Application of Streamline Simulation to Gas Displacement Processes

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ABSTRACT

Performance evaluation of miscible and near-miscible gas injection processes is available through conventional finite difference (FD) compositional simulation. Streamline methods have also been developed in which fluid is transported along the streamlines instead of using the finite difference grid. In streamline-based simulation, a 3D flow problem is decoupled into a set of 1D problems solved along streamlines. This reduces simulation time relative to FD simulation, and suppresses the numerical dispersion errors that are present in FD simulations. Larger time steps and higher spatial resolution can be achieved in these simulations. Thus, streamline-based reservoir simulation can be orders of magnitude faster than the conventional finite difference methods. Streamline methods are traditionally only applied to incompressible flow processes. In this paper, the method is adopted and assessed for application to compressible flow processes. A detailed comparison is given between the results of conventional FD simulation and the streamline approach for gas displacement processes. Finally, some guidelines are given on how the streamline method can potentially be used to good effect for gas displacement processes.

1. INTRODUCTION

The Finite Difference (FD) method is widely used for solving large-scale multiphase displacement problems (e.g. displacement of oil by water/gas in heterogeneous petroleum reservoirs) [1]. While FD simulation has many advantages, it also suffers from some disadvantages. These include numerical dispersion, grid orientation, small time step size and excessive computation time. In addition, and specifically for compositional simulation, low-resolution compositional simulation is adversely affected by numerical dispersion and may fail to represent geological heterogeneities adequately, while high-resolution simulation may be expensive in computation time. The number of fluid components can possibly be reduced but only at the price of less accurate representation of the phase behavior. Partly to overcome such problems, streamline methods have been developed in which fluid is transported along streamlines instead of through a finite difference grid.

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Larger time steps and higher spatial resolutions may readily be achieved using this simulation technique [2].

A simple definition of a streamline is a path following the instantaneous fluid velocity within a reservoir system. Streamlines define these flow paths and then model the fluid displacement along them by generating numerical solutions to the governing fluid equations in one dimension. Hence, capturing the physics of the process occurred inside the reservoir. This technique decouples the computation of saturation and the pressure variation in time and space [4]. Using a FD method, the pressure field is initially solved for a specific time step, which is independent from that used in the saturation solution. The velocity field is then computed from the pressure field and the streamlines are traced according to the method of Pollock [15]. The new saturation field is then updated several times, usually using smaller time steps than that originally used for the pressure field. The streamline process is simply described using the schematic diagram shown in Figure 1.

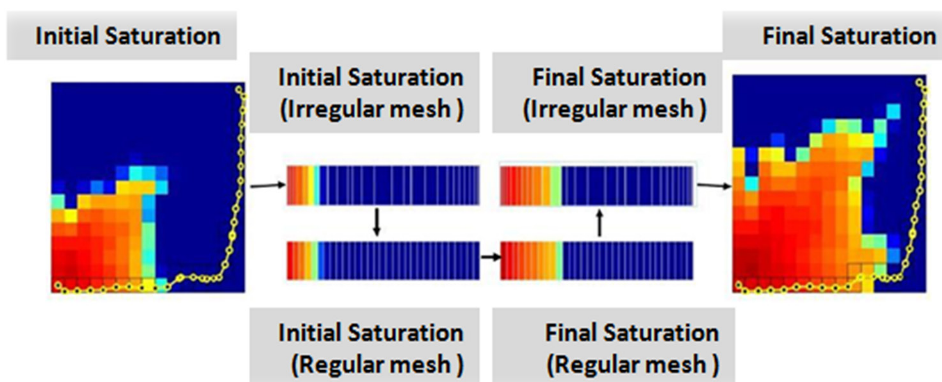

Figure 1: Schematic Diagram of the Streamline Saturation Process Solution [6].

There are many advantages to implementing SL simulation for reservoir modeling. One of these advantages is the computational speed which initially attracted reservoir engineers to this technology. This is mainly due to the fact that the 1D transport calculations are not constrained by grid size and therefore allow the use of larger time steps. The streamline simulation has been reported to be up to 3 times faster than the conventional FD simulation [8]. In streamline simulation, the number of time steps is independent of the model size, heterogeneity, and any other geometrical description of the 3D model, and it is mainly a function of the number of well events and the displacement fluids. For compressible systems, generally smaller splitting steps need to be taken because of the stronger coupling [4]. Gas displacement processes are one of the critical areas in SL simulation, as the compressibility remains a significant issue. Crane et al [26] used 1D fully implicit solutions of FD simulation to solve for pressure and fluid compositions together along each streamline, and account for the changes of the phase behavior that depend on the changes in pressure. It was tested and compared against FD compositional simulator using the SPE 9 Model. This work on SL showed that it is significantly faster and require less memory. Tanaka et al. [27] developed a 3D 3 phase compositional simulator for CO2 injection accounting for both gravity and capillary effects using orthogonal projection. This proposed approach enables larger time steps to be taken compared with conventional operator splitting. The results showed a good agreement and more efficient in comparison to the FD compositional simulator.

Our focus is to study the feasibility of streamline applications for gas displacement processes in more detail. SL represents a reservoir dynamic response to the fluid velocity field (defined here as the total multiphase Darcy velocity divided by the porosity) through strict observation of differences in area pressure. This concept is more simply represented in the term "Time of Flight". Time of flight is the time taken for a flux line, or a pressure response, to move from one point to another. In this way, fluid leaving an injector for example can be tracked, and fluid velocity can be monitored, particularly in regions of higher permeability, where a fast-moving tracer will lead for instance to early arrival [5]. The base case assumption in SL simulation is that the fluid compressibility is zero, since water is used as the displacing fluid. On the other hand, in conventional compressible fluid flow, the effects of compressibility are negligible for flows with Mach number less than 0.3 [2]. Therefore, in view of the large advantage of SL over FD in terms of CPU usage, we are motivated to determine classes of compressible flow problems which may be amenable to solution by SL. The main objective of this research is to minimize the differences between FD and SL in gas injection cases. This can be done by running a series of sensitivity studies for the streamline case, using tuning factors, until a reasonable match is obtained. The sensitivities are based upon many factors, such as the number of streamlines, tracing the SL and the saturation equation solver for each streamline. There are three available saturation solvers that can be used as follows: Front tracking, Finite difference and Gravity segregation [4].

3D black oil streamline models are constructed and integrated with an existing FD simulator to study water flooding by injecting water inside the reservoir as a secondary recovery technique, WAG (water alternating gas) via injecting water then gas inside the revoir in a cyclic period, and gas injection in a heterogeneous five spot pattern. The 3D multi-component material balance equation is decomposed into 1D equations along the SL using the streamline time of flight as the spatial coordinate. The pressure field is solved in the conventional FD manner and streamlines are traced from injector to producers. Gravity effects are added using an operator splitting technique to account for the gravity segregation due to density differences. Conversely, the streamline method is not well suited to complex physics displacements (high compressibility, capillary effects, complicated phase behavior). Indeed, there is no one numerical method that can efficiently solve the governing equation for all cases. In this work, both FD and SL employ the same PVT (Pressure, Volumes and Temperatures) data tables in both cases, with the gas being slightly compressible in the base case gas injection model. The same base mesh was used for FD and for the pressure solution of SL. In addition to that, all models have the same amount of oil in place and numbers of producers and injectors. Well constraints are the same in all models and these are mainly to have fair and reasonable comparisons.

Our aim is to produce some guidelines on how to use SL simulation for Gas Displacement processes for improved oil recovery. SL represents a reservoir dynamic response to the fluid velocity field (here, the total multiphase Darcy velocity divided by the porosity) through strict observation of the differences in area pressure/spatial representation.

2. OBJECTIVES AND METHODOLOGY OF THE RESEARCH

The objectives of this investigation are to evaluate the performance of SL simulation techniques in situations where it is not normally used. Also, we provide guidelines as to when we can use SL simulation in such uncommon cases for SL simulation. To achieve the objectives of this research, several injection methods were tested, such as water injection, water alternating gas and gas injection. Streamline technology has been proven for waterflood applications especially above the bubble point. We used the commercial FD simulator (Eclipse 100) and streamline simulator (FrontSim) for comparison. The main objective is to quantify the differences between FD simulations and SL simulations under a variety of conditions, especially for gas injection processes. In each comparison run, simulation results were analyzed, graphs were generated, interpreted and subsequently results were compared. The results were compared in detail to capture any differences in total volume of production, rates of production at each producer, and rates of injections, etc. The two simulator performances were compared by capturing the number of time steps, frequency of pressure field updates, linear and non-linear iterations, and CPU time. In the following sections, we present the results of three modeling cases chosen to show the comparisons.

3. MODEL DESCRIPTION

The model used for this investigation was developed from the original Tenth SPE Comparative Solution project (Christie and Blunt, 2001). The Original Tenth SPE Comparative Solution Model was developed with a Dead Oil PVT structure. The model consists of a 5-spot pattern (i.e., four producer wells placed at each corner of the reservoir and one injector at the center). The model has a simple geometry, with no variation in the top structure and no faults. At the fine geological model scale, the model is described on a regular Cartesian grid. The model is described on a regular Cartesian grid with 15x55x17 (14025) grid cells and it consists of two formations: Tarbert formation in the top 10 layers, where the permeability is relatively smooth, and a fluvial Upper-Ness in the bottom. The two formations contain large permeability variations, approximately 10 orders of magnitude as can be seen in Figure 2. Also, the most heterogeneous structure is in the Upper-Ness formation. The model was adapted for different secondary recovery techniques, e.g., Water Injection, Water Alternate Gas (WAG) and Gas Injection, as per the objective. All models have the same number of grid cells namely, 14,025 cells as described earlier, PVT, rock properties, and fluid densities. For the case of gas injection, the model becomes a three-phase run (i.e., water, gas and oil phases). Since we consider a three-phase fluid description for gas injection, live oil (i.e., dissolved gas with oil) was used. Well completion and operation constraints for the four different models remain the same, with simulation periods over the same duration of time. Figure 2 represents a 3D Model with the permeability distribution and well configurations as for the Tarbert formation. Four oil producers and one injector comprises one 5- spot pattern, all the four producers are completed in all vertical grid cells.

i. Water Flood Model

In this case, the model was developed to improve the production of this heterogeneous reservoir using water injection. Having observed the steady depletion of production of the four producers over a 6 years production period, considering the nature of the reservoir, being more of a water drive reservoir, a probable solution was to adopt the water flooding or water injection as the first measure to tackle the problem of improving the oil production.

Figure 3 shows a comparison of the oil production and the total oil production of both the finite difference (FD) and the streamline (SL) simulations of the water flood models. As can be seen, there is a very good match between the two different models with no major differences on the performance predicted using the two different simulation methods.

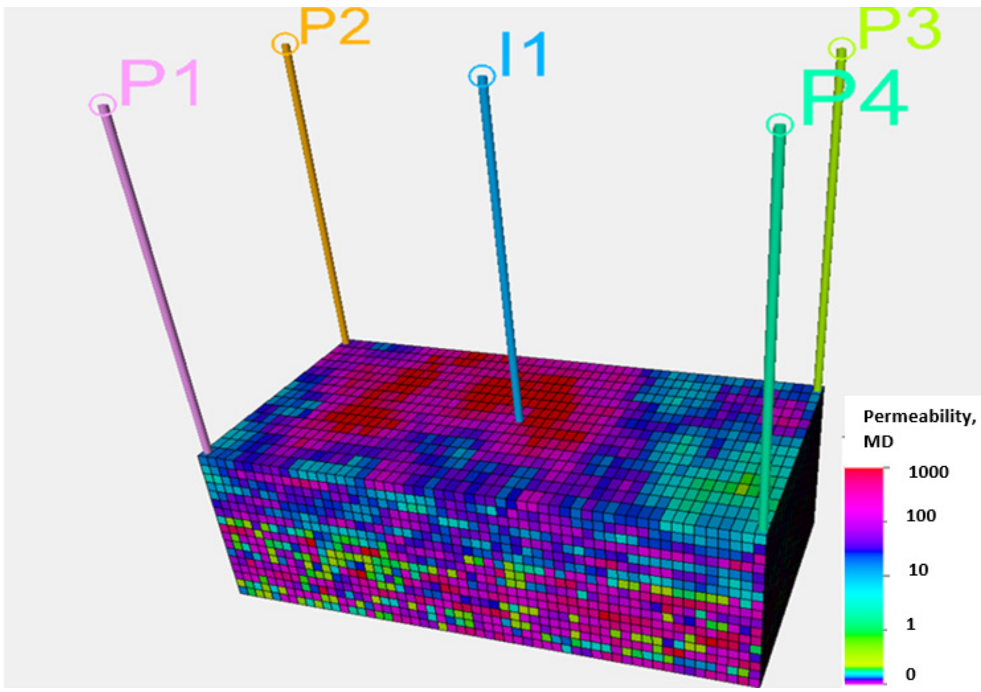

Figure 2: 3D Permeability Distribution and Well Configurations for the Tarbert Formations of 14025 Grids SPE 10 model (15x 55 x 17).

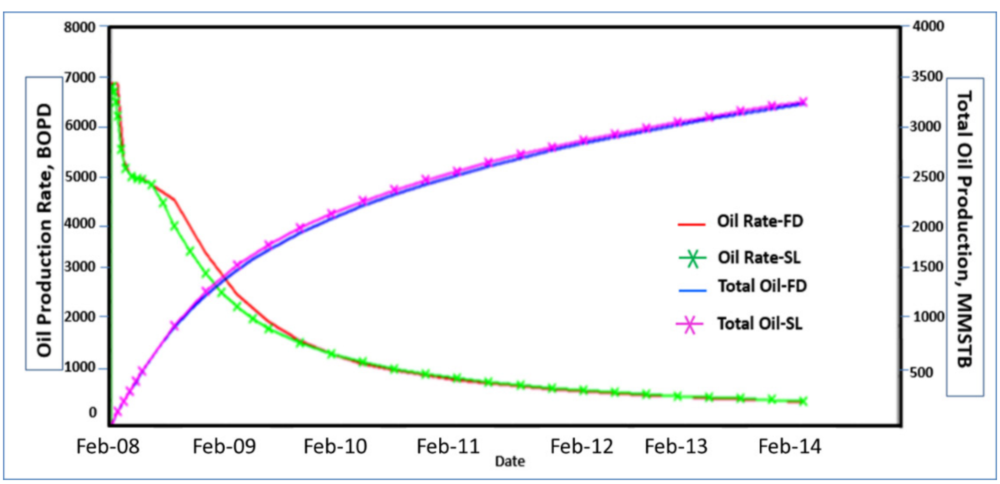

Figure 3: Oil Production Profile for both FD and SL Waterflood Model.

ii. Water Alternating Gas (WAG) Models

This model was also modified from the initial water flooding model. In this model, we considered the alternation of both water and gas injection into the reservoir to achieve increased recovery. With the WAG injection, cumulative oil production of 2.4 million barrels over a 6 year period was achieved. Water was initially injected for a duration of 90 days to understand the effect of displacement of oil in the reservoir, and a cumulative of over 600,000 barrels was achieved. Gas was later injected into the reservoir for the same number of days. Gas injection yielded a cumulative of over 158,000 barrels. Both injections were alternated subsequently for the next six years with injection periods of 90 days each. Oil production profiles for WAG models are presented in Figure 4.

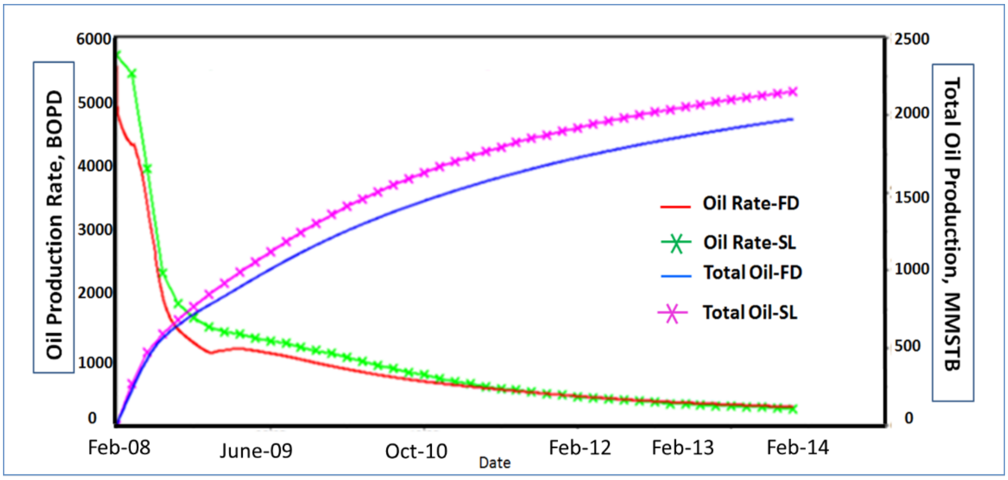

Figure 4: Oil Production Profile for Water Alternating Gas Injection(WAG) Model.

iii. Gas Injection Models

The initial model set up was the same as the original SPE10 water injection scheme, except the gas is to be injected instead of water, but all other model parameters are same as the water flood model: completion intervals, well placements, the PVT data and relative permeability curves used are the same. A 3D rectangular reservoir model is investigated on the SPE 10 model and the grid dimensions are 17*55*15 grid blocks. Figure 5 shows oil production performance for both the SL and FD models and as per the plot, the stream line model runs only for six months of the production before the model stops running.

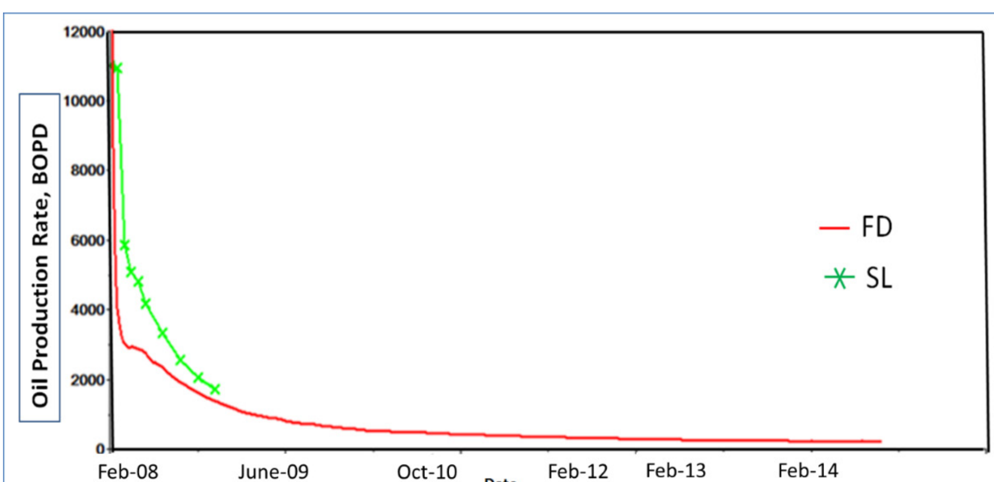

Figure 5: FD Vs SL Oil Production Rate of the Initial Case of the Gas Injection Model Results.

A subsequent analysis showed that there is a material balance problem in the model, when gas can no longer be injected into the reservoir with the properties of the dead oil initially characterized in the water injection case. At sufficiently low pressure, the oil does not contain dissolved gas or a relatively thick oil or residue that has lost its volatile components. The dead oil PVT and relative permeability responses no longer allow the injection of the gas into the reservoir and hence the oil can no longer be displaced. It was concluded that dead oil cannot be used in streamline simulation for the case of gas displacement processes.

Live oil was then used and indeed the flow dynamics in the reservoir is improved considerably, so that the streamline model could be run for the same period as the FD simulator. Figure 6 shows the comparison between the two simulators after the adjustment of the relative permeability curves used in the live oil model. The plot shows the oil saturation distribution for the FD model versus the SL simulation model. As can be seen, the streamlines reveal gas displaced from injector to producers.

Performance of FD against SL is also presented in Figure 7 for the oil production profiles. As can be seen from the graph, there were still mismatches in terms of oil rate and all other vectors calculated by SL.

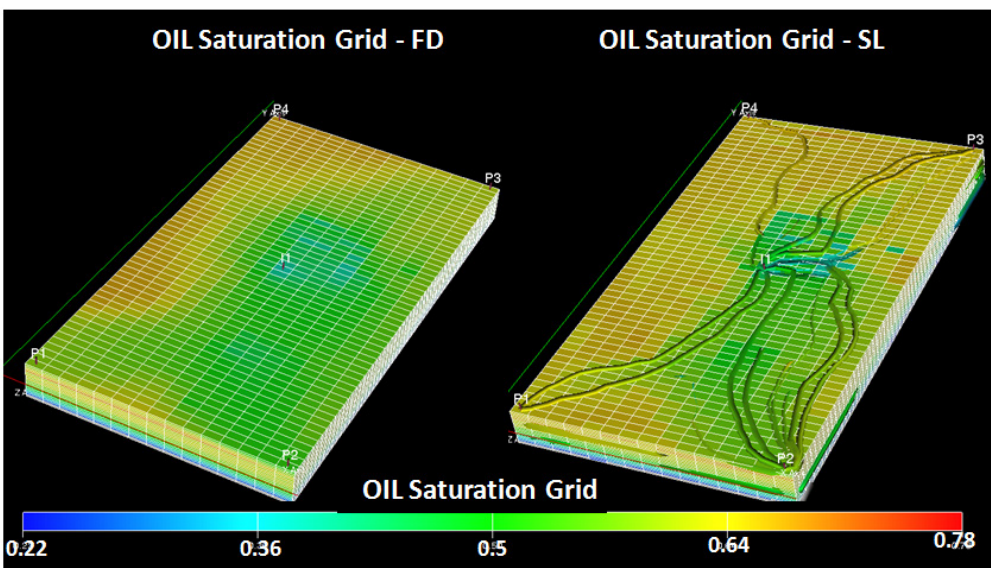

Figure 6: Oil Saturation Displayed Grid for both FD and SL Gas Injection Models at First time step after Initialization.

There is a mismatch in the oil rate right from the start date. The streamline simulation shows similar maximum scaling of the oil rate. However, there is enhanced oil production (the area under the rate graph) compared to the FD model in the early period of simulation time, for approximately the first 100 days. After 100 days the SL streamline oil rate decreases more quickly in this ‘middle period’. At around 1000 days the rates begin to converge again in a classic asymptotic decline pattern. In the following section we investigate and explain how the flow regimes inside the models are different, and what is required to improve the flow in the streamline model in order to minimize the differences between FD and SL. For gas injection will focus on matching and the fine tuning of the streamline simulation model, quantifying and analyzing the differences and trying to minimize them to be within the applicable limits such as the water injection streamline case. This can be done in two ways. Firstly, analyzing how SL simulation works and the implications of the gas displacement process on the fluid movement into the reservoir. Secondly, understanding the parameters and controlling factors in the simulation in order to improve the flow and minimize the differences, then an acceptable match can be reached. It was concluded that SL time steps calculations and reporting is still not capable of matching the FD results, as FD is able to report and handle any required time steps. To control this and to improve the SL calculation, additional tuning improvements and fine controlling of the time steps are still required to reach an acceptable level of match. Therefore, in order to enhance the match, additional control parameters were introduced from FD to SL and sensitivities were performed. For example, the initial rates and large numbers of time steps help to improve and minimize the error differences between FD and SL. A series of iterations and sensitivities have been performed.

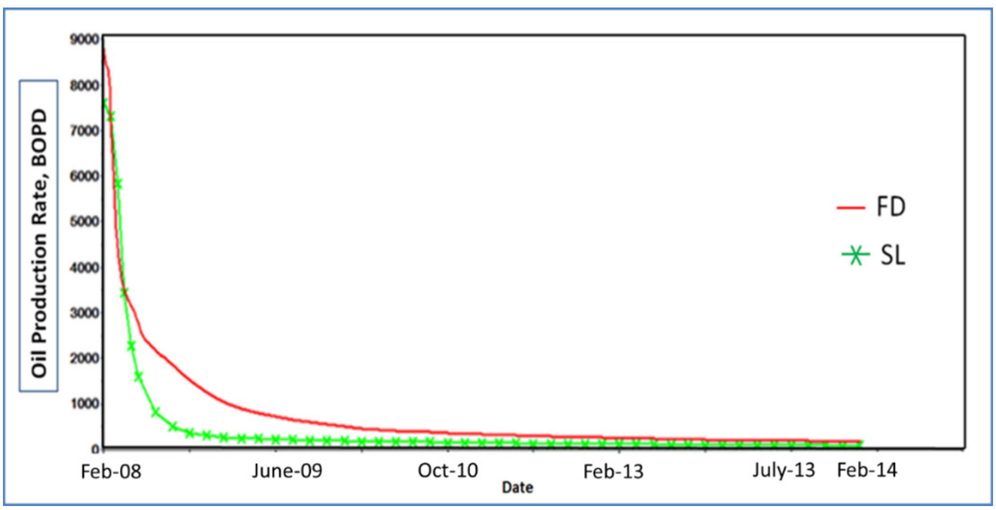

Figure 7: Oil Production Profile for both FD and SL (Live Oil) of the Base Case Gas Injection.

3.1. Detailed Gas Injection Model with Fine Tuning

Streamline simulation is based on a sequential approach. The pressure solution is calculated at the end of the time step based on the saturations at the beginning of the time step. The boundary conditions are generally based on open wells with given rate targets and limits, aquifer modeling, pressure boundaries, and flux boundaries defined by the user. The sensitivities are based upon many factors and reasoning such as; Gravity Segregation and Number of streamlines. A series of sensitivities were performed using the tuning options. Table 1 and Figure 8 shows the sensitivity results on parameter 2 and the impact on oil production rate and how the rate improved and the difference. The sensitivities mainly were done using the options TUNESFSSA.

The next section describes the work that was performed in order to condition the fluid regime in the streamline simulation model and how the best match was achieved. A series of sensitivities were performed using the tuning options described in the previous section, and the graph below shows the results and the impact on oil production rate and how the rate improved and the difference. The sensitivities mainly were done using the options TUNESFSSA. Figure 9 shows the sensitivity results and comparisons of the oil production rate versus time using streamline simulation with different tuning and controlling parameters. The comparisons are always made against the FD simulation results.

These are the tuning parameters normally used in SL as simulation control output tuning. However, FD simulation does not need such tuning. The details of these tuning parameters and their impacts are presented in Table 3 Appendix B. Several iterations were performed on these tuning parameters in order to assess/determine the most one affecting SL simulation performance and results.

As per the results presented in Figure 9, a final acceptable degree of match has not yet been obtained (less % relative errors between FD and SL), and according to the analysis of these results, it was concluded that SL time steps calculations and reporting is still not capable to match FD results, as FD is able to report and handle any required time steps. To

Table 1: Streamline simulation control output tuning parameters:

TUNESSFA	Parameter	Value used
1	Gravity Segregation, Default is 1	1
2	StreamDens, number of streamline used by saturation solver	0.7
3	StreammapNs, number of streamlines used in a cell Default is 0, recommended 0	Default
4	StreammapNi, Number of sampling points Default is 0, recommended 10	Default
5	Addlines, When set, FrontSim checks whether each cell has been visited by at least one streamline	Yes
6	Reserved for future use.	No
7	FluxMult, This multiplier adjusts the threshold flux, Default is 1	Default (1)
8	StartType:where to start tracking streamline, either INJ , PROD, or Both	Default (Both)

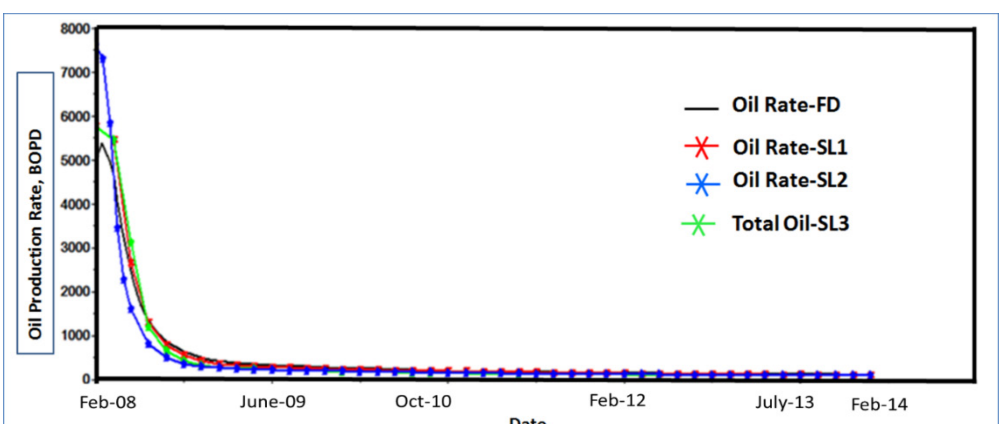

Figure 9: Sensitivity Results (Oil Production Profile) for FD and SL Simulation Models.

control this and to improve the SL calculation, additional tuning improvements and fine controlling of the time steps is still required to reach an acceptable level of match with less % relative error. So, in order to enhance the match, additional control parameters were introduced from FD to SL and sensitivities were performed. For example, the initial rates and large numbers of time steps help to improve and minimize the error differences between FD and SL.

3.2. Gas Injection Model Results

A special program was developed in order to properly define and quantify the difference between the FD and SL simulations. It was mainly used as a post processor for the simulation results and mainly to quantify and plot the error difference between the two separate runs. Another development was subsequently added on how old and new sets of runs can be evaluated simultaneously and showing a comparison before and after the sensitivities. In the following series of graphs, a full evaluation and comparisons between the FD and SL simulations for gas displacement processes are presented.

The program creates a new vector for each parameter calculated on the dynamic simulation (e.g. oil production rates, cumulative oil production, gas production rates, cumulative gas production, gas injection rates, gas injection totals and field pressures). Then, we will be able to evaluate, assess and quantify the error difference between the FD and SL simulations.

Figure 10 represent a comparison of the relative error for the oil production rates in the initial runs setup and the final matches in both the FD and SL models. The red line represents the difference in the oil production rate on both models initially and the average is about 60%. However, the black line represents the final match with the required fine tuning explained earlier in the previous section and the relative error is 5 to 10%. For the total oil production, Figure 11 illustrates the relative error and comparison between the initial model sets and the final model sets of both the FD and SL Models.

For the computational comparisons, Figure 12 represents a comparison between the total CPU time consumed in both the FD and SL simulations. The red line represents the total CPU time consumed for FD simulation, and black line represents the total CPU time consumed for SL simulation. As can be deduced from the graph below, the total CPU time consumed for SL simulation (represented by the black line) is merely 15 seconds compared to the 120 seconds of total CPU time consumed by FD simulation (represented by the red line). This eight-fold

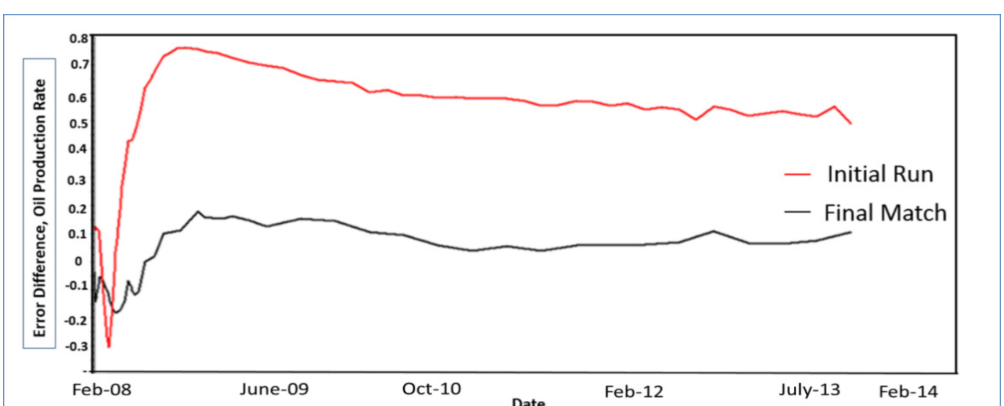

Figure 10: Analysis of The relative Error between the Initial Model Sets and Final Match Set for Field Oil Production Rates.

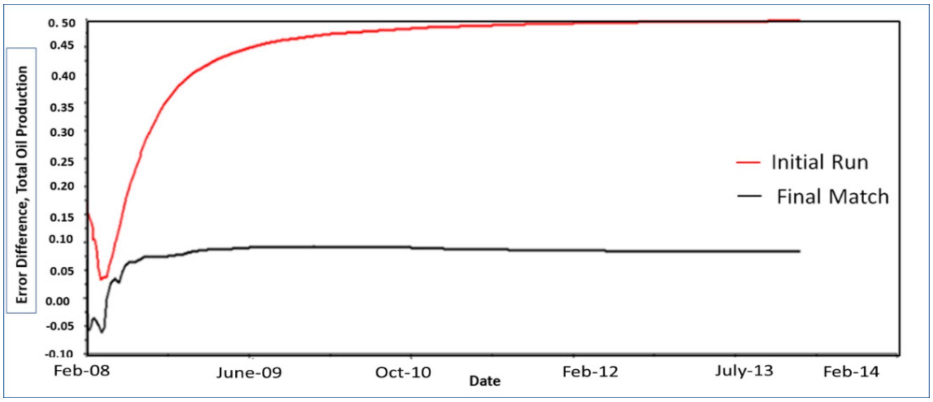

Figure 11: Analysis of the Error Differences between Initial Model Sets and Final Match sets of the Field Oil Production Totals.

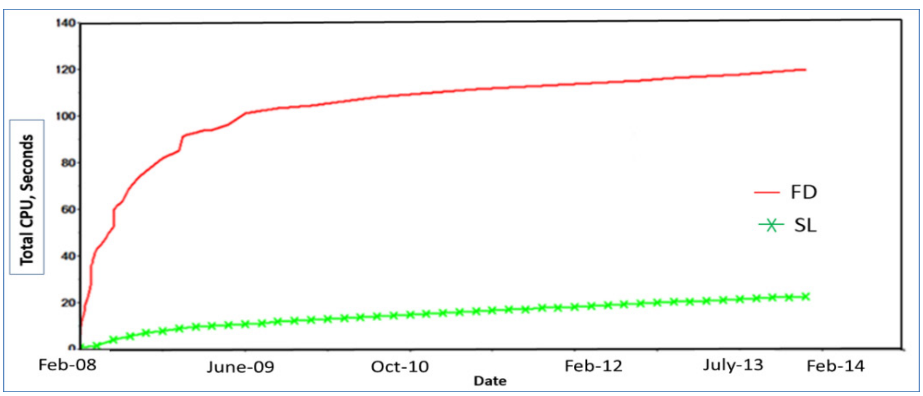

Figure 12: Total CPU for Gas Injection Model in the FD and SL Models.

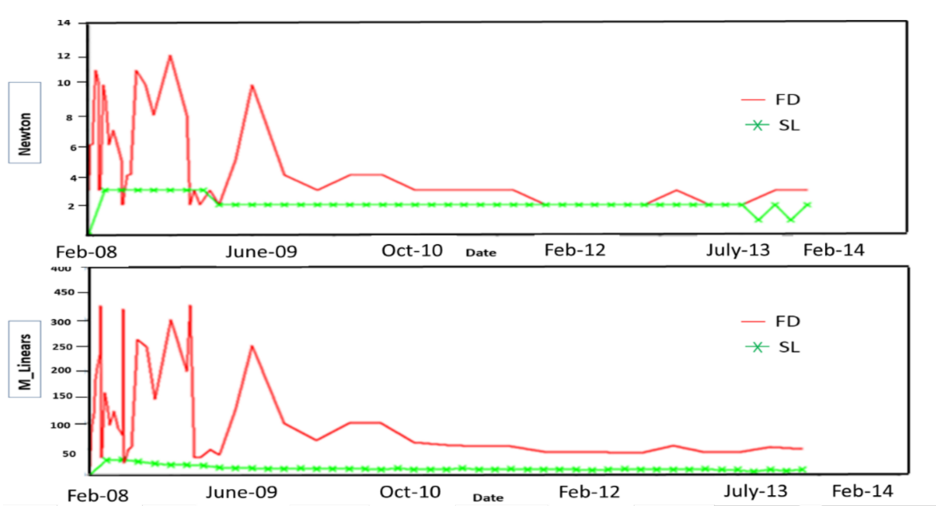

Figure 13: Total Number of Linear and Newton Iterations for FD and SL Models.

decrease in time goes to show that in this case, SL simulation is much more efficient than its counterpart FD in terms of CPU consumption.

For the model stability comparisons, Figure 13 shows the number of linear iteration (Lower chart) and the number of non-linear (Newton) iterations (Top chart) that were used by the equation solver of both FD and SL models. In this figure, the green line in both graphs indicates SL model and the red lines are for the FD model and the comparisons indicate that the SL model is more stable in comparison to the FD model.

3.3. Additional sensitivities:

3.3.1. Compositional Model

The base case gas injection model was modified to run in compositional mode in both conventional FD and SL simulation. PVT and relative permeability data in the base case were replaced by compositional data to test and evaluate SL accuracy in predicting production performance, and to compare the results with conventional compositional FD simulation. Table 1 represents compositional PVT data used, while Appendix C represents oil and gas relative permeability data used for the compositional modeling. Figure 14 represents the performance of compositional SL modeling vs FD compositional modeling and as can be seen in as can be seen in the graph the left plot is for oil production rate and black line represents SL. The red line is for FD, the same as total oil production on the right corner.

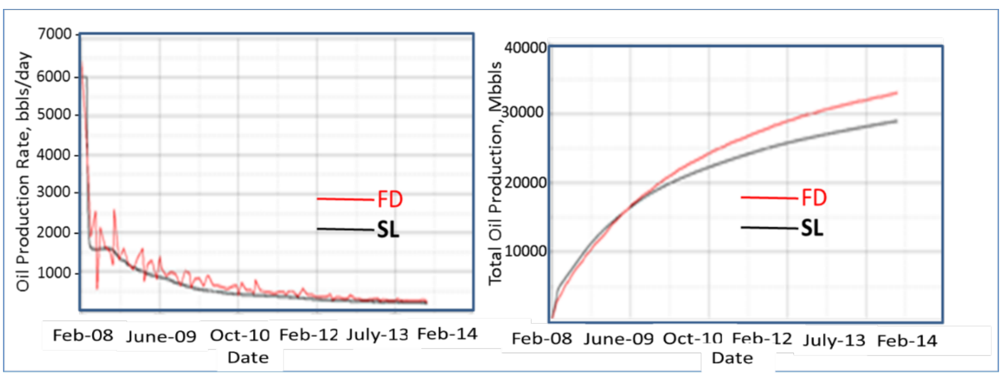

Figure 14: Comparisons between FD and SL Models Results for Compositional Modeling

3.3.2. Miscible Gas Injection Model

The miscible Enhanced Oil Recovery (EOR) process involves the use of supercritical CO2 to displace the oil from a depleted oil reservoir with suitable characteristics, typically light oil.

The injected miscible CO2 mixes thoroughly with the oil within the reservoir such that the interfacial tension with these two substances disappears. The CO2 has the ability to dissolve in, swell and then reduce the viscosity of oil. In our case, PVT and relative permeability data were replaced by a miscible gas injection set of data and tested on the model. On this data set we have to use the MISC keyword as it is required in runs which use the solvent option in miscible flood. The miscibility functions table is required also, which controls the transition from miscible to immiscible relative permeability. This table usually consists of two columns; one for the local solvent fraction and the second for the corresponding miscibility, and the scale from zero to one as it should be increasing upward. This means that first value must be zero and last value must be one. The local solvent fraction is shown in equation 1 below.

To model and characterize fluids in the simulators as miscible floods, the model needs to be adjusted to work on four different fluid phases. These phases are: Oil, Water, Gas and Dissolved gas. Appendix D represents the new relative permeability data set used for the miscible gas injection testing.

$$Local\ Solvent\ fraction\ = \left(\frac{S_{solvent}}{(S_{solvent}+S_{gas})}\right)\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

Figure 15 represents the performance of miscible flood SL modeling vs FD miscible flood modeling and, as can be seen in the graph, the left plot is for oil production rate and the black line represents SL and the red line represents the FD. As can be seen in the plots, both models have the same initial oil rate. However, the decline rate of the SL model is gentler in comparison to the FD model and this will result in a slight miss match in the total oil production. On the right, is the cumulative oil production forecasted in both cases FD and SL. As can be seen from the plot, the total oil production calculated by SL is slightly higher in comparison to the FD model and this mainly results from the miss match of the oil rate represented earlier.

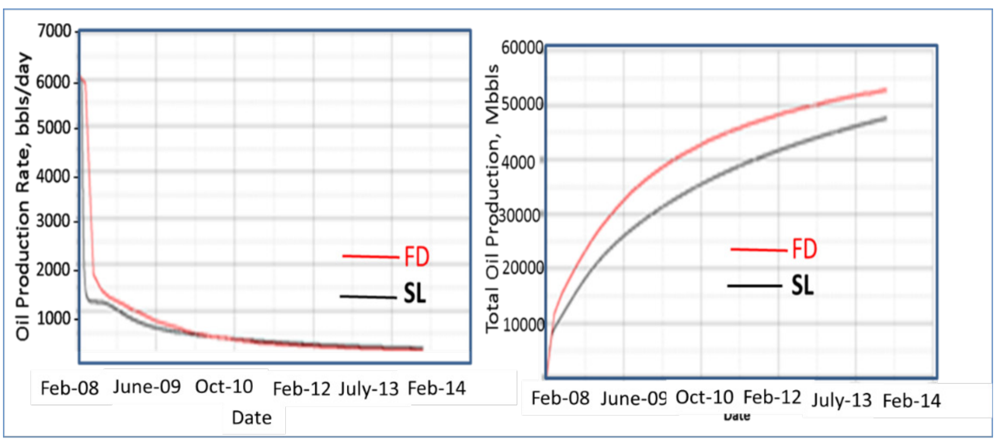

Figure 15: Comparisons between FD and SL Model Results for Miscible Flood Model.

Additional sensitivities were also performed for the gas injection model. These sensitivities covered the following: Depletion case (No Gas Injection), Different Gas Injection rates and Different Bottom Hole Pressures. The results of these sensitivities are presented in the following section.

3.3.3. Depletion case (No Gas Injection Model)

As a unique sensitivity study, a trial test was done to assess SL simulation calculation in the depletion case, which had not been done before, as generally SL simulation is used to track the fluid injection into the reservoir. In this sensitivity study, the gas injection rate for the gas injector was set to zero to represent the no gas injection case. Figure 16 represents the results of this run as the left plot represents oil production rates vs time, while the right plot is for total oil production. The black line represents the FD simulator. As can be seen in the graph, the red line represents SL simulation and the black line is for FD. Both FD and SL predicted oil rates honoring the same trend, but SL simulation predicted a higher rate in comparison to FD simulation. This mismatch was mainly because SL simulation is generally used to track the fluid displacement by another fluid, hence the time of flight will be calculated, and in this case, there is no fluid pushing the other fluid into the reservoir.

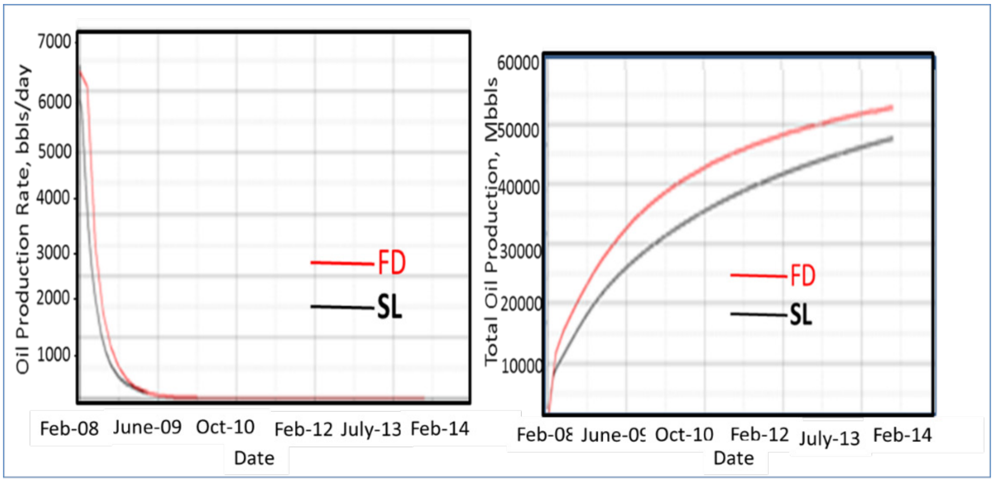

Figure 16: Comparisons between FD and SL Model Results for Depletion Case Model.

4. RESULTS AND ANALYSIS

Figure 17 represents the average error differences for the four different test simulation cases for oil rate, total oil production, gas production and gas injection rates. As concluded from the plot, the highest error difference was noticed from the no gas injection case model, which is acceptable as SL works mainly on the time of flight and flood front and in this case there was no fluid injected in the model. All other cases are within the acceptable limit.

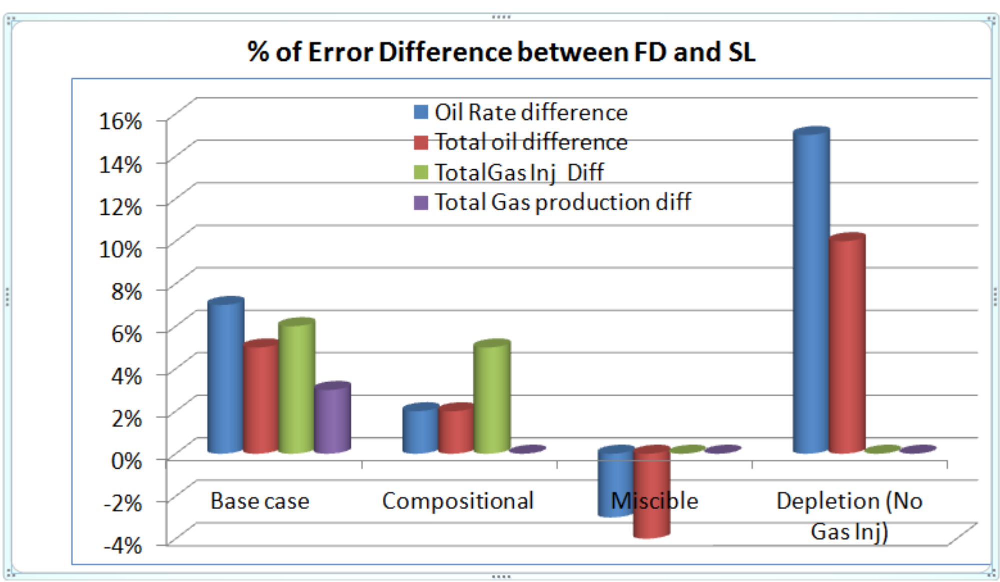

Figure 17: Comparisons of % of the Error Differences between FD and SL

To assess computational calculation times and simulator performance; Table 2 and Figure 18 below represent the total CPU consumed in the cases of FD vs SL in the four tested cases. As can be seen from the summary plots below in Figure 18, FD simulation consumed almost double of the CPU consumed by SL, as this is the main advantage of SL among FD as SL is more efficient in terms of energy requirements.

Table 2: Summary of Total CPU used by FD and SL

Case	TCPU, seconds - SL	TCPU, seconds - FD
Base Case	28	42
Compositional	280	440
Miscible	280	650

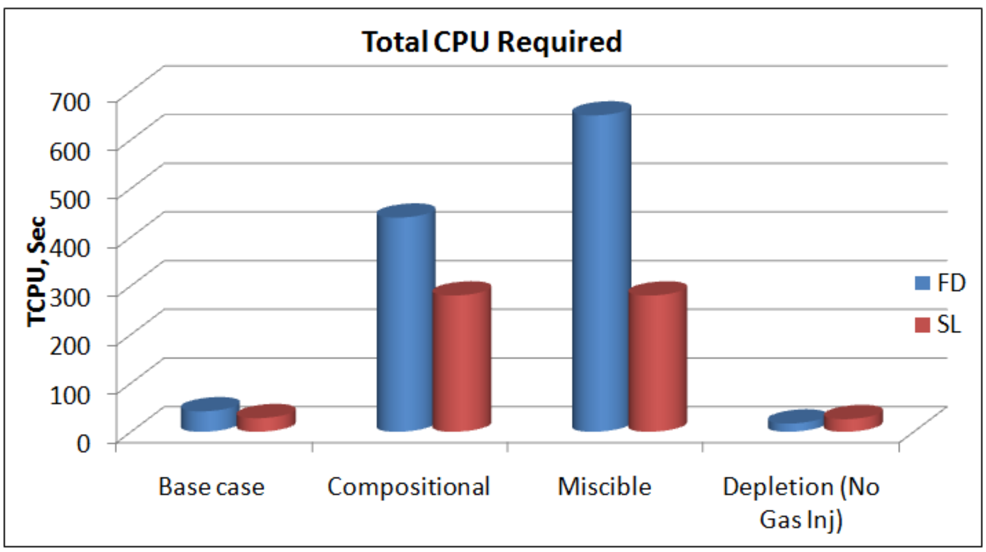

Figure 18: Comparison of Total CPU for Gas injection models in FD and SL.

Appendix A summarizes PVT and relative permeability input data and tuning parameters for streamline runs in addition to CPU comparison and calculated streams errors for the cases presented above.

5. CONCLUSIONS

This work indicates that streamline simulation can be potentially used for gas displacement processes. The cases investigated show that careful choice of the simulation tuning parameters helps in ensuring that we can still have the advantage of the speed of SL simulation, while not compromising the accuracy of the simulation results when compared with finite difference simulation. The evaluation criteria included the down-hole conditions, well productivities and simulator performance indicators. The CPU time requirements and numerical dispersion can be reduced significantly while allowing the engineer to use a finely gridded model that captures the heterogeneity of the reservoir.

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APPENDIX A

A- Model / Grid data

NX	DXV, Ft	NY, ft	DYV, ft	NZ	Dzv, ft
15	80	55	40	17	10

B- Fluids Data

1-PVT Properties of Live Oil

Ref Pressure, psia	Formation volume factor	Gas Oil Ratio	Viscosity, Centi Poise
3000	1.0985	1270	0.98

2-PVT Properties of Gas

Ref Pressure, psia	Formation volume factor	Viscosity, Centi Poise
3000	0.74	0.0165

3-PVT Properties of Water

Ref Pressure, psia	Formation volume factor	Compressibility	Viscosity, Centi Poise
3000	1.029	0.000316	0.31

4-Fluid Densities

Oil	Water	Gas
49.1	64.79	0.06054

C- Equilibrium data

Datum Depth, ft	Datum Pressure, Psia	Oil water contact, ft	Capillary Pressure at contact
12000	6000	12200	0

D-Well Configuration

Well	Type	Fluid	Well Location, Grid Cell I, J		Control Mode	Bottom Hole Pressure Limit, psia	Rate, Barrel per day oil or MSCF per day Gas
I1	Injector	Water or Gas	8	28	BHP	10000	5000
P1	Producer	Oil	1	1	BHP	4000	2000
P2	Producer	Oil	15	1	BHP	4000	2000
P3	Producer	Oil	15	55	BHP	4000	2000
P4	Producer	Oil	1	55	BHP	4000	2000

APPENDIX B

Table B1: Oil and Gas Relative Permeability Data (Dead Oil).

Water - Oil Relative Permeability			Gas to Oil Relative Permeability		
Water Saturation	**Water Relative Permeability**	**Capillary Pressure to Water**	**Gas Saturation**	**Gas Relative Permeability**	**Capillary Pressure to Gas**
0.0	0.0	0.00	0.20	0.000	1.00
0.04	0.0	0.20	0.25	0.007	0.84
0.10	0.02	0.50	0.30	0.028	0.69
0.20	0.10	1.00	0.35	0.062	0.56
0.30	0.24	1.50	0.4	0.111	0.44
0.40	0.34	2.00	0.45	0.17	0.34
0.50	0.42	2.50	0.5	0.25	0.25
0.60	0.50	3.00	0.56	0.34	0.17
0.70	0.81	3.50	0.60	0.44	0.11
0.78	1.0	3.90	0.66	0.56	0.06
			0.70	0.69	0.03
			0.75	0.84	0.07
			0.80	1	0.00

Table B2: Alternative Oil and Gas Relative Permeability Data Set used for the Base Case (Live Oil).

Water - Oil Relative Permeability			Gas to Oil Relative Permeability		
Water Saturation	**Water Relative Permeability**	**Capillary Pressure to Water**	**Gas Saturation**	**Gas Relative Permeability**	**Capillary Pressure to Gas**
0.22	0	7.0	0.00	0.00	0.0
0.30	0.07	4.0	0.04	0.00	0.2
0.40	0.15	3.0	0.10	0.02	0.5
0.50	0.24	2.5	0.20	0.10	1.0
0.60	0.33	2.0	0.30	0.24	1.5
0.80	0.66	1.0	0.40	0.34	2.0
0.90	0.83	0.5	0.50	0.42	2.5
1.00	1.00	0.0	0.60	0.50	3.0
			0.70	0.81	3.5
			0.78	1.00	3.9

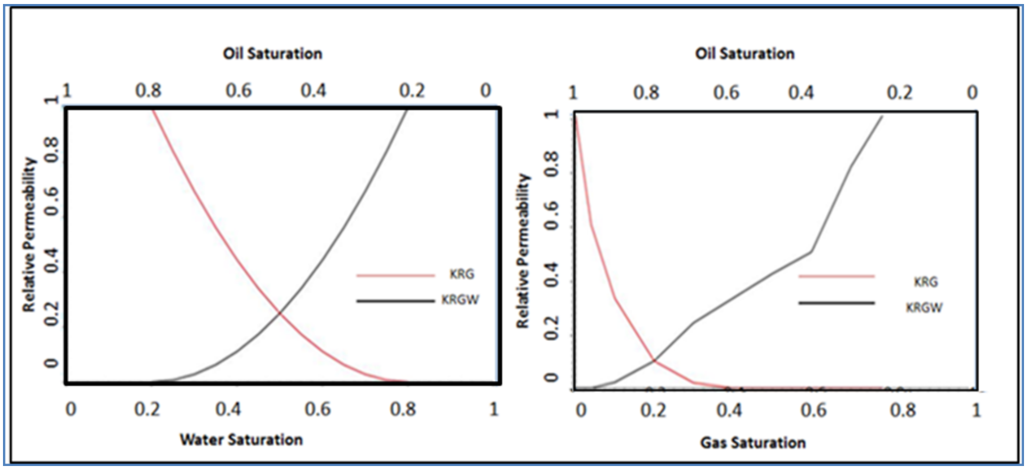


Figure B1: Oil and Gas Relative Permeability Data Set used for the Initial Run (Dead Oil).

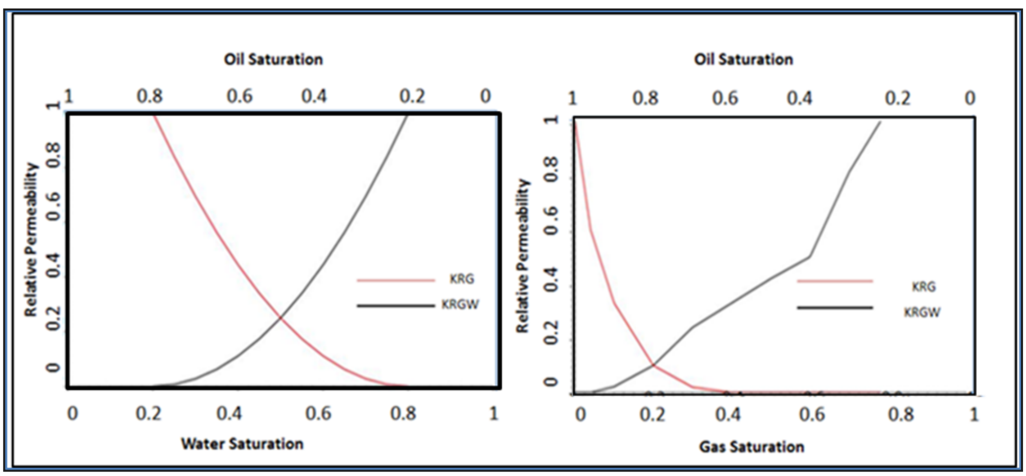
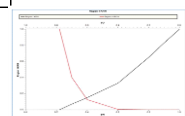
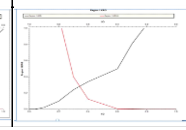
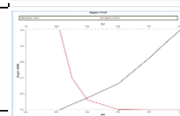
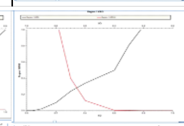
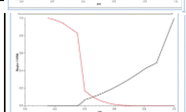
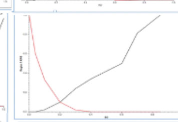
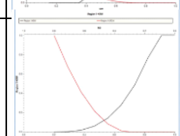
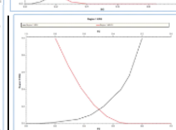


Figure B2: Live Oil and Gas Relative Permeability Data Set used for the Initial Run (Dead Oil).

Table B3: Summary of the models input data

	Model Description	PVT			Rel Perms		SL Tuning Paramateres for Sturation solver TUNEFSSA						TCPU		Error Difference %			
		Oil	Water	Gas	KROW	KRGO	Gravity Segregation	Stream Dens	StreamMaps Ns	StreamMaps Ni	Add Lines	Reserved for Future used	FD	SL	Oil Rate	Total oil	Gas rate	Gas Inj
Base Case	Tenth SPE Comaprative Solution Project, with 15x55x17 coarse grid, Live oil /Dissolved Gas 5 spot pattern 4 Oil producers 1 gas injector	Density 45	Density 63.02 Ref Press 3000 Bw 1.00341 Compressiblity 3.0D-6 Viscosity 0.96	Density .0702			1	0.7	1*	1*	Yes	No	42	28	7	6	6	3
High Resolution	Tenth SPE Comaprative Solution Project, with 30x110x17 Fine grid, Live oil /Dissolved Gas 5 spot pattern 4 Oil producers 1 gas injector	Density 45	Density 63.02 Ref Press 3000 PSI Bw 1.00341 Compressiblity 3.0D-6	Density .0702			1	0.7	1*	1*	Yes	No	880	280	15	15	5	5
Compositional	Tenth SPE Comaprative Solution Project, with 15x55x17 coarse grid, Compositinal Gas injection 5 spot pattern 4 Oil producers 1 gas injector	Density 1*	Density 63.02 Ref Press 3600 Bw 1.00341 Compressiblity 1.0D-6 Viscosity 0.96	Density 1*			1	0.7	1*	1*	Yes	No	440	280	2	2	5	0
Miscible Gas	Tenth SPE Comaprative Solution Project, with 15x55x17 coarse grid, Miscible Gas injection 5 spot pattern 4 Oil producers 1 gas injector	Density 38.53	Density 62.4 Ref Press 3600 Bw 1.00341 Compressiblity 1.0D-6 SORWMIS 0.0 1.0	Density 0.06864 Solvent surface 0.06243 SORWMIS 0.1			1	0.7	1*	1*	Yes	No	650	280	-3	-4	0	0

APPENDIX C

C names	T critical	P critical	Z critical	MW	ACF
C1	343	668	0.29	16	0.01
C3	666	616	0.28	44	0.15
C6	913	437	0.26	86	0.30
C10	1112	304	0.26	149	0.49
C15	1270	200	0.25	206	0.65
C20	1380	162	0.24	282	0.85

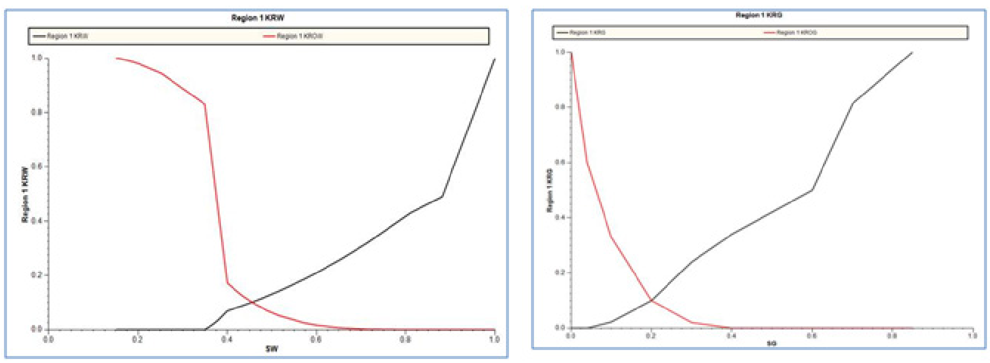


Figure C1: Compositional modeling Relative Permeability data used in FD and SL simulation

APPENDIX D

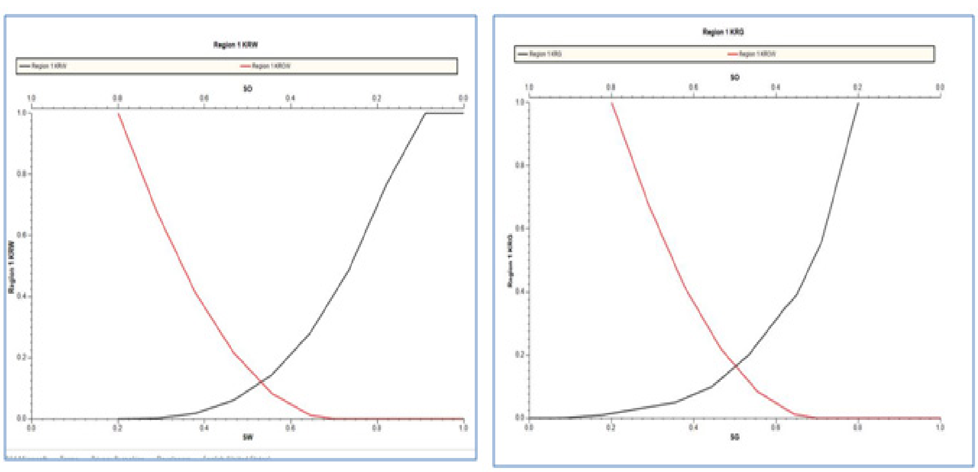


Figure D1: Miscible Gas Relative Permeability data used in both FD and SL simulation