23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

2D HIGH PERFORMING COMPOSITIONAL PETROLEUM RESERVOIR SIMULATION IN CONJUNCTION WITH UNSTRUCTURED GRIDS

Ivens da Costa Menezes Lima
Vanílson Nogueira Avedo
José Cláudio Batista de Oliveira
João Henrique Gomes Gomes Bessa
Joaquim Bento Cavalcante Neto
Francisco Marcondes
Universidade Federal do Ceará, Campus do Pici – CEP 60455-900, Fortaleza, CE
ivenscml@yahoo.com.br
vanilson.nogueira@gmail.com
joseclaudio91@gmail.com
joao.hgomes@hotmail.com
joaquimb@lia.ufc.br
marcondes@ufc.br

Kamy Sepehrnoori
The University of Texas at Austin, Austin, TX 78712
kamys@mail.utexas.edu

Abstract. *Petroleum reservoir simulators are essential tools for enhanced oil recovery (EOR), optimization of well configurations, history matching, among other applications. In order to be efficient tools for the oil industry, these simulators need to produce accurate results with efficient computational time. There are many ways to improve the speed of a simulator, but the main focus of this work is on the parallelization, i.e. give the simulator the ability to reduce the wall clock through put time by using many processors. In this work, we used some open source libraries like FMDB (Flexible Distributed Mesh Database), ParMetis (Parallel Graph Partitioning and Fill-reducing Matrix Ordering), and PETSc (Portable, Extensible Toolkit for Scientific Computation). The numerical approach is based on Element based Finite Volume Method (EbFVM). The FMDB and ParMetis libraries are used to divide and manage the grid data transfer between the processes, and PETSc for solving the linear systems arising from the discretization of the governing equations. In fact, the main challenge of this work is to organize the grid, fluid, and reservoir data set in such a way that the communication between the processes is reduced. The difficulty to transfer the information between the processors is mainly due to the use of unstructured grids. In the current implementation, we use the UTCOMP simulator. UTCOMP simulator is a compositional, multiphase/multicomponent simulator designed to handle several hydrocarbon recovery processes that was developed at The University of Texas at Austin. The results of this work are presented in terms of oil and gas production, and CPU time for various case studies.*

Keywords: *Parallelization, UTCOMP, EbFVM,2D unstructured grids*

1. INTRODUCTION

The petroleum industry relies most of its production strategies on simulation of oil fields and historical adjustments based on data acquired during the production period. Reservoir simulation is a widely used tool because it allows engineers to predict the behavior of fluid flow in the reservoir in order to achieve the best strategy for the production, i.e., well configuration, composition of injected fluid, cycle time for WAG (Water Alternating Gas) production, etc.

The main features that a simulator must have are reliability and speed. There are many ways to improve the computational speed for the reservoir simulators. One can increase the degree of implicitness of the variables, use faster computers, or parallelize the software, i.e., give the software the capability to run by using more than one processor at the same time. The main focus of this paper is in the last approach.

This work aims to show how the parallelization of a reservoir simulator can significantly reduce the total computational time. Other authors have already studied this process, such as Wheeler et al. (1999) and Dogru et al. (2002). However, most works found in the literature are devoted to parallelization of Cartesian grids. This paper addresses the parallelization of 2D unstructured grids using the compositional model in conjunction with the Element based Finite-Volume Method (EbFVM). The numerical approach is based on an IMPEC (Implicit Pressure Explicit Composition).

In additional to OpenMPI that was used to perform the communication between the processes, we used three open source libraries: ParMetis, FMDB, and Petsc. ParMetis and FMDB were used to respectively, divide and manage the 2D grids in each processor, and Petsc was used to solve the linear system of equations.

The simulator used to perform the implementation is UTCOMP; UTCOMP is a multicomponent/multiphase compositional reservoir simulator developed at The University of Texas at Austin (Chang, 1990). The IMPEC formulation of Acs et al. (1985) in conjunction with the Element based Finite-Volume Method (EbFVM) were used to linearize and discretize the differential partial equations.

2. PHYSICAL MODEL

One of the formulations of the UTCOMP simulator is based in the IMPEC (Implicit Pressure Explicit Composition) formulation. The pressure equation is obtained by a volume balance between the porous volume and total fluid volume available. Further details can be found in Chang (1990). The pressure equation is given by

$$\left(V_p^0 c_f - \frac{\partial V_t}{\partial P}\right)\left(\frac{\partial P}{\partial t}\right) - \sum_{i=1}^{n_c+1} \overline{V}_{ti} \vec{\nabla}.\sum_{j=1}^{n_p} \lambda_j \xi_j x_{ij} \overline{\overline{k}}.\overrightarrow{\nabla P} =$$
$$\sum_{i=1}^{n_c+1} \overline{V}_{ti} \vec{\nabla}.\sum_{j=1}^{n_p} \lambda_j \xi_j x_{ij} \overline{\overline{k}}.\left(\overrightarrow{\nabla P_{cj}} - \gamma_j \overrightarrow{\nabla D}\right) + \sum_{i=1}^{n_c+1} \overline{V}_{ti} \vec{\nabla}.\sum_{j=1}^{n_p} \phi \xi_j S_j \overline{\overline{K}}_{ij}.\overrightarrow{\nabla x_{ij}} + \sum_{i=1}^{n_c+1} \overline{V}_{ti} q_i \qquad (1)$$

where P is the pressure, t is time, V_p is the standard porous volume, c_f is the compressibility factor, V_t is the total volume of fluid, V_{ti} is the derivative of total volume with relation to the number of moles of component i, λ_j is the mobility of phase j, ξ_j is the molar density of phase j, x_{ij} is the molar fraction of component i in phase j, K is the rock permeability tensor, P_{cj} is the capillary pressure of phase j related to the oil phase, γ_j is the specific gravity of phase j, D is the depth which is positive in downward direction, ϕ is the rock porosity, S_j is the saturation of phase j, K_{ij} is the dispersion tensor of component i in phase j, and, finally, q_i is the molar rate of component i through the well.

The mole balance equation is given by

$$\frac{1}{V_b}\frac{\partial N_i}{\partial t} = \vec{\nabla}.\sum_{j=1}^{n_p} \lambda_j \xi_j x_{ij} \overline{\overline{k}}.\left(\overrightarrow{\nabla P} + \overrightarrow{\nabla P_{cj}} - \gamma_j \overrightarrow{\nabla D}\right) + \vec{\nabla}.\sum_{j=1}^{n_p} \phi \xi_j S_j \overline{\overline{K}}_{ij}.\overrightarrow{\nabla x_{ij}} + \frac{q_i}{V_b} \qquad (2)$$

where V_b is the bulk volume and N_i is the total number of moles of component i.

2.1 EbFVM approach

In the EbFVM approach, the domain is divided into elements and each element is divided according to the number of vertices. The conservation equations are then integrated for each sub-element. In general, the sub-elements are called sub-control volumes, since the equations are integrated for each sub-element. The approximate equations for each vertex are obtained through the summation of all sub-elements that share the same vertex. Figure 1 shows a domain with 8 elements and 10 vertices. The conservation equation for vertex 5 is obtained using the sub-control volume 1 (scv1) from element 1, scv3 from element 2, scv1 from element 7, scv4 from element 6. Further details of EbFVM approach can be found in Marcondes and Sepehrnoori (2010), Marcondes et al. (2013).

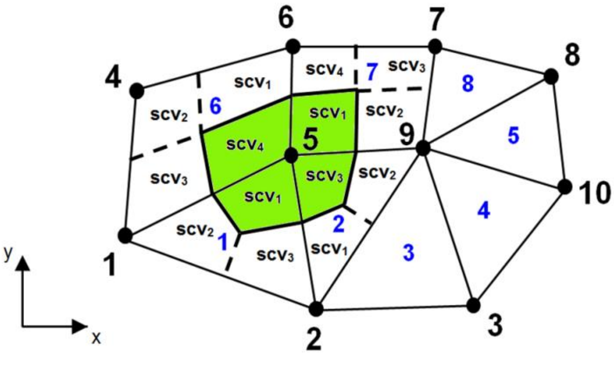
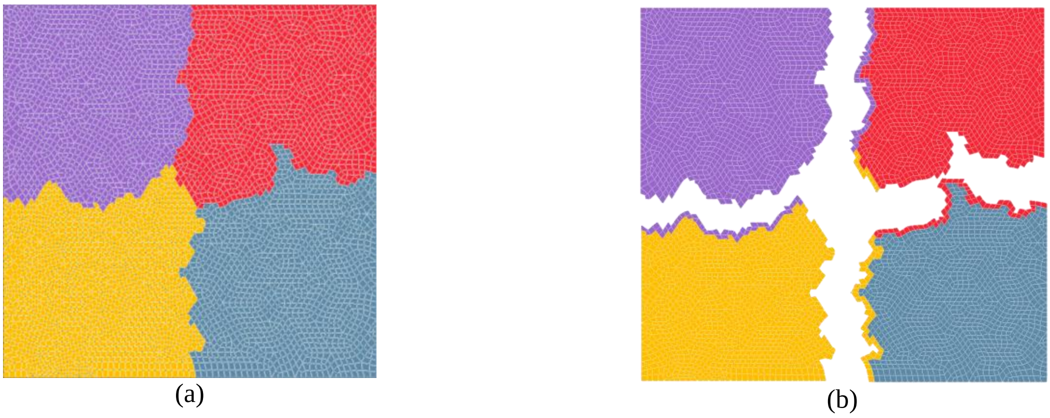


Figure 1 – Grid division and control volume.

3. PARALLELIZATION

The task of managing and splitting the grids between the processes were undertaken using two open source libraries: Parmetis (Parallel Graph Partitioning and Fill-reducing Matrix Ordering) (Karypis and Schloegel, 2013) and FMDB (Flexible Distributed Mesh Database) (Fmdb, 2013). The Parmetis takes into account the global number of vertices of the grid and automatically performs the grid balance between the processes. This ensures that no process will have a significantly heavier load than the others. FMDB provides the tools necessary to develop the routines used for the grid management; this means to divide the grid among the processes and to provide each process with all required data, including ghost layer information. Figure 2 shows an example of a two-dimensional grid divided in four processes. The colored elements on the border of each piece of the grid consist on the ghost layer of that process. As shown in Fig. 2, elements are not randomly distributed between the processes. Instead, Parmetis distributes them so that communication between the processors is minimized. As mentioned before, FMDB provides the managing functions so that the ghost layer can be correctly assembled, as well as each process would know the coordinates and indices of each vertex inside its portion of the grid.



(a)

(b)

Figure 2.Two-dimensional grid division for parallel simulation. (a) – Grid partition (b) – Grid partition and ghost layers.

The grid partition, performed by Parmetis, is based on the k-way partitioning, where the grids can be partitioned as nodal or dual graphs and k is the number of desired subdomains. This partitioning tries to minimize the number of edges that are cut by the partition (edge-cut). Figure 3 shows the idea of the k-partition.

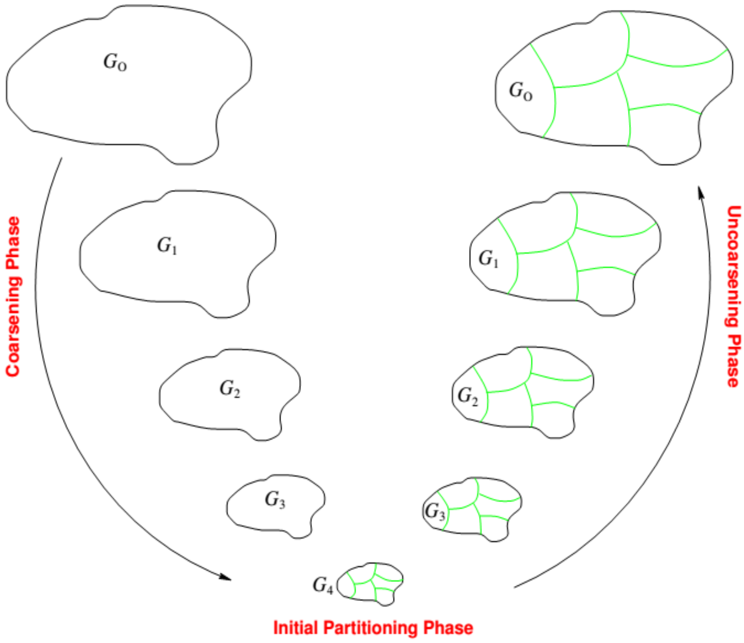


Figure 3. Multilevel k-partitioning.

The whole process consists of the integration of many parts and libraries in order to deal with the parallelization. Initially the grid is loaded by the FMDB, which is followed by the Parmetis partition, aided by another library called Zoltan (Zoltan, 2005). The next step is the ghost layers assembling in each process interface. Finally, the functions are put together with the solver for the simulation. The grid is given using a TXT/CFX5 format file which is converted to a SMS format. After this step is performed, the integration starts in all processes. At the end of the whole integration process, the files generated on run time (SMS/DPT) are excluded.

4. SIMULATION RESULTS

In order to check the accuracy and performance of the procedure outlined in the last section, we present the results for two case studies. In the first case, a gas flooding process characterized by three hydrocarbon components is used. Initially, only two phases are present in the reservoir (oil and water). As the recovery process proceeds, a gas phase appears in the reservoir. For the first case, a quarter-of-five-spot configuration is employed and the domain is discretized through a triangular grid with 10,114 vertices. The reservoir data, reservoir and injection fluid compositions, and operational conditions are given in Tables 1 through 3, respectively.

Table 1. Reservoir properties – Case 1.

Property	Value
Dimension (height, width and depth)	170.7 m, 170.7 m, 30.5 m
Porosity	0.30
Rock permeability (x,y,z)	100, 100, 10 mD
Temperature	299,82 K
Pressure	20684,28 kPa
Initial water saturation	0.25

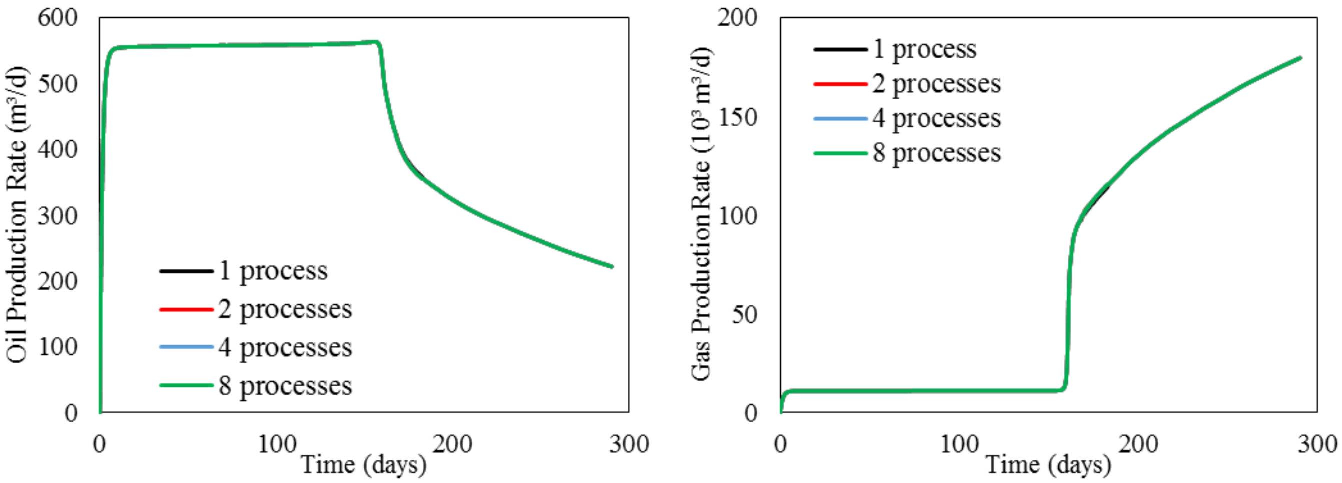
Table 2. Reservoir and injection fluid compositions – Case 1.

Component	Initial reservoir composition	Injection composition
CO2	0.01	0.95
C1	0.19	0.05
nC16	0.80	-

Table 3. Operational conditions – Case 1.

Well	Operation mode	Operation constraint
Injector	Constant volume injection	2,83x10^5 m³/d
Producer	Constant bottom hole pressure	20684,28 kPa

The oil and gas production rates obtained with 1 through 8 processes are presented in Figure 4. From this figure, we can observe a good match for the oil and gas rates obtained with all the processes investigated.



(a) (b)

Figure 4. Standard volumetric rates for case 1. a) Oil production b) Gas production

The wall clock time (s) and speed-up obtained for this case study is presented in Table 4. From the results presented in Table 4, we can verify that the performance of the calculation is enhanced as the number of processes increases.

Table 4. Wall clock time and speed-up - Case 1.

Number of processes	Wall clock time (s)	Speed up
1	15275.00	1.00
2	9027.00	1.69
4	6243.00	2.45
8	4308.00	3.55

For the second case study, we used another gas flooding problem, which is characterized by six components. In this study, the reservoir is represented by a more complex geometry than the one used previously. Figure 5 presents the reservoir composed of one injecting well and two producing wells. The irregular grid used to simulate this case study is composed of 27,271 vertices and 53,132 triangular elements. In Figure 5, the blue and red dots represent, respectively, the injection and production wells. The data sets used for this case study are presented in Tables 5 through 7.

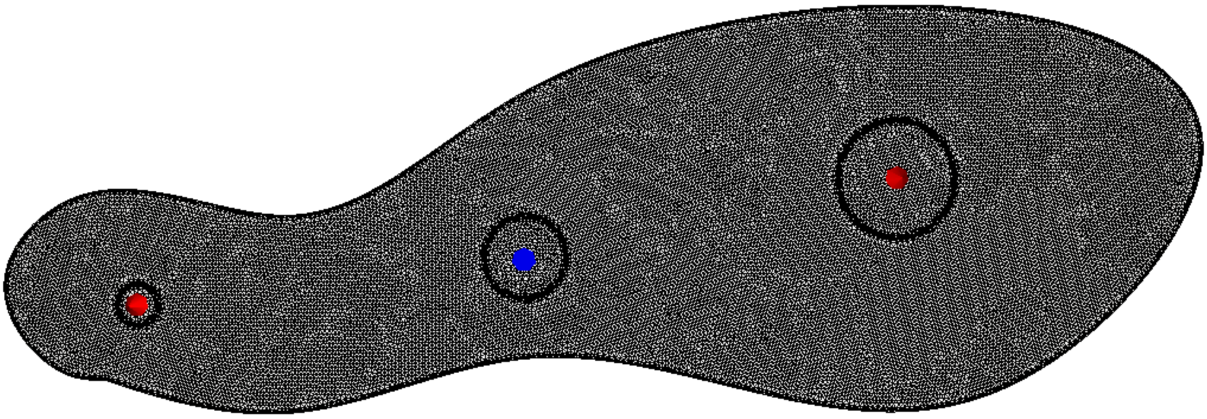
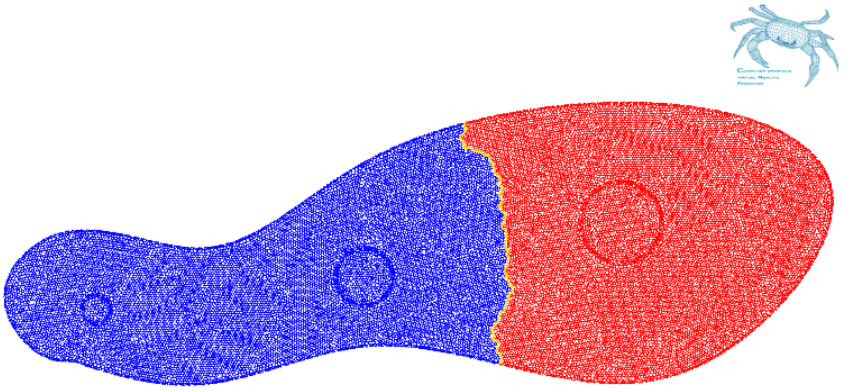
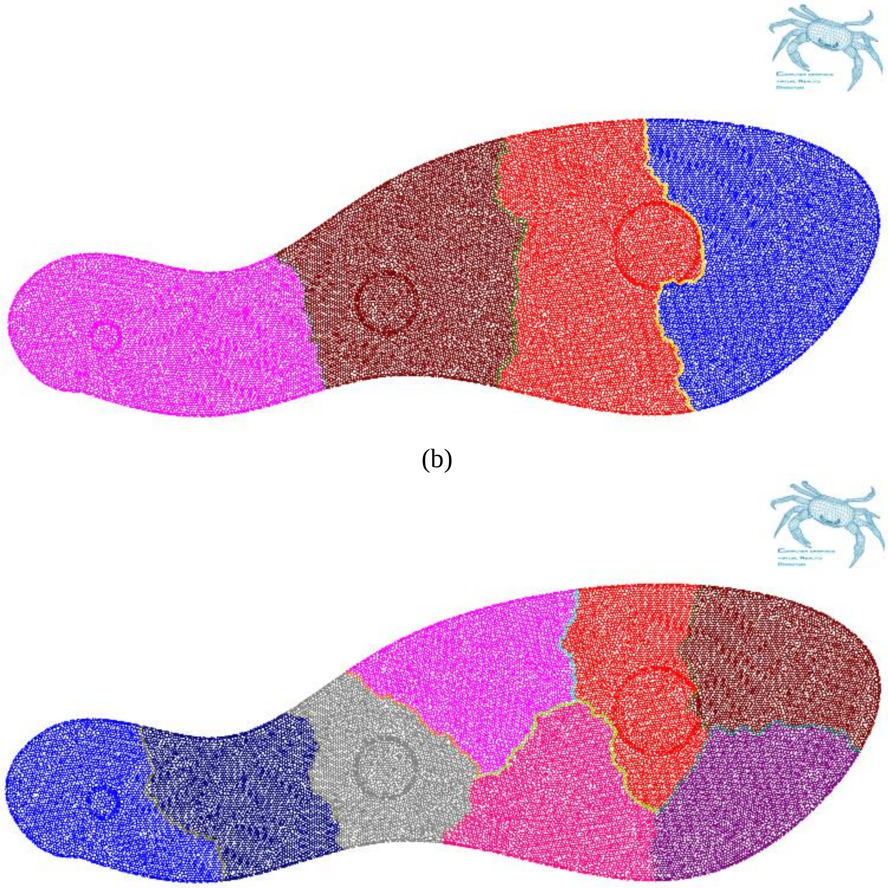


Figure 5. Irregular triangular grid with 27,271 vertices and 53,132 elements - Case 2.

Figure 6 presents how the mesh is divided among the processes. This case was run with 1, 2, 4, and 8 processes. In Fig. 6 is also possible to see the ghost layers between the processes. These images were generated using CrabMesh, an in-house grid pre and post-processor.



(a)



(b)

(c)

Figure 6. Domain decomposition for various processors – Case 2. a) two processors b) 4 processors c) 8 processors

Table 5. Reservoir properties – Case 2.

Property	Value
Dimension (height, width and depth)	170.7 m, 170.7 m, 30.5 m
Porosity	0.35
Rock permeability (x,y,z)	10, 10, 10 mD
Temperature	344,26 K
Pressure	10342 kPa
Initial water saturation	0.17

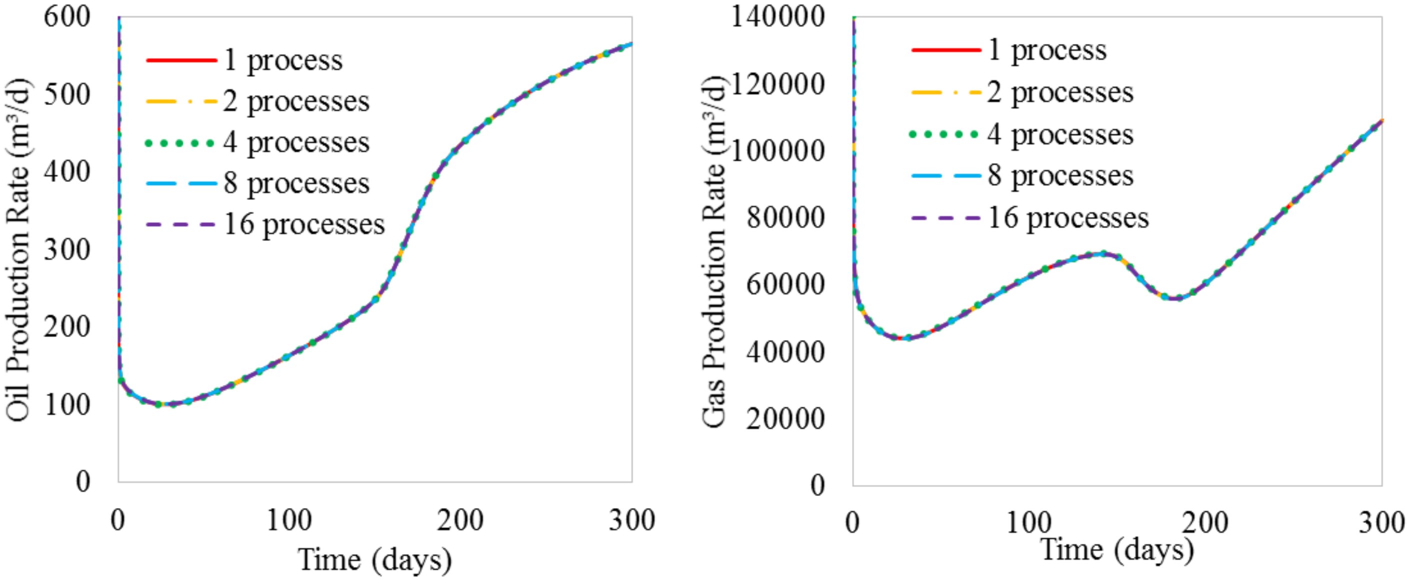
Table 6. Reservoir and injection fluid compositions – Case 2.

Component	Initial reservoir composition	Injection composition
C1	0.50	0.77
C3	0.03	0.20
C6	0.07	0.01
C10	0.20	0.01
C15	0.15	0.005
C20	0.05	0.005

Table 7. Operational conditions – Case 2.

Well	Operation mode	Operation constraint
Injector	Constant volume injection	2,83x10^5 m³/d
Producer	Constant bottom hole pressure	8963,19 kPa

The results in terms of total oil and gas production curves are shown in Fig. 7. Once again, we can observe a good match between the curves. The wall clock time and speed-up for this case study is presented in Table 8.



(a) (b)

Figure 7. Standard volumetric rates for case 2. a) Oil production b) Gas production

Table 8. Wall clock time and speed-up - Case 2.

Number of processes	Wall clock time (s)	Speed-up
1	5109	1.00
2	3005	1.70
4	1690	3.02
8	885	5.77

From these results presented in Table 8, we observe that the performance is improved when the number of processes is increased.

5. CONCLUSIONS

In this work the parallelization of a compositional reservoir simulator in conjunction with 2D triangular grids based on the Element based Finite-Volume Method (EbFVM) was presented. The numerical approach that was used to solve the material balance equations is based on an Implicit Pressure Explicit Composition (IMPEC). The results of the parallelization were presented in terms of oil and production as well as wall clock times and speed-ups. The results demonstrated that the implementation was correctly performed and that the CPU time can be largely reduced when the numbers of processes are increased. We also expect that the speed-up will increase when the grids are refined.

6. ACKNOWLEDGMENTS

The authors would like to thank PETROBRAS for the financial support as well as The University of Texas at Austin for permission to use the UTCOMP simulator to perform the parallel processing implementation.

7. REFERENCES

Ács, G., Doleshcall, S., and Farkas, E., 1985. “General Purpose Compositional Model”. *SPE Journal*, vol. 25, pp. 543-553.

Chang, Y.B., 1990. “Development and Application of an Equation of State Compositional Simulator”. PhD Thesis. The University of Texas at Austin, Austin.

Dogru, A.H. Sunaidi, H.A., Fung, L.S., Habiballah, W.A., Al-Zamel, N., andLi, K.G. 2002. A Parallel Reservoir Simulator for Large-Scale Reservoir Simulation. SPEREE5 (1): 11-23. SPE-75805-PA. doi: 10.2118/75805-PA.

Fmdb, 2013. "The FMDB User's Guide", Rensselaer Polytechnic Institute, 2013.

Marcondes F., and Sepehrnoori K., 2010. "An Element-Based Finite-Volume Method Approach for Heterogeneous and Anisotropic Compositional Reservoir Simulation". *Journal of Petroleum Science & Engineering*, vol. 73(1-2), p. 99-106.

Marcondes, F., Santos, L. O. S., Varavei, A., and Sepehrnoori, K., 2013. A 3D Hybrid Element-based Finite-Volume Method for Heterogeneous and Anisotropic Compositional Reservoir Simulation. *Journal of Petroleum Science & Engineering*, v. 108, p. 342-351.

Karypis, G. and Schloegel, K., 2013. Parmetis: Parallel Graph Partitioning and Sparse Matrix Ordering Library, Version 4.0, University of Minnesota, Department of Computer Science and Engineering.

Wheeler, M.F., Arbogast, T., Bryant, S., Eaton, J., Lu, Q., Peszynska, M., Yotov, I., 1999. A parallel multiblock multidomain approach for reservoir simulation. Paper SPE 51884, Proceedings of Fifteenth SPE Symposium on Reservoir Simulation, Houston, Texas, pp. 51–61.

Zoltan, 2005. "Zoltan: Data management services for parallel applications", Sandia National Laboratories.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.