.96% increment) orientation, because, the methods considered the other 8 adjective points surrounding it. The areas covered by nine point scheme method is larger since the flow travel more blocks compare to two point weighting method.

However, based on the overall results, including combination methods, for parallel grid orientation, combination for the three methods studied is more effective, since the line getting more towards the theoretical value with the highest increment (9.15%). Different case happens towards the combination for diagonal grid orientation, probably caused by error in simulation.

4.5 COMPARISON OF DIAGONAL AND PARALLEL METHODS

The Figure 4.12 shows the comparison of a selected case from parallel orientation and a selected case from diagonal orientation.

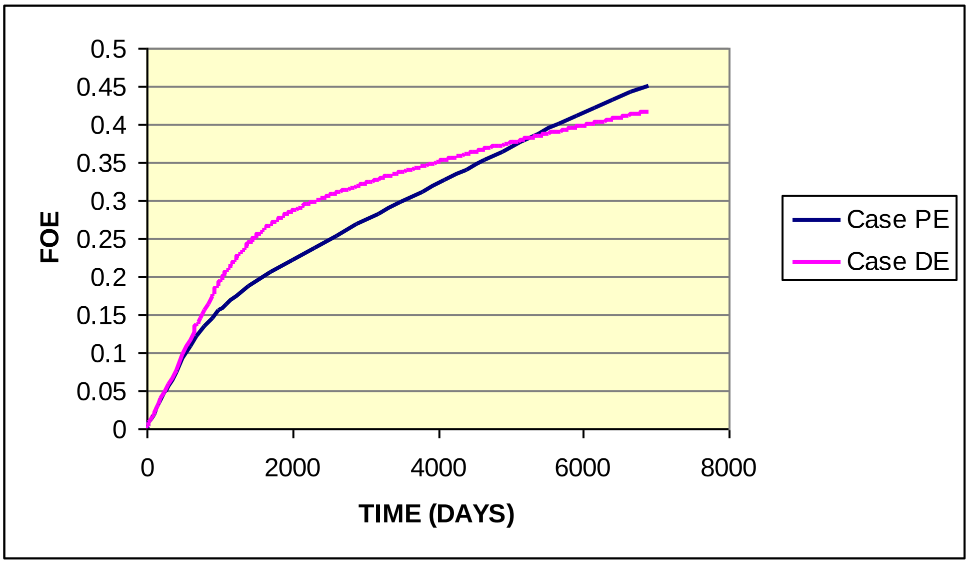

Figure 4.12: Field Oil Production Efficiency (FOE) for Case PE and Case DE

For this study, comparison has been made between the highest result for parallel orientation, Case PE and the lowest result for diagonal orientation, Case DE. The purpose of the comparison is to know the convergence or divergence for both cases. Selected FOE is taken based on the same time for both cases as shown in Table 4.2.

Table 4.2: Selected FOE for both cases

Time (days)	FOE	
	Parallel	Diagonal
0	0	0
1	0.000151	0.000198
6	0.00076	0.001002
16	0.0022	0.0027
40	0.0062	0.0071
100	0.0174	0.0188
200	0.0368	0.0383
250	0.0465	0.0481
300	0.0563	0.0579
400	0.0750	0.0776
500	0.0923	0.0973
600	0.1078	0.1169
700	0.1217	0.1361
800	0.1340	0.1551
900	0.1450	0.1733
1000	0.1549	0.1903
1100	0.1639	0.2055
1400	0.1858	0.2413
1700	0.2046	0.2670
2000	0.2215	0.2847
2300	0.2372	0.2976
2600	0.2523	0.3082
2900	0.2672	0.3180
3200	0.2818	0.3272
3500	0.2965	0.3360
3800	0.3111	0.3443
4100	0.3258	0.3523
4400	0.3404	0.3601
4900	0.3643	0.3724
5400	0.3876	0.3842
5900	0.4500	0.3953
6400	0.4311	0.4060
6900	0.4508	0.4162

The percentage average is calculated using the following equation;

$$\text{Average} = \frac{\sum \left| (\text{FOE for time parallel} - \text{FOE for time diagonal}) \right|}{\sum \text{Number of time taken}} \times 100$$

The average result is 6.906013%. Since the result is around 7%, it can be concluded that both cases are converging towards each other.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The objective of this project is to simulate the various methods to reduce grid orientation effect in miscible flooding simulation. From the simulation, each method are compared and analysed to determine the most feasible and efficient method and combination of methods to be used. The application of the findings in a case model opens the opportunities to assimilate and apply the knowledge and findings in the real life model. From literature reviews and the results obtained, a few conclusions were made.

a) Finer grid yields a more reliable result as there are more grid cells which made up the reservoir as more computations have to be carried out which yields a more reliable results. The 50 × 50 × 30 grid block gives the best option for the simulation. However, 15 × 15 × 9 grid block is used as base case model, since the result does not vary too much indicating the simulators insensitive to number of grid blocks used.
b) Comparing all three methods, it showed that nine point scheme gives the highest recovery.
c) However, in overall results, combination of three methods in parallel orientation showed the highest recovery of 9.15%.
d) The average result for comparing Case PE, the highest in parallel orientation and Case DE, the lowest in diagonal orientation is 6.906%. Since the result is around 7%, it can be concluded that both cases are converging towards each other.

5.2 RECOMMENDATION

As for recommendation, further simulations should be conducted on methods to get more accurate results. More new developed methods such as curvilinear grid and triangular grid should be tested in order to see the effectiveness of those methods to reduce the Grid Orientation Effect (GOE). Simulation should be tested in actual reservoir field in order to implement these methods, where many factors need to be considered.

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[2] Brand, C.W., Stanford U.; Heinemann, J.E., Mining U. Leoben; Aziz, K., Stanford U., 1991, *"The Grid Orientation Effect in Reservoir Simulation", Society of Petroleum Engineers.*

[3] Todd, M.R., O'Dell, P.M., and Hiraski, G.J.:"*Methods for Increased Accuracy in Numerical Reservoir Simulators*," SPEJ (Dec. 1968)

[4] Ko, Stephen C.M., Au, Anthony D.K., Computer Modelling Group *"A Weighted Nine-Point Finite-Difference Scheme for Eliminating The Grid Orientation Effect in Numerical Reservoir Simulation"*

[5] "*A New Grid Block System for Reducing Grid Orientation Effect*" by Emeline Chong, Zuher Syihab, Erwinsyah Putra, Dewi T. Hidayati, and David S.Schechter from Department of Petroleum Engineering, Texas A&M University, College Station, Texas, USA

[6] Staggs, H.M. and Herbeck, E.F.: "Reservoir Simulation Models – An Engineering Overview," JPT (Dec. 1971)

[7] Emeline E. Chong "*Development of a 2-D Black-oil Reservoir Simulator using a Unique Grid-block System"*

[8] William D. McCain, Jr., *"The Properties of Petroleum Fluids (Second Edition)"*

[9] Yanosik, J.L. and McCracken, T.A.,"*A Nine-Point Finite-Difference Reservoir Simulator for Realistic Prediction of Adverse Mobility Ratio Displacement*"

APPENDICES

APPENDIX 1

DATA FILE FOR WATER FLOODING

```
--=================================================================
RUNSPEC
TITLE
  Basic Water Flood Model 3D

DIMENS
  5   5   3   /

OIL
WATER

FIELD

TABDIMS
  1   1   3*  /

WELLDIMS
  2   6   2   1   /

START
  1   JAN   2007   /

NSTACK
 1*         /

UNIFOUT
--===================================================================
GRID

BOX
  1   5   1   5   1   3   /
ENDBOX

EQUALS
  DX      500    1   5   1   5   1   3   /
  DY      500    1   5   1   5   1   3   /
  DZ      50    1   5   1   5   1   3   /
  PERMX   200      1   5   1   5   1   1   /
  PERMX   1000     1   5   1   5   2   2   /
  PERMX   200      1   5   1   5   3   3   /
  PERMY   150      1   5   1   5   1   1   /
  PERMY   800      1   5   1   5   2   2   /
  PERMY   150      1   5   1   5   3   3   /
  TOPS    8000     1   5   1   5   1   1   /
  PORO    0.2      1   5   1   5   1   3   /
/

COPY
  PERMX   PERMZ   /
/

MULTIPLY
  PERMZ   0.1   /
/
--=============================================================
PROPS
DENSITY
          49    63     0.01  /
PVDO
      300     1.25     1.0
      800     1.2     1.1
      6000    1.15    2  /

ROCK
```

```
  4500    4E-06  /

PVTW
  4500    1.02    3.06E-06    0.8 /


SWOF
  0.25                  0            0.9          4
  0.5                   0.2          0.3          0.8
  0.7                   0.4          0.1          0.8
  0.8                   0.55         0.0          0    /

--==================================================================
SOLUTION
EQUIL
      8075   4500      8200      0    /

RPTSOL
     PRES   SWAT   SOIL  FIP /

RPTRST
 BASIC=2 ALLPROPS
/
--=====================================================================
SUMMARY

 WBHP
/
 FOPT
 FWPT
 FGOR
 FOE
 FVPT
 FVIT
 FOVIS
 FODEN
 FPR
 FOPR
 FVIR
 FVPR
 RUNSUM
 EXCEL
 SEPARATE
 TCPU
 ELAPSED

--=====================================================================
SCHEDULE
--
RPTSCHED
     PRES   SWAT    /

WELSPECS
        PROD   G1     1    1    8000    OIL     /
         INJ   G2     5    5    8000    WATER  /
/

COMPDAT
        PROD   1   1   1   3   OPEN    2*   1 /
        INJ    5   5   1   3   OPEN    2*   1 /
/

WCONPROD
        PROD    OPEN    LRAT  3*          10000   /
/


WCONINJE
         INJ   WATER    OPEN      RATE     11000    /
/

TSTEP
25*200  /

END
```

APPENDIX 2

DATA FILE FOR MISCIBLE FLOODING

```
--===================================================================
RUNSPEC
TITLE
  Miscible Flood Model 3D

DIMENS
  15   15   6   /

OIL
GAS
WATER

FIELD

TABDIMS
  1   1   3*  /

WELLDIMS
  2   12   2   1   /

MISCIBLE
 1   1*  TWOPOINT /

NINEPOIN

TABDIMS
   1    1   100 100   3 /

REGDIMS
   1   1   /

START
  1   JAN 2007   /

NSTACK
100         /

UNIFOUT
--=====================================================================
GRID

BOX
  1   15   1   15   1   6   /

ENDBOX

EQUALS
  DX      167    1   15   1   15   1   6   /
  DY      167    1   15   1   15   1   6   /
  DZ      30    1   15   1   15   1   6   /
  PERMX   200      1   15   1   15   1   2   /
  PERMX   1000     1   15   1   15   3   4   /
  PERMX   200      1   15   1   15   5   6   /
  PERMY   150      1   15   1   15   1   2   /
  PERMY   800      1   15   1   15   3   4   /
  PERMY   150      1   15   1   15   5   6   /
  TOPS    8000     1   15   1   15   1   1   /
  PORO    0.2      1   15   1   15   1   6   /

/

COPY
PERMX   PERMZ   /
/
```

```
MULTIPLY
   PERMZ   0.1   /
/


--==================================================================
PROPS
--              OIL       WAT       GAS
DENSITY
                49          63          0.01  /

SDENSITY
  0.1159  /
--
--            P      Bo       Vis
PVDO
            300     1.25     1.0
            800     1.2     1.1
             6000    1.15    2  /
--

--             PREF    COMPR

ROCK
              4500    4E-06  /
--
--             SWAT      KRW      KROW      PCOW

SWFN
            0.25        0            4
             0.5         0.2          0.8
            0.7          0.4          0.8
              0.8        0.55        0    /

SORWMIS
 0           0.0
 1.0         0.0 /


SOF2
 0          0
0.15        0
0.19        0
0.25        0.05
0.31        0.1
0.34        0.13
0.3885      0.16
0.4433      0.2
0.4967      0.3
0.5567      0.43
0.5949      0.54
0.646       0.7
0.6949      0.84
0.74        0.98
0.75        1     /


PVTW
   4500    1.02    3.06E-06    0.8 /

PVDG
  200       17.08380866          0.018
  2000      1.145811194          0.026
  3000      0.690046089          0.04
  4000      0.547804063          0.051
/
TLMIXPAR
 0.667 /
-====================================================================

SOLUTION
--
--             DATUM   Pi@DATUM           WOC        Pc@WOC    GOC  Pc@GOC
EQUIL
```

```
              8075       4500                      8200       0    7950/
--
RPTSOL
              PRES   SWAT   SOIL  FIP /

RPTRST


BASIC=2 ALLPROPS
/

--=================================================================
SUMMARY
--

WBHP
/
FOPT
FGPT
FWPT
FGOR
FOE
FVPT
FVIT
FOVIS
FGVIS
FODEN
FPR
FOPR
FGPR
FVIR
FVPR
WWCT
/
RUNSUM
EXCEL
SEPARATE
TCPU
ELAPSED



--=================================================================
SCHEDULE

--
RPTSCHED
    PRES   SWAT    /
--
--                        WELL            WELL                LOCATION          BHP                 PREF.
--                      NAME            GROUP                I    J              DATUM               PHASE
WELSPECS
                         PROD             G1                  2    2             8000                OIL    /
                          INJ             G2                  14   14                     8000                 GAS  /
/
COMPDAT
           PROD      2           2           1           6          OPEN       2*          1 /
            INJ     14          14           1           6          OPEN                   2*          1 /
/

--                      WELL   STATUS             CONTROL              TARGET RATES or UPPER LIMITS
--                      NAME                 MODE            OIL   WAT   GAS   LIQ            RV         BHP
WCONPROD
                        PROD              OPEN       LRAT                3*                    8000       /
/


--                    WELL     FLUID     STATUS              CONTROL             TARG                BHP
--                     NAME   TYPE                                      MODE              RATE                 LIMIT
WCONINJE
                      INJ        GAS       OPEN                        RATE                  13000     /
/

TUNING
           /
```

```
        /
  2*    150     /


TSTEP
21*200  /

END
```

APPENDIX 3

DATA FILE FOR MISCIBLE FLOODING FOR PARALLEL GRID ORIENTATION

```
--===================================================================

RUNSPEC
TITLE
   Miscible Flood Model 3D (Parallel)

DIMENS
   13   13   3     /

OIL
GAS
WATER

FIELD
MISCIBLE
  1   1*  TWOPOINT /
NINEPOIN
TABDIMS
    1    1   100 100   3 /

REGDIMS
    1   1   /

WELLDIMS
    2   4    2    1 /

START
   1 JAN 2007  /

NSTACK
  20 /

UNIFOUT


--=====================================================================
GRID

BOX
1   6   1    1   1   3  /
EQUALS
  ACTNUM  0  /
/
ENDBOX

BOX
1   5   2    2   1   3  /
EQUALS
  ACTNUM  0  /
/
ENDBOX

BOX
1   4   3    3   1   3  /
EQUALS
  ACTNUM  0  /
/
ENDBOX

BOX
1   3   4    4   1   3  /
EQUALS
  ACTNUM  0  /
/
```

```
ENDBOX

BOX
 1  2  5  5  1  3/
EQUALS
  ACTNUM  0  /
/
ENDBOX

BOX
 1  1  6  6  1  3  /
EQUALS
  ACTNUM  0  /
/
ENDBOX


COPYBOX

  ACTNUM  1  6  1  1  1  3   8  13   1   1  1  3 /
  ACTNUM  1  6  1  1  1  3   1   6  13  13  1  3 /
  ACTNUM  1  6  1  1  1  3   8  13  13  13  1  3 /

  ACTNUM  1  5  2  2  1  3   9  13   2   2  1  3 /
  ACTNUM  1  5  2  2  1  3   1   5  12  12  1  3 /
  ACTNUM  1  5  2  2  1  3   9  13  12  12  1  3 /

  ACTNUM  1  4  3  3  1  3  10  13   3   3  1  3  /
  ACTNUM  1  4  3  3  1  3   1   4  11  11  1  3  /
  ACTNUM  1  4  3  3  1  3  10  13  11  11  1  3 /

  ACTNUM  1  3  4  4  1  3  11  13   4   4  1  3 /
  ACTNUM  1  3  4  4  1  3   1   3  10  10  1  3  /
  ACTNUM  1  3  4  4  1  3  11  13  10  10  1  3  /

  ACTNUM  1  2  5  5  1  3  12  13   5   5  1  3 /
  ACTNUM  1  2  5  5  1  3   1   2   9   9  1  3 /
  ACTNUM  1  2  5  5  1  3  12  13   9   9  1  3 /

  ACTNUM  1  1  6  6  1  3  13  13   6   6  1  3 /
  ACTNUM  1  1  6  6  1  3   1   1   8   8  1  3 /
  ACTNUM  1  1  6  6  1  3  13  13   8   8  1  3 /
/

EQUALS
  DX     252.5381  1   13   1   13   1  3/
  DZ     150   /
  PORO   0.2  /
  TOPS   8000  1  13  1  13  1  1  /
  PERMX  200  /
  PERMY  150  /
  PERMX  1000  1  13  1  13  2  2  /
  PERMY  800  /
/
COPYBOX
  PERMX  1  13  1  13  1  1   1  13  1  13  3   3 /
  PERMY  /
/
COPY
  PERMX  PERMZ  /
  DX     DY   /
/
MULTIPLY
  PERMZ  0.1  /
  DZ     0.33333  /
/

BOX
 1  1  7  7  1  3  /
EQUALS
 MULTPV  1.75  /
/
ENDBOX
BOX
  2  2  6  6  1  3 /
```

```
EQUALS
  MULTPV  1.5  /
/
ENDBOX

COPYBOX

MULTPV   1 1 7 7 1 3 13 13  7  7 1 3 /
MULTPV  1 1 7 7 1 3  7  7  1  1 1 3 /
MULTPV  1 1 7 7 1 3  7  7 13 13 1 3 /

MULTPV  2 2 6 6 1 3  3  3  5  5 1 3 /
MULTPV  2 2 6 6 1 3  4  4  4  4 1 3 /
MULTPV   2 2 6 6 1 3  5  5  3  3 1 3 /
MULTPV   2 2 6 6 1 3  6  6  2  2 1 3 /

MULTPV   2 2 6 6 1 3  8  8  2  2 1 3 /
MULTPV   2 2 6 6 1 3  9  9  3  3 1 3 /
MULTPV   2 2 6 6 1 3 10 10  4  4 1 3 /
MULTPV   2 2 6 6 1 3 11 11  5  5 1 3 /
MULTPV   2 2 6 6 1 3 12 12  6  6 1 3 /

MULTPV   2 2 6 6 1 3 12 12  8  8 1 3 /
MULTPV   2 2 6 6 1 3 11 11  9  9 1 3 /
MULTPV   2 2 6 6 1 3 10 10 10 10 1 3 /
MULTPV   2 2 6 6 1 3  9  9 11 11 1 3 /
MULTPV   2 2 6 6 1 3  8  8 12 12 1 3 /

MULTPV   2 2 6 6 1 3  6  6 12 12 1 3 /
MULTPV   2 2 6 6 1 3  5  5 11 11 1 3 /
MULTPV   2 2 6 6 1 3  4  4 10 10 1 3 /
MULTPV   2 2 6 6 1 3  3  3  9  9 1 3 /
MULTPV   2 2 6 6 1 3  2  2  8  8 1 3 /

/

--==================================================================
PROPS
--          OIL    WAT    GAS
DENSITY
            49    63     0.01  /

SDENSITY
  0.1159  /
--
--      P      Bo       Vis
PVDO
       300     1.25     1.0
       800     1.2     1.1
       6000    1.15    2  /
--
--  PREF    COMPR
ROCK
   4500    4E-06  /
--
--  SWAT      KRW      KROW      PCOW

SWFN
   0.25      0             4
   0.5       0.2           0.8
   0.7       0.4           0.8
   0.8       0.55          0     /

SORWMIS
 0           0.0
 1.0         0.0 /


SOF2
 0           0
0.15         0
0.19         0
0.25         0.05
0.31         0.1
0.34         0.13
```

```
0.3885     0.16
0.4433     0.2
0.4967     0.3
0.5567     0.43
0.5949     0.54
0.646       0.7
0.6949     0.84
0.74        0.98
0.75        1     /


PVTW
   4500    1.02    3.06E-06    0.8 /
PVDG
200         17.08380866          0.018
2000       1.145811194          0.026
3000       0.690046089          0.04
4000       0.547804063          0.051
/
TLMIXPAR
 0.667 /


--======================================================================

SOLUTION
--
--    DATUM   Pi@DATUM   WOC    Pc@WOC    GOC  Pc@GOC
EQUIL
       8075   4500      8200     0       7950   0    /
--
RPTSOL
     PRES   SWAT   SOIL  FIP /

RPTRST


BASIC=2 ALLPROPS
/

--=========================================================================
SUMMARY
--

FGPT
FOPT
FWPT
FGOR
FOE
FVPT
FVIT
FOVIS
FGVIS
FODEN
FGDEN
FPR
FOPR
FGPR
FVIR
FVPR
RUNSUM
EXCEL
SEPARATE
TCPU
ELAPSED

--=========================================================================
SCHEDULE


--
RPTSCHED
     PRES   SWAT    /
--
--       WELL  WELL   LOCATION   BHP    PREF.
```

```
--      NAME  GROUP   I    J   DATUM   PHASE
WELSPECS
       PROD   G1    1    7    8000    OIL    1*   1*  /
        INJ   G2    13    7    8000    GAS  /
/
COMPDAT
       PROD   1   7   1   3   OPEN    2*   1 /
       INJ   13   7   1   3   OPEN    2*   1 /
/

--      WELL   STATUS  CONTROL   TARGET RATES or UPPER LIMITS
--      NAME           MODE    OIL   WAT   GAS   LIQ   RV   BHP
WCONPROD
       PROD    OPEN    BHP  5*  4300     /
/


--      WELL   FLUID   STATUS  CONTROL   TARG       BHP
--      NAME   TYPE            MODE     RATE      LIMIT
WCONINJE
        INJ   GAS    OPEN      RATE  10000   /
/
TUNING
/
/
2*  200 /

TSTEP
0.2  0.3 0.5 5  10  24  60  10*100  11*300  5*500  /

END
```