ANALYSIS OF SEVERAL SOFTWARE USED IN PETROLEUM RESERVOIR SIMULATION

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Abstract. *One of the most important tools for forecasting the behavior of a reservoir is a reservoir simulator. For instance, a simulator can be used for optimizing and monitoring the production of old fields, or can be used to peform an economical analysis of new fields. Nowadays, there is a large number of commercial simulators that use structured and non-structured meshes which are used by most oil companies in the world. The accuracy of the simulator is the most important factor in predicting the performance of a reservoir under study. The goal of the present work is to compare the results of two commercial simulators and a simulator called SIM2D developed at the Federal University of Ceará using the finite volume method and corner point mesh. Two simulators from CMG – Computer Modeling Group (IMEX and STARS) will be used for this study. Cartesian and corner point meshes (using STARS, IMEX, and SIM2D) and unstructured meshes (using STARS) will be used to carry out this study. The results are presented in terms of oil and water volumetric flow rate, and well bottom pressure. Water saturations are also shown. In addition, some considerations in regard to user friendly interface of the two commercial simulators will be discussed.*

Keywords*: Petroleum reservoir, IMEX, STARS, Corner point mesh, unstructured mesh.*

1. Introduction

Numerical simulation is an important tool available to reservoir engineers for planning the production strategy and estimating the ultimate hydrocarbon recovery from the oil and gas reservoirs. Capturing the reservoir geology, such as irregular boundaries and location of faults in a reservoir simulator is an important role in reservoir simulation studies. Several commercial simulators, among them IMEX and STARS from CMG-Computer Modeling Group have special features in regard to mesh generation to capture the reservoir geometry in the simulations. STARS works with structured and unstructured meshes (triangular meshes for 2D cases). On the other hand, IMEX works only with structured corner point grid. STARS has options for thermal and black-oil models while IMEX is a black-oil simulator.

One very important assumption when boundary fitted coordinates are used in most commercial petroleum reservoir simulators is to neglect the cross terms in the evaluation of mass flow rate at the interfaces of control volume, Ponting (1999), Sammon (2000) and Cordazzo et al. (2002). When the mesh is quasi-orthogonal, then those terms are not important, as discussed in Maliska (2004). However, it is very difficult to employ an orthogonal mesh that deals with most important features of the reservoir such as irregular domains. Hence, non-orthogonal meshes are used in most cases. Neglecting cross terms, when evaluating the mass flow rate decreases the band width of the linear system. However, the method results in a mass balance error when the mesh is highly distorted.

The main goal of this work is to compare the results obtained using IMEX and STARS from CMG with a simulator developed at the Federal University of Ceará that uses boundary-fitted coordinates and the finite volume method, Coutinho et al. (2003). The university code (SIM2D) is a black-oil simulator. The results for two-dimensional cases will be presented in terms of fluid flow of oil and water in a reservoir. The tests will be performed done using Cartesian and corner point meshes for (IMEX and SIM2D) and Cartesian, corner point, and triangular meshes for STARS. The results are presented in terms of water iso-saturation, oil and water volumetric flow rate, and production bottom-hole pressure.

2. Black-Oil Model

The black-oil model is formulated based on mass fraction and is given by

$$\frac{\partial}{\partial t}\left[\phi\rho^{m} Z^{c}\right] = \nabla.\left[\sum_{np} X^{cp}\lambda^{p'}\nabla\Phi^{p}\right] - \sum_{np} X^{cp}\tilde{m}^{p} \tag{1}$$

where, ρ^m is the average density of the mixture, Z^c is the global mass fraction of component c, X^{cp} is the mass fraction of the component c in phase p, and $\lambda^{p'}$ is the mobility of phase p multiplied by the mass density of phase p, ρ^p**.** Summing the equations for the oil and water components results in the following equation:

$$\frac{\partial}{\partial t}\left[\phi\rho^{m}\right] = \sum_{np}\nabla.\left[\lambda^{p'}\nabla\Phi^{p}\right] - \sum_{np}\tilde{m}^{p} \tag{2}$$

Equation (2) denotes the mass global conservation. Equations (1) and (2) when solved for oil and water, gives two equations for three unknown (P, Z^o and Z^w). The closure equation comes from mass conservation equation which requires:

$$Z^{w} + Z^{o} = 1 \tag{3}$$

3. Transformation of the Equations

Equations 1 and 2 can be written in a boundary fitted coordinate system using the following transformation

$$\xi = \xi(x,y) \quad ; \quad \eta = \eta(x,y) \tag{4}$$

Using the above mentioned relations, Eqs. (1) and (2) can be solved in a rectangular domain that is usually called the computational domain, Thompson et al. (1985) and Maliska (2004). For notation purpose the global mass equation, Eq. (2), is called the pressure equation. Eq. (1) is written for water component, henceforth will be called the water equation. In performing the transformation of the Eq. (1) from physical plane to computational plane, the following equations are rendered:
Water equation:

$$\frac{1}{J}\frac{\partial}{\partial t}\left(\phi\rho^{m}Z^{w}\right) + \frac{\tilde{m}^{w}}{J} = \frac{\partial}{\partial\xi}\left[D_1^{w}\frac{\partial\Phi^{w}}{\partial\xi} + D_2^{w}\frac{\partial\Phi^{w}}{\partial\eta}\right] + \frac{\partial}{\partial\eta}\left[D_2^{w}\frac{\partial\Phi^{w}}{\partial\xi} + D_3^{w}\frac{\partial\Phi^{w}}{\partial\eta}\right] \tag{5}$$

Pressure equation:

$$\frac{1}{J}\frac{\partial}{\partial t}\left(\phi\rho^{m}\right) + \frac{1}{J}\left(\tilde{m}^{w} + \tilde{m}^{o}\right) = \sum_{p=o,w,g}\left(\frac{\partial}{\partial\xi}\left[D_1^{p}\frac{\partial\Phi^{p}}{\partial\xi} + D_2^{p}\frac{\partial\Phi^{p}}{\partial\eta}\right] + \frac{\partial}{\partial\eta}\left[D_2^{p}\frac{\partial\Phi^{p}}{\partial\xi} + D_3^{p}\frac{\partial\Phi^{p}}{\partial\eta}\right]\right) \tag{6}$$

where D_i^p coefficients are given by

$$D_1^{p} = \frac{\lambda^{p'}}{J}\left(\xi_x^2 + \xi_y^2\right) \; ; \; D_2^{p} = \frac{\lambda^{p'}}{J}\left(\xi_x\eta_x + \xi_y\eta_y\right) \; ; \; D_3^{p} = \frac{\lambda^{p'}}{J}\left(\eta_x^2 + \eta_y^2\right) \tag{7}$$

The expression for the jacobian (J), and the direct metrics of the transformation can be found in Maliska (2004). Equations (5) and (6) are integrated in space and time using a fully implicit procedure. The derivative in the final equations are evaluated using a central differencing scheme. The saturation field, for oil and water, can be directly obtained from global mass fraction and pressure, Cunha (1996). The resultant equations are linearized by the Newton method. The cross derivatives are included in the jacobian matrix, rendering a fully implicit procedure. Details can be found in Cunha (1993).

5. Comparison of: STARS, IMEX, and SIM2D using Cartesian Meshes

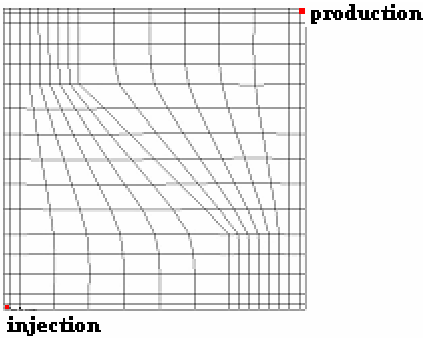
The results obtained with IMEX, STARS, and SIM2D in terms of water saturation and pressure, for a quarter of five-spot are now presented. The data for this case are shown in Tab. 1. In this table, h is the reservoir thickness, A the reservoir area, r_w the well radius, B the formation volume factor, Pc the capilar pressure, c the fluid compressibility, q_{wi} the injected water volumetric flow rate, P_{wf} the bottom hole pressure, i denotes initial data, r reference pressure, and or the residual oil. We also present the results obtained with STARS using control volume finite element method

(CVFEM). Figure 1b shows the triangular mesh used for this case. It is worthwhile to mention that a small compressibility for fluids was used just to allow the inversion of the diagonal block of each volume. The largest variation of the densities was less than 1.4×10^{-5} for water, and 1.18×10^{-5} for oil, respectively. Constant surface volumetric flow rate in the injection well and constant bottom hole pressure for production well were used, in all simulated cases. In order to avoid the well model effect, the well index was fixed to 10^{-9} m^3 in all simulators. Also, the following criteria for Newton iteration was used in CMG and SIM2D simulators: 68.9 kPa for pressure and 10^{-4} for saturation in IMEX and STARS, and 10^{-4} in global water mass fraction (SIM2D). Finally, the maximum time-step was fixed to 50 days for all codes.

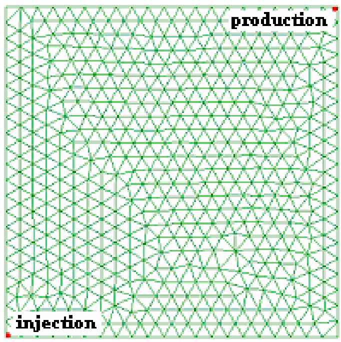
Table 1 – Physical data of the reservoir: case 1

Data of the reservoir	Initial conditions	Physical properties
$k=1.0 \times 10^{-12}$ m^2(1000 mD)	$S_{wi} = 0.20$	$B_o = B_w = 1$ a P_r
h = 15 m	$P_i = 207.33$ kPa	$P_c = 0$
$A = 2.14048 \times 10^6$ m^2	$P_r = 207.33$ kPa	$c_o = c_w = 1.00 \times 10^{-13}$ Pa^{-1}
$\phi = 0.20$	$S_{or} = 0.20$	$\|\|q_{wi}\|\| = 1,1574 \times 10^{-3}$ m^3/s
$r_w = 0.122$m		P_{wf} (Production well) = 207.33 kPa

Figures 2 and 3 present the water iso-saturation curves after 5124 and 15124 days of simulations, respectively. It should be emphasized that the output files of IMEX and STAR with structured meshes were transferred to the CFD-SCICIEW1.0 of SINMEC Laboratory in order to avoid differences due to the use of different post-processors. For STARS using unstructured meshes, this option was not possible to use since the simulator does not give the nodal values of the unknowns. Although the mesh presented in Fig. 1b was used for unstructured grid in STARS, the results are interpolated to obtain values for a Cartesian mesh. From the results shown in Figs. 2 and 3, it can be seen that good agreements were obtained in the results shown. The oil and water volumetric flow, and the bottom hole pressure are also presented in Fig. 4. From Fig. 4, it can be observed that the results from SIM2D are very close to those of STARS and IMEX. This behavior was expected since all codes use the same numerical procedure and the same type of mesh, except that one that uses triangular mesh. Only a small difference in the results are observed with STARS using non-structured mesh. However, this difference is attributed to the fact that the wells in the triangular mesh are not located in the same position of the regular mesh. The wells in the triangular mesh are located in the vertices of the triangles (red points in Fig. 1b).



(a) - Corner point -16x16 volumes

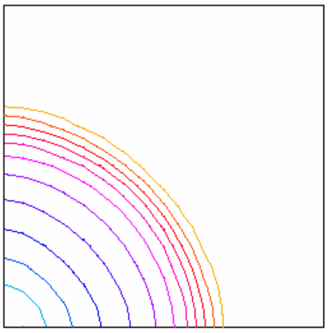


(b) - STARS - CVFEM (537 volumes)

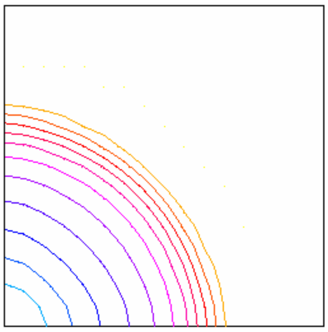
Figure 1 – Corner point and triangle meshes

Figure 5 presents the meshes used for a quarter of five-spot with a fault perpendicular to the line that connects the injector and production wells. For SIM2D, the only change made is the elimination of the mass flow rate for the interfaces belonging to the fault. The cross terms in this case are null since the mesh is orthogonal. To simulate the fault using unstructured mesh in STARS it is necessary to give small values of absolute permeability that are defined in the vertices of each triangle. As each volume is built surrounding each vertex, the fault was modeled in this case using volumes with a low permeability. Since it is not possible to prescribe a null value, by STARS restrictions, the smallest possible value for permeability was set to 10^{-8} mD.

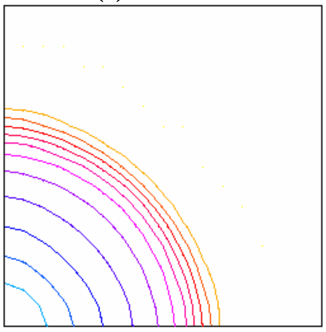
Figures 6 and 7 present the water iso-saturation contours for two different simulated times, using IMEX and SIM2D simulators. Some differences can be observed in the water iso-lines obtained with CMG and SIM2D simulators, mainly next to the water breakthrough, as can be observed in Fig. 7. Similar behavior was obtained for Cartesian mesh without fault as expected, since the methodologies and the mesh are exactly the same. Figure 8 presents the volumetric oil and water, as well the bottom hole pressure in the production well. From this figure, despite the observed difference in Fig. 7, it is possible to see in the water iso-saturation lines, a good agreement between all the results were obtained with SIM2D, IMEX and STARS using Cartesian meshes. One possible reason, for the observed difference between STARS using unstructured mesh and the other software can be justified to different localization of the fault, as can be observed in Figs. 5a and 5b.



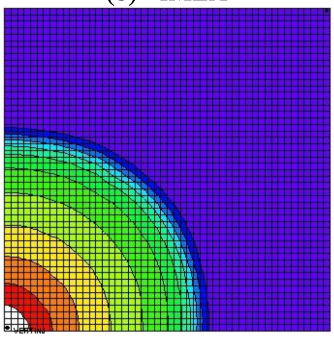
(a) – SIM2D



(b) - IMEX

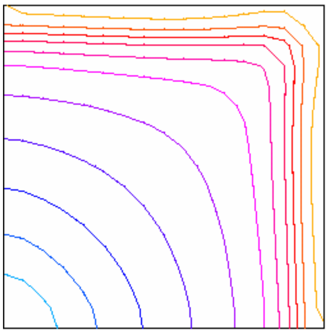


(c) - STARS - 16x16 Cartesian

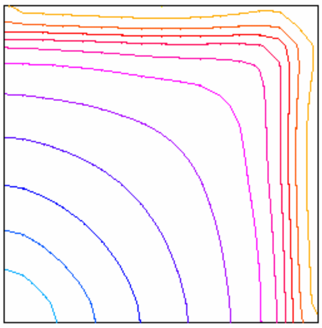


(d) - STARS-CVFEM

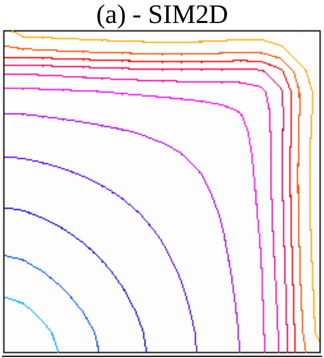
Figure 2 – Water iso-saturation in 5124 days



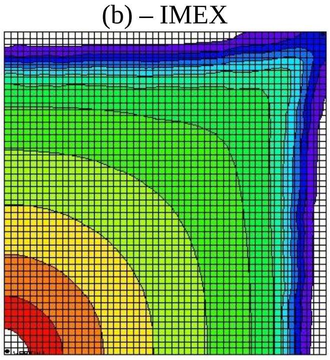
(a) - SIM2D



(b) – IMEX



(c) – STARS 16x16 Cartesian

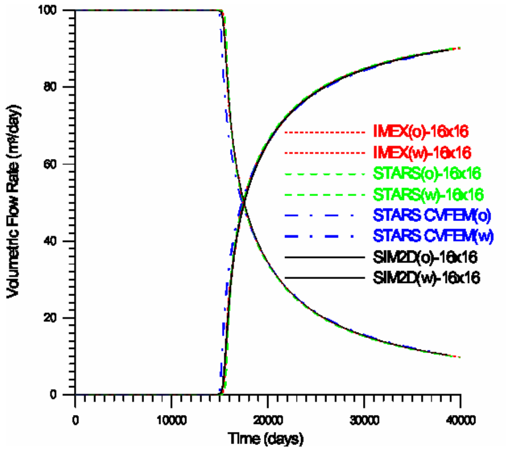


(d) - STARS-CVFEM

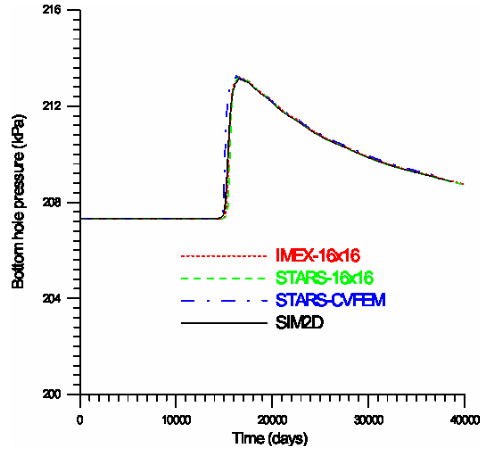
Figure 3 – Water iso-saturation in 15124 days

5. Comparison of: STARS, IMEX, and SIM2D using Corner Point Meshes

In this section, some results using corner point mesh employing STARS and IMEX simulator (a the five point scheme for mass flow rate approximation) are compared with SIM2D simulator, using a 9 point scheme for approximation of the mass flow rate. The first case refers to a quarter of five-spot mentioned before where the Cartesian mesh was distorted (Fig. 1b). The same data presented in section 4 was used to this case. Also, the results for STARS using unstructured mesh will not be presented, since the results are identical to those shown in Figs. 2 through 5.

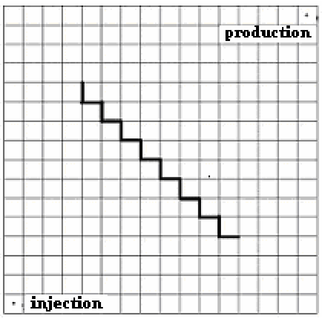


(a)

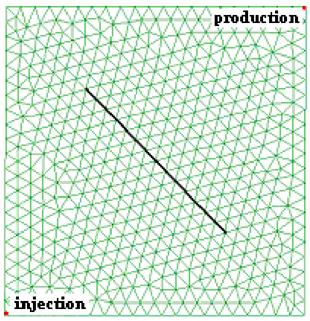


(b)

Figure 4 – Water and oil volumetric flow rate, and production bottom hole pressure

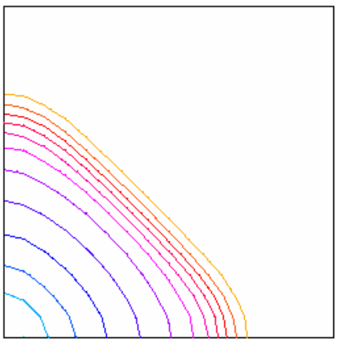


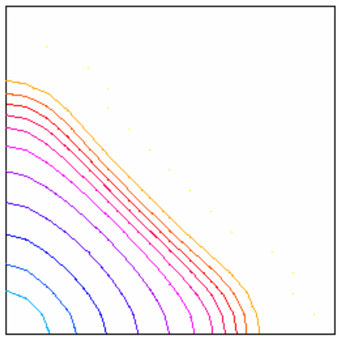
(a) – Cartesian mesh with fault – 16x16

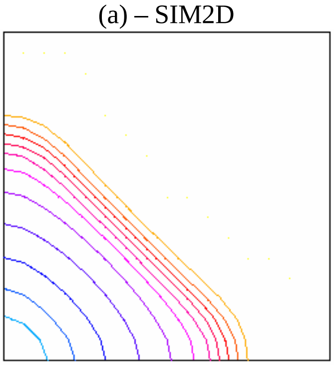


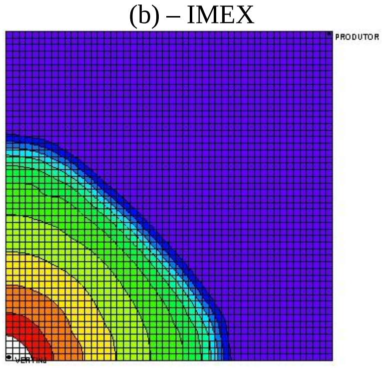
(b) – Triangular mesh with fault - 542 volumes

Figure 5 – Meshes for case 2


(a) – SIM2D

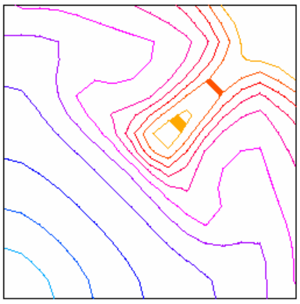

(b) – IMEX

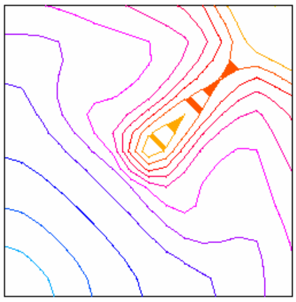

(c) – STARS 16x16 Cartesian

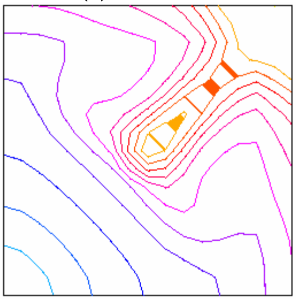


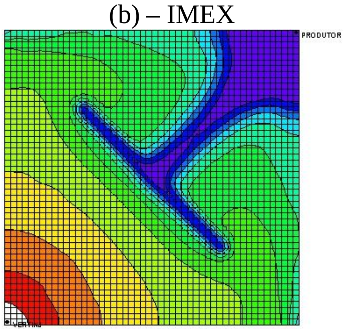
(d) – STARS CVFEM 542 volumes

Figure 6 – Water iso-saturation in 5132 days


(a) – SIM2D

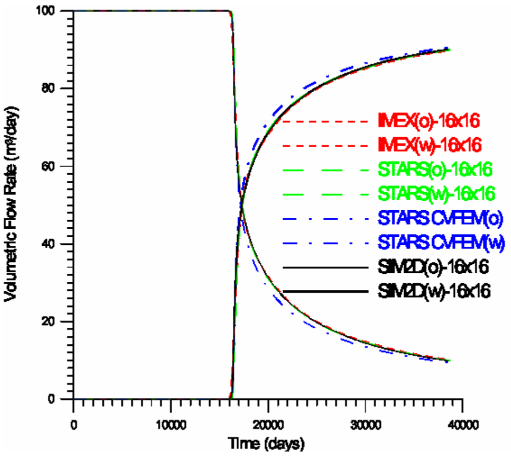

(b) – IMEX


(c) – STARS

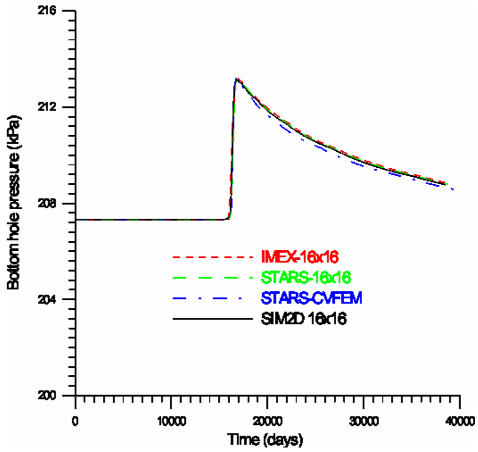


(d) – STARS CVFEM 542 volumes

Figure 7 – Water iso-saturation in 15132 days



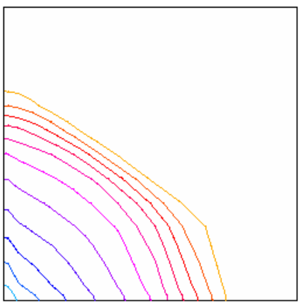
(a)

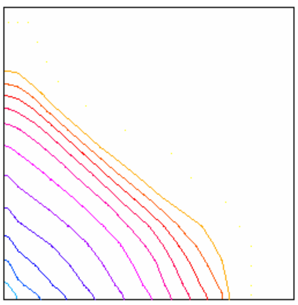


(b)

Figure 8 – Oil and water volumetric rate, and production bottom pressure.

Figures 9 and 10 show the water iso-saturation in two simulated times. If the results shown in Figs. 9 and 10 are compared with those presented in Figs. 2 and 3 for Cartesian meshes, it is possible to observe that the results obtained with SIM2D code are much closer to the ones shown in Figs. 2 and 3. Although the final simulation times are not exactly the same, they are very close; thus it is expected to produce approximately the same behavior, since only the mesh was changed.


(a) – SIM2D


(b) – IMEX

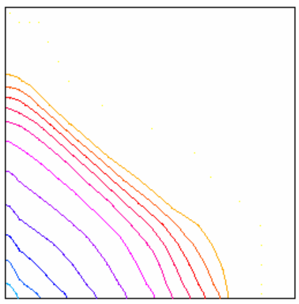
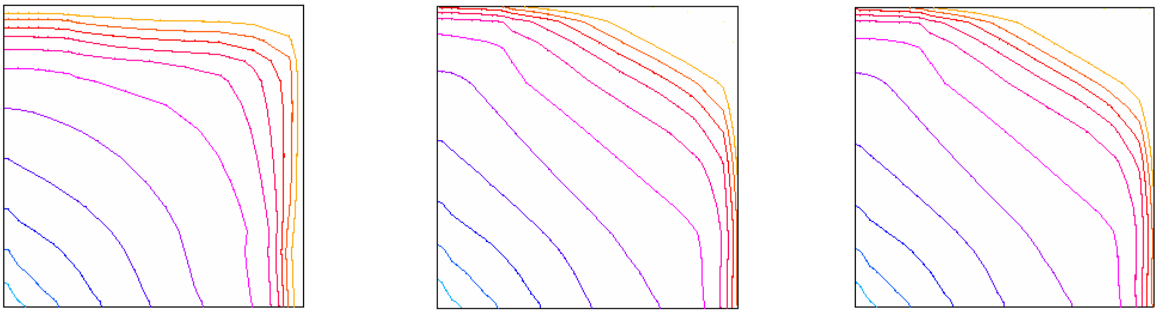

(c) – STARS

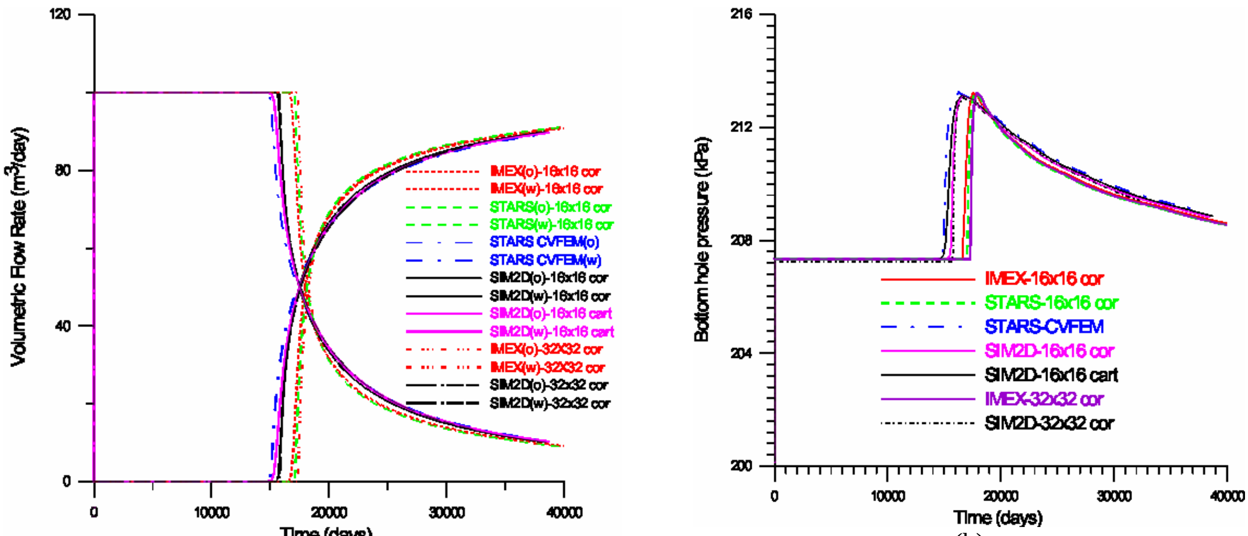
Figure 9 – Water iso-saturations in 5130 days



(a) – SIM2D (b) - IMEX (c) – STARS 16x16 gen

Figure 10 – Water iso-saturations in 15130 days

Figure 11 presents the oil and water volumetric flow rate as well the production bottom hole pressure. The results using IMEX (corner point), STARS (triangles and corner point), and SIM2D (Cartesian and corner) are presented. We note here that only the results for SIM2D, using Cartesian mesh, are shown since those were identical to STARS and IMEX using this type of mesh (Figs. 2 through 5). Despite the corner point mesh being different from the regular Cartesian mesh, the results obtained with SIM2D are very close to the previous results with Cartesian mesh for all the variables. In addition, the results obtained with IMEX and STARS despite being very close, are distinct from those using Cartesian mesh. In order to verify the behavior of the solution, a mesh refinement study was performed and the results for 16x16 and 32x32 mesh configurations are presented in Fig. 11 for IMEX and SIM2D. Although there are small differences in the water breakthrough for 16x16 and 32x32 meshes obtained with SIM2D, it can be observed that the solutions obtained with SIM2D are almost similar. In addition, this solution is close to the results obtained with the Cartesian mesh and STARS using the triangle mesh. However, the solution obtained with IMEX with the refined mesh is more distant from those obtained with triangle mesh. It seems that the numerical errors are not decreased with the mesh refinement. As a matter of fact, this behavior was expected, since the flux approximation using only two points does not approximate the flux correctly. In other words, independent of the mesh used, the mass flux will not be evaluated exactly, since one important part of mass flux is neglected.



(a) (b)

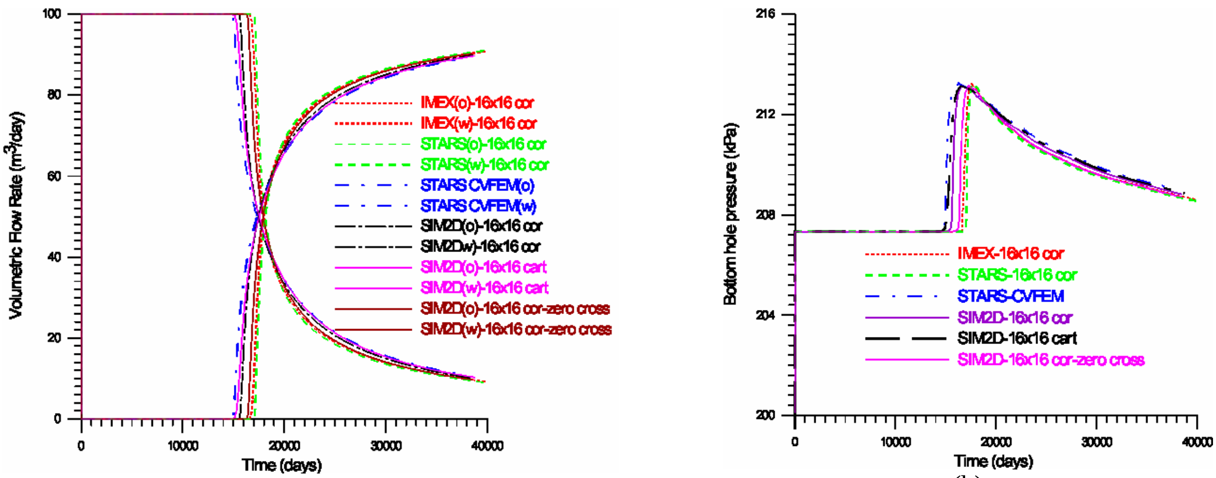
Figure 11 – (a) Oil and water volumetric flow rates. (b) Production bottom hole pressure

Finally, in order to investigate the effects of cross terms in the solution, those terms were neglected in the SIM2D code. Figure 12 presents the results in terms of oil and water volumetric flow rate, and bottom hole pressure. Now, it can be inferred that the results of the SIM2D code are much closer to the IMEX and STARS. The only difference between the academic and CMG codes, in this case, is the interface area used to evaluate the mass flow rate. In the academic code the area of each interface was used, while in the CMG codes the projected area of the interface is used. The closer agreement in the results obtained with the SIM2D and CMG simulators can be interpreted as a clear signal that the cross terms cannot be neglected. Those terms are more important when the mesh is much distorted. In this case, large errors in the mass flow rate are expected when the cross terms are neglected.

6. Conclusions

In this work the results obtained using different simulators in conjunction with triangular, regular and irregular quadrilaterals elements were compared. Several test cases were used to study the effects of mass flux using five points in corner point meshes. The CMG commercial simulators (IMEX and STARS) and an academic code (SIM2D) that uses boundary-fitted coordinates and 9 points were employed.

Some main conclusions can be drawn from this investigation. First, for orthogonal or quasi-orthogonal meshes the five point approximation used by STARS and IMEX were very close to STARS using triangle meshes and SIM2D code using 9 points approximation. On the other hand, for the cases where the mesh was much distorted, the solutions using IMEX and STARS in conjunction with corner point mesh were different from SIM2D and STARS using CVFEM. Moreover, the grid refinement study that was carried out did not produce a closer agreement in the simulation results using different simulators. It should be mentioned that the use of quasi orthogonal meshes in petroleum reservoir simulations is almost impossible due to the irregular features of most reservoirs such as boundaries and faults. Thus, if corner point mesh is used, there will be some errors in the numerical solution if the cross terms are eliminated.



(a) (b)

Figure 12 – (a) Oil and water volumetric flow rate. (b) – Production bottom hole pressure

7. References

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