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New Parallelized Adaptive Implicit Methods for Large Compositional Reservoir Simulations

Y. Caillabet, J.F. Magras and O. Ricois*

أساليب ضمنية تكييفية متوازية لمحاكاة المكمن كبير التركيب

ي. كيلابيت، ج. ف. ماقراص وأ. ريكواس

لا تزال محاكاة نماذج تركيبات المكامن الكبيرة والمقبولة لتوقيت وحدة المعالجة المركزية المفتاح لأي منظومة محاكاة مكمنية. وهكذا فإن النمذجة المتوازية مطلوبة لزيادة سرعة المحاكاة وكذلك نحتاج إلى تطبيق الحلول العددية القوية لضمان نتائج دقيقة خاصة عند محاكاة مركبات معقدة الطبيعة. في هذا السياق الأنظمة الضمنية الكلية التقليدية غالبا ما تكون غير مستعملة لسبب الذاكرة ومتطلبات وحدة المعالجة المركزية.

نحن نقترح أساليب جديدة حكيمة والتي تمزج الدقة والاستقرار للأساليب الضمنية الكاملة وأداءات وحدة المعالجة المركزية واستهلاك قليل للذاكرة للمجموعة الواضحة. بحدود هذه الطرق نظام ضمني كامل يطبق بأجزاء من المكمن ذو الاختلالات في الخواص الطبيعية العالية. وأسلوب واضح يستخدم في المجموعة الأخرى. الأسباب الواضحة تحدد باستقرار ظروف CFL الخلايا الواضحة ذو الافتلاتات الكبيرة من غير المعروفة تفتح ديناميكيا للأخريات الضمنيات لتحسين أداءات وحدة المعالجة المركزية المحاكاة العالمية. هذه الحالات للحسابات وضعت أساسا على معايير أما مبدئية أو طيفية. إقفال الشبكة الضمنية ربما تحكم باستعمال أنظمة ضمنية كاملة أو أنظمة شبه ضمنية اعتمادا على اختلافات مركبات المائع.

هذه الأنظمة المختلفة تم موازاتها وتكاملها بمنظومة محاكاة صناعية متعددة الأغراض. معايير CFL تم مناقشتها واختبارها بحالات أكاديمية وبعدها تم مقارنة الأساليب المتوفرة والتي تم عرضها لدراسات حالات حقلية حقيقية لمركبات كبيرة على منصات معدنية متوازية ومختلفة.

Abstract: *Simulation of large compositional reservoir models in an acceptable CPU time still remains a key issue for any reservoir simulation software. Parallel computing is thus required to speed up the simulations and robust numerical solutions need to be implemented to insure accurate results especially for simulations of complex compositional physics. In that context, classical fully implicit schemes are often not practical or, even unusable, due to memory and CPU restrictions. We propose new time discretization methods which mix the accuracy and stability of the fully implicit methods and CPU performances and low memory consumption of the explicit ones. Within these approaches, a fully implicit scheme is applied in parts of the reservoir with highest physical property variations, and an explicit method is used in the other ones. Explicit schemes are delimited by a stability CFL condition. Explicit cells with large variations on the unknown are switched dynamically to implicit ones to improve global simulation CPU performances. These status computations are based on either threshold or spectral criteria. Implicit grid blocks may also be discretized using fully*

*Institut Français du Pétrole, France.

implicit or quasi-implicit schemes depending on the fluid composition variations.

These different schemes have been parallelized and integrated in a multi-purpose industrial reservoir simulator. The CFL criteria are discussed and tested on academic reference cases and then, comparisons of the available methods are presented for large compositional real case studies run on different parallel hardware platforms.

INTRODUCTION

High performance computing has always been used in the petroleum industry for the simulation at fine scale of large full field reservoirs. With the emergence of low-price multiprocessor hardware platforms, such as PC clusters or clusters of symmetric multiprocessing (SMP) architectures, commercial simulator software have been adapted to always give the best performance. Given these increased capacities, the reservoir engineers now require a more detailed characterization of the reservoir structure resulting in mega-cell discretized reservoir models. Moreover, gas condensate or volatile-oil reservoir modeling requires a large number of hydrocarbon components to insure better description of oil and gas compositions.

Due to these requirements, the traditional fully implicit models are not adapted to treat these problems within acceptable computing time and/or memory requirements. On the other hand, simulations of complex compositional recovery processes in a heterogeneous or largely faulted reservoir is not viable with IMPES conventional approaches[1] due to the low level of implicitness used and due to the well-known stability criterion which requires reducing the time step length to impractical values. Improved formulations with reduced time and memory requirements have to be defined to solve these large problems.

In this paper, some hybrid formulations of the equations addressed in reservoir simulation are exposed and discussed. All these formulations define regions where more robust and, thus, more expensive schemes are needed and others where simpler schemes are sufficient. Criteria are defined to automatically switch status of the reservoir cells from one region to another. Different criteria have been tested and their advantages and drawbacks are discussed.

Moreover, all these formulations have been optimized through a parallel algorithm to achieve good performances for large compositional reservoir models run on multiprocessor hardware.

Some applications of these techniques are displayed on a large compositional model with more than one million active cells and a 9-component oil representation.

MODEL DESCRIPTION

General Considerations

The main equations to be solved in reservoir simulation are mass conservation equations for each component.

Mass conservation for the water component,

$$\frac{\partial}{\partial t}(\rho_w S_w \phi) + div(\rho_w v_w) = f_w \quad (1)$$

Mass conservation for a hydrocarbon component i,

$$\frac{\partial}{\partial t}(\rho_o S_o X_i \phi + \rho_g S_g Y_i \phi) + div(\rho_o X_i v_o + \rho_g Y_i v_g) = f_i \quad (2)$$

In reservoir simulation, these equations are solved using a Newton method and the transport term may be written using either an explicit[2] or implicit[3] formulation. The implicit formulation is unconditionally stable and allows large time steps. It is commonly used in reservoir simulations, however, for large compositional cases it is limited both in terms of memory and CPU time. The explicit formulation has a CFL condition, which limits the time step extension. However, this method is cheaper in terms of memory and Newton resolution time.

Adaptive Implicit Method (AIM)

Work has already been carried out to adequately mix these two formulations[4,5,7,10]. The main idea is to have an unconditionally stable formulation for cells with the greatest variations on variables (typically near the wells or near a saturation front where the CFL condition is most critical) and to use an explicit and cheaper formulation for the cells where the CFL condition is less constraining. This method is called Adaptive Implicit or AIM and should take advantage of the two above methods with large time steps and small memory and CPU costs. The main difficulty is to adequately define a way to switch cells from an explicit status to an implicit one.

In our work, two different criteria have been tested. The first one is based on an approach already

presented by Russell[10], which uses a CFL condition on the pressure only, and threshold criterion on both the saturation and composition variations.

The second criterion is based on a more complex approach and intends to define the CFL condition for both pressure and saturation variations. Some approaches have also been proposed in other papers[5] which take into account the composition variations. But, in our study, we have found that the calculations of this more general CFL to be quite expensive and we have chosen a practical approach mixing quick CFL calculations and threshold conditions.

Moreover, the CFL calculations proposed for compositional model[4,5], in general, do not take into account the capillary pressure effects and the EOS equilibrium between the different phases. So in this paper, we only focus on the transport phenomenon and a CFL criterion is built for transport between independent phases. The capillary effects are not taken into account by the criterion and both the phase apparition and composition variations due to EOS equilibrium are treated by saturation and composition thresholds.

Using these assumptions, the mass conservation equations may be simplified. The resulting equations for a non-perforated reservoir cell can be written as follows:

$$\frac{\partial}{\partial t}(\rho_w S_w \phi) + div(\rho_w v_w) = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho_o S_o \phi) + div(\rho_o v_o) = 0 \tag{4}$$

$$\frac{\partial}{\partial t}(\rho_g S_g \phi) + div(\rho_g v_g) = 0 \tag{5}$$

where,

$$S_w - S_o - S_g - 1 = 0 \tag{6}$$

Using Darcy's law, the phase velocity is related to the pressure gradient,

$$v_w = -\frac{TK_{rw}}{\mu_w}\nabla(P - \rho_w g z + P_{cw}) \tag{7}$$

a first order system, a new variable q is defined by the following equation,

$$\nabla P - q = 0 \tag{8}$$

Here, it should be noted that this system of equations ((3) to (8)) only gives some information on the approximate local CFL, and the mass conservation equations are otherwise solved using a Newton's method. So, the CFL calculations aim at addressing the cell status based on a flux criterion.

For simplicity sake, the problem is first written in 1D. For each reservoir cell, fluxes between neighboring cells are computed separately and a CFL is defined for each cell. The gradient term in the above equations may then be computed in a given direction (hereafter called x), and the system of equations gives,

$$\frac{\partial P}{\partial x} - q = 0 \tag{9}$$

$$S_w + S_o + S_g - 1 = 0 \tag{10}$$

$$\frac{\partial}{\partial t}(\rho_w S_w \phi) - \frac{\partial}{\partial x}(TM_w(q - \overline{\rho_w} g z)) = 0 \tag{11}$$

$$\frac{\partial}{\partial t}(\rho_o S_o \phi) - \frac{\partial}{\partial x}(TM_o(q - \overline{\rho_o} g z)) = 0 \tag{12}$$

$$\frac{\partial}{\partial t}(\rho_g S_g \phi) - \frac{\partial}{\partial x}(TM_g(q - \overline{\rho_g} g z)) = 0 \tag{13}$$

where, $M = \rho Kr / \mu$ is the phase mobility.

The system is written using a quasi-linear first order form.

$$A(P,q,S,x)R_x + B(P,q,S,x)R_t + C(P,q,S,x) = 0 \tag{14}$$

R is the unknown vector (P, q, Sw ,So ,Sg). The parameters constituting the matrices A and B are arranged as follows:

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ X & -TM_w & -Tq\frac{\partial M_w}{\partial S_w} & -Tq\frac{\partial M_w}{\partial S_o} & -Tq\frac{\partial M_w}{\partial S_g} \\ X & -TM_o & -Tq\frac{\partial M_o}{\partial S_w} & -Tq\frac{\partial M_o}{\partial S_o} & -Tq\frac{\partial M_o}{\partial S_g} \\ X & -TM_g & -Tq\frac{\partial M_g}{\partial S_g} & -Tq\frac{\partial M_g}{\partial S_g} & -Tq\frac{\partial M_g}{\partial S_g} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ X & 0 & \rho_w\phi & 0 & 0 \\ X & 0 & 0 & \rho_o\phi & 0 \\ X & 0 & 0 & 0 & \rho_g\phi \end{bmatrix}$$

The terms X contain the derivatives of the system with respect to P which are later eliminated. The stability of the system may be seen as an eigen-value problem,

$$\det(B - \mu A) = 0 \tag{15}$$

And the CFL is respected if the following relation is true,

$$\Delta t \le \Delta x . \min_{i=1,5}|\mu_i| \tag{16}$$

The system has zero eigen-values corresponding to the pressure variable. As the pressure is always an implicit variable, these zeros may be discarded and we only focus on the non-zero eigen-values for the stability study. Moreover, the size of the system may be reduced if the pressure is eliminated and if we note $\lambda=1/\mu$,

$$\det(B-\mu A)=\mu_1 A_{11}.\det(F-\lambda G)=0 \qquad (17)$$

The CFL criterion becomes $\Delta t \le \Delta x.\max_{i=1,4}|\lambda_i|$ and F and G have the following expressions,

$$F=\begin{bmatrix} 0 & -1 & -1 & -1 \\ TM_w & Tq\frac{\partial M_w}{\partial S_w} & -Tq\frac{\partial M_w}{\partial S_w} & -Tq\frac{\partial M_w}{\partial S_g} \\ TM_o & -Tq\frac{\partial M_o}{\partial S_w} & -Tq\frac{\partial M_o}{\partial S_o} & -Tq\frac{\partial M_o}{\partial S_g} \\ TM_g & -Tq\frac{\partial M_g}{\partial S_w} & -Tq\frac{\partial M_g}{\partial S_o} & -Tq\frac{\partial M_g}{\partial S_g} \end{bmatrix}$$

$$G=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & -\rho_w\phi & 0 & 0 \\ 0 & 0 & -\rho_g\phi & 0 \\ 0 & 0 & 0 & -\rho_g\phi \end{bmatrix}$$

This small system is solved using direct methods and the eigen-values are determined along the x direction (1-D problem) of each reservoir cell.

In 3-D reservoir geometries, The CFL for each reservoir cell may be written as in 1D for a given direction. For a unit vector n, the CFL condition for the stability of an explicit discretization of a reservoir cell i has the following expression,

$$\lambda(n)\Delta t^{n+1}.\left(\max\left(|n_x|\Delta x_i,|n_y|\Delta y_i,|n_z|\Delta z_i\right)\right)^{-1} \le 1 \qquad (18)$$

The global CFL is then the maximum of the above expression for all vectors n. This relation is too restrictive for reservoir simulations and more cells than needed are switched to implicit. So, we use a CFL using total fluid velocity[5], which requires that the domain of dependence of the system of equations remains within a rectangular prism on the neighboring cells. The CFL on a cell is calculated for a unit vector n parallel to the total fluid velocity v. So, we can write, $n = v/\|v\|$, with $v=v_w+v_o+v_g$.

$$\lambda_{\max}.\Delta t^{n+1}\max\left(\frac{|v_x|}{\Delta x_i},\frac{|v_y|}{\Delta y_i},\frac{|v_z|}{\Delta z_i}\right)/\|v\| \le 1 \qquad (19)$$

This last condition assured good stability in our tests and is quite cheap to evaluate.

Implicit Explicit Method (IMPEX)

Another solution has already been proposed to mix advantages of explicit and implicit treatment of the flow terms in the transport equations. Quandalle and Savary[6] presented in 1989 a method, implicit in pressure and saturations and explicit in compositions for compositional models. More recently, robustness and efficiency of this method have been verified on synthetic compositional models[7]. In this approach, the full Jacobian matrix, reduced to a 3 x 3 - block matrix by elimination of selected equations is used to solve the implicit P, Sw, and Sg unknowns. The variations of oil and gas compositions are next calculated easily from these implicit unknowns. Behind this method is the assumption that pressure and saturation unknowns are strongly coupled by mobility and relative capillary pressure terms, while component mole fractions are less strongly coupled from grid block to neighboring ones. This is often the case even with compositional models unless the diffusion/dispersion fluxes are modeled.

Advantages of this approach are numerous. It is easy to implement in a multipurpose reservoir simulator, and benefits from optimized and efficient Black-oil implicit linear solvers. The parallelization of the method should give better speed-up than AIM because problems of load balancing between implicit and explicit regions of the reservoir could be avoided and it can be used without constraint on the time step length by any CFL condition.

Hybrid AIM-IMPEX Method (AIMPEX)

This scheme is a further optimization of the AIM scheme. It mixes both AIM and IMPEX approaches and three different statuses may be addressed to the reservoir cells. A fully implicit formulation is used for the cells with the greatest variations. An IMPEX formulation is applied for the cells with important pressure and saturation variations and weak mole fraction variations, an explicit formulation is used for the remaining cells.

High Performance Computing Aspects

The parallel version of the IFP Group multipurpose reservoir simulator is designed for parallel shared memory platform (SMP nodes) and used the

OpenMP paradigm[11] for the management of the parallelism. A hybrid version is under development and will mix MPI (Message Passing Interface)[12] for high level communications and OpenMP for low level parallelism. This version will work on clusters of SMP nodes, the inter-nodes communications will be handled by MPI and the intra-nodes parallelism will be managed either by MPI and or by OpenMP.

This paper only concerns the development and the results obtained with the OpenMP version of the software but the hybrid version to come will have the same features.

The conventional implicit (SOLSS) and explicit (IMPEM) formulations implemented in the software have already been parallelized in former works[8]. The new models AIM, IMPEX and AIMPEX described here before, which mix implicit and explicit models, mainly use the SOLSS and IMPEM parts of the program but some specific optimizations have been performed to take advantage of the particular structure and reduced number of unknowns of the matrix of the linear system.

As the ratio between implicit and explicit cells changes during the simulation in the AIM and AIMPEX models, we designed dynamic data structures for the linear solver which are updated when status of cells changes.

With these structures, we reduced significantly the memory requirements. For instance, the memory used by the AIM model for the one million grid blocks test is 40% less than the memory required to run the simulation with the fully implicit scheme.

The critical part of the program is the parallel linear solver. The software uses the Bi-Conjugate Gradient Stabilized (Bi-CGSTAB)[9] algorithm preconditioned with the Incomplete LU Factorization of degree zero either on the pressure unknowns (P-ILU0P) or on the full Jacobian matrix.(P-ILU0). The Bi-CGSTAB implementation is mainly made of two calculation units, a matrix/vector product and the pre-conditioner.

The test cases described hereafter in this paper are very interesting because of the conductive fault and the injector wells which introduce heterogeneities on the distribution of implicit cells inside the reservoir. As a same calculation for an implicit cell is much more CPU time-consuming than an explicit one, these heterogeneities create bad load balancing on the processors and slow down the code running on a parallel computer.

Typically, matrix/vector products in the linear solver are very sensitive to this and a dynamic and optimized load balancing for parallel calculations was developed. This algorithm automatically computes at each time step the best way to distribute the calculations above the processors. As the load balancing was very bad without this algorithm, the speedup of this part of the code was limited to a value lower than half times of the number of processors. Now, with this algorithm, even if the load balancing still remains not perfect because the number of treated elements is never exactly the same and some cache memory effects have important impacts, we recorded on the treated cases a speedup of 8 for the matrix/vector products on 8 processors.

As explained before, two parallel pre-conditioners P-ILU0P and P-ILU0 are implemented in the software. For the simulations, we used the P-ILU0P method. This pre-conditioner is not affected by the distribution of the implicit cells because only pressure unknowns are considered as for explicit formulations. The parallelization of the P-ILU0/P-ILU0P pre-conditioners is based on a partitioning of the matrix graph of the linear system. An in-house graph partitioner has been developed, based on matrix graph and selected grid properties. The parallel algorithm of the P-ILU0/P-ILU0P pre-conditioners alternates calculations on domains and inter-domain zones[8].

If the distribution of the implicit cells has no impact on the performances of P-ILU0P, it is not the case for P-ILU0. Optimization of this algorithm still has to be done and the idea is to build a better partitioning by adding constraints on the nodes of the matrix graph as inputs of the partitioner. These added constraints should be for example the number of implicit unknowns of the cells represented by a node. The dynamic aspect of the AIM and AIMPEX models makes more difficult the use of this method because the graph partitioning should be updated when the status of the cells changes. Such update should be very expensive in CPU time. A solution could come from the grid partitioning algorithm such as ParMETIS[13] which allows re-partitioning with lower calculation costs.

RESULTS AND DISCUSSION

These different methods have been implemented in a commercial release of the IFP Group multipurpose reservoir simulator and have been tested on a compositional field case study. Two grids have been build, one with roughly 180,000 active cells (later referred as 180k case), and the other with one

million active cells (later referred as 1M case). The reservoir has an area of 3.75 km*10.2 km, and the 180k case has a 75*204*12 grid with 50m*50m cell dimensions (Fig. 1). The 1M case uses a 150*408*17 discretization grid with 25m*25m cell dimensions. The reservoir is slightly slanted from west to east and an aquifer is located on the eastern flank. The porosity varies from 0.01 to 0.2 and is better on the reservoir crest and in its northern part. Horizontal permeabilities are about 20 mD and vertical permeabilities are ten times lower. Moreover, there is a conductive fault in the southern part of the reservoir. This fault is oriented from east to west (from the aquifer to the crest) and extends for 3 km. Its permeability is about 1.5D and is modeled using the conductive fault model integrated in the simulator[13].

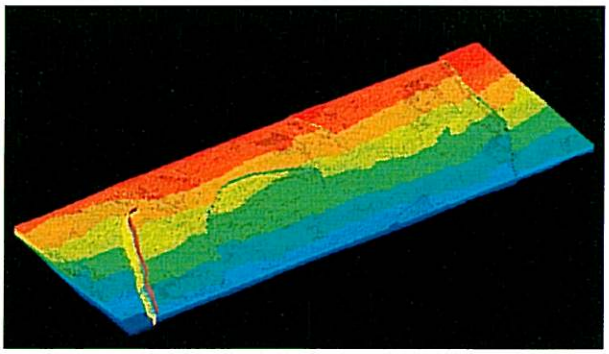

Fig. 1. Reservoir grid.

The oil is modeled by a compositional model with 9 components (C1, N2, C2-COH, C3-C4, C5-C6, C7-C9, C10-C13, HCO1, and HCO2). The initial oil in place is 191 Mm^3 at standard conditions and initial pressure is 450 bars at a depth of 3500 m (the reservoir is located between 3100 and 3800m) and the initial water-oil contact is located at 3800m depth.

Eight (8) oil producers are situated in the crest and 6 water injectors are located on the flank near the aquifer. The surface oil rate of each producer is set constant at 2500 m3/d and the surface water injection of each injector is 4000 m3/d. The injection is automatically calculated by the simulator such that the total reservoir injection rate equals its total voidage production rate. The wellhead pressure of the producers is controlled and limited to 17 bars. The bottom-hole pressure of the injectors is limited to 600 bars. The reservoir is produced for 20 years.

The presence of the conductive fault disables the use of explicit scheme because of the water invasion at its vicinity. The simulation runs using the AIM, the IMPEX and the AIMPEX formulations were made on parallel computers. The test cases presented in this paper were run on different parallel SMP platforms:

-a Dell Precision 530, bi-processor Pentium4 Xeon @2,4GHz with 2GB DDRAM,

-a SGI O2000, 20 processors R10K @195MHz, 10GB memory,

-an IBM p690 Turbo, 32 processors Power4 @1,3GHz, 64GB memory.

180k Case Study

At the end of the simulation, the injected water has invaded large areas of the reservoir and oil has been displaced to the producers. Using AIM schemes, correlation may be found between implicit cells and water invaded cells (Figs. 2 and 3). During the simulation, important saturation variations occurred in these cells and those have been switched from explicit to implicit by the simulator. During the simulation 82,813 cells (45 %) have switched to an implicit status.

The mixed formulation of the equations (AIM or IMPEX) allows great reduction in the simulation time. The results are displayed in Table-1 and Figure-7 for different machines for the 180k compositional case.

Table 1. Comparisons on a Linux computer.

	Step	Newton it.	Solveur it.	CPU time
AIM	278	278	13559	24315
AIMPEX	278	278	13177	22250
IMPEX	278	278	13870	20194
SOLSS	278	278	14813	73169

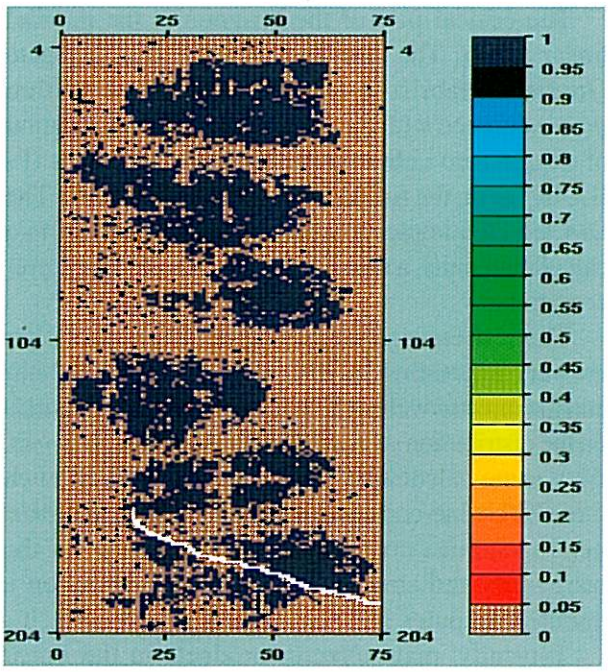

Fig. 2. Implication map in the most invaded layer.

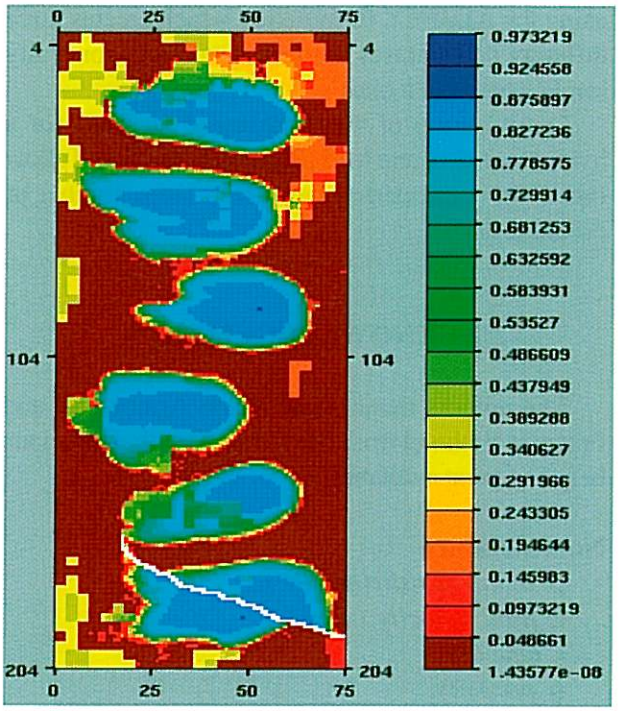

Fig. 3. Water saturation map in the most invaded layer.

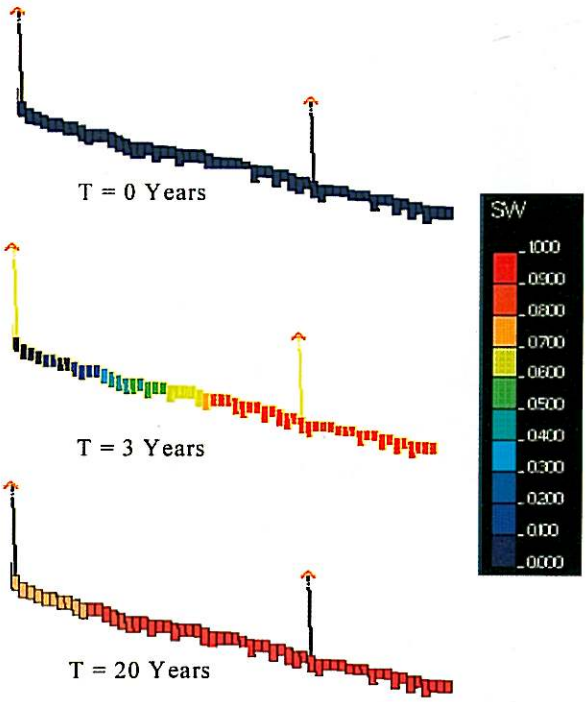

Fig. 4. Water invasion in the conductive fault.

The adaptive implicit method switches from explicit to implicit the most varying cells given our proposed CFL based criteria. The physical results are very similar to the fully implicit ones which is to say that the criterion adequately takes into account the saturation fronts and switch to implicit the cells located near the fronts (Figs. 5 and 6). The conductive fault is also quickly invaded by the water coming from the injectors and the water cut of the producing well located near the fault increases rapidly (Figs. 4 and 6). The fault-cells are treated implicitly due to their strong variations during the time steps. Moreover, the required memory is also decreased from more than 2Gb to less than 1Gb (55% gain).

Furthermore, hybrid formulations (AIM or AIMPEX) allow to reduce both time and memory requirements and ensure good physical results.

1M Case Study

The full production history has been run on 8 processors of the IBM P690 machine using the AIMPEX formulation. Partial simulations were carried out on 1, 4 and 8 processors in order to evaluate speedups for the other formulations. The obtained results are displayed on Figure 8. AIMPEX runs three times faster than the fully implicit model and makes feasible a large compositional simulation overnight. The IMPEX simulation is faster than the AIM. This is explained by the high number of implicit

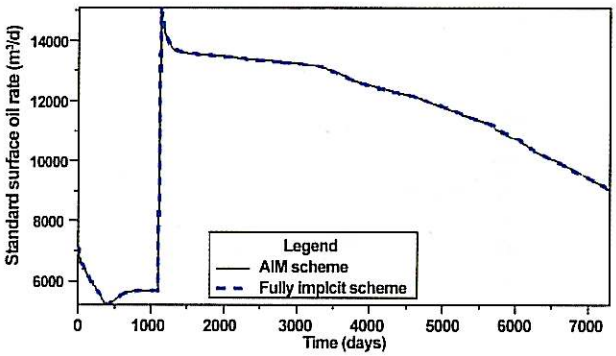

Fig. 5. Total oil rate comparison.

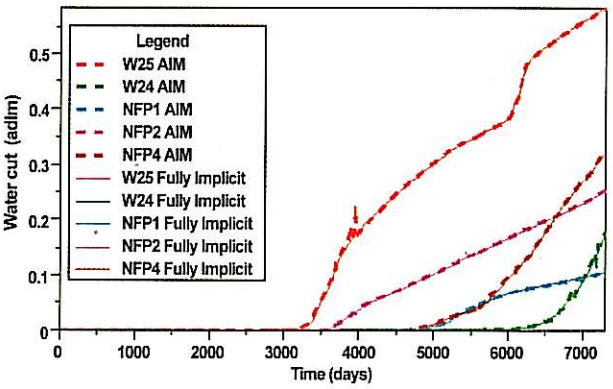

Fig. 6. Water cut comparison.

cells imposed by saturation variations. Nevertheless, it has been observed that for simulations with high oil or gas composition variations, AIM becomes faster than IMPEX. The field performance for this case is the same as for the 180k case.

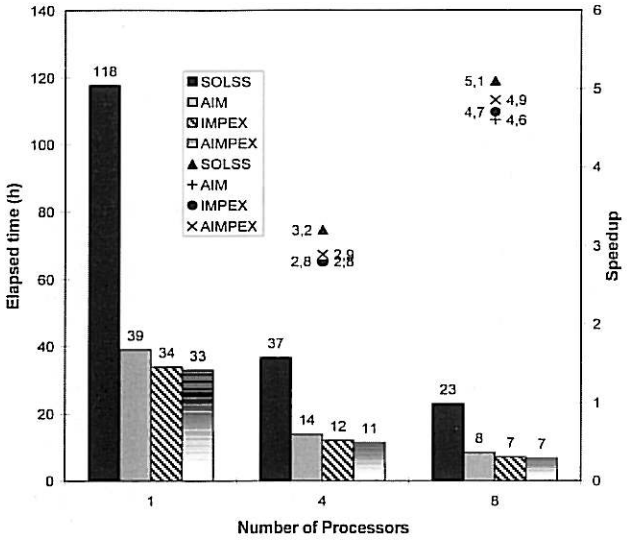

Fig. 7. Elapsed times and speedups for 180k case on SGI O2000.

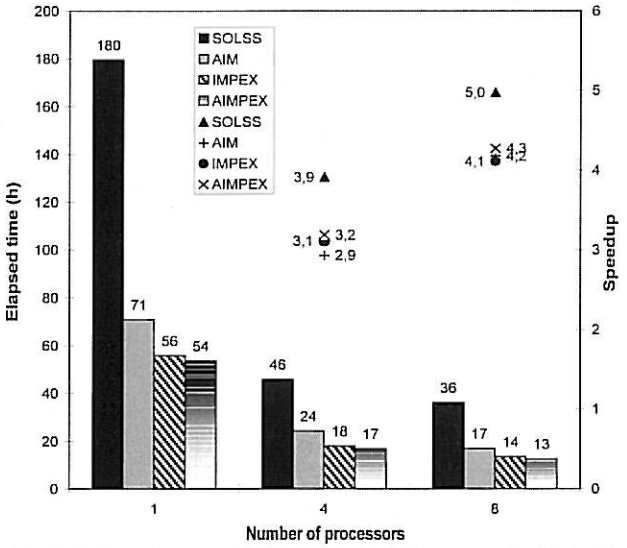

Fig. 8. Elapsed time and speedups for 1M case on IBM p690 Turbo.

The SOLSS fully implicit simulation requires 20 Gb whereas, the AIM, AIMPEX and IMPEX schemes only need less than 7Gb memory.

Our parallelized hybrid algorithms perform large compositional simulations where classical fully implicit methods, even parallelized, exceed computer capabilities in terms of memory and CPU time.

CONCLUSIONS

We propose integrated parallelized numerical schemes to perform large compositional reservoir simulations. In the presented results, the global simulation time is greatly reduced by using hybrid formulations. Best performances in terms of simulation time and physical results were obtained using the AIMPEX formulation which creates three different cell statuses in the grid varying from fully implicit to explicit ones.

Optimization of these advanced methods for a hybrid OpenMP and MPI parallelization should allow obtaining better performance on a large number of processors.

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Nomenclature

ρ, *molar density*($mol.m^{-3}$).
v, *fluid velocity* ($m.s^{-1}$).
t, *time* (s).
ϕ, *porosity*.
T, *transmissivity* (m^3).
M, *mobility* ($Pa^{-1}.s^{-1}$).
S, *saturation*.
P, *pressure* (Pa).
w, *water phase*.
o, *oil phase*.
g, *gas phase*.
X, *molar fraction in oil phase*.
Y, *molar fraction in gas phase*.

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