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Performance of IMPSAT and IMPSAT-AIM Models in Compositional Simulation

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Abstract

The current trend in industry is to use finer and finer grid with larger and larger number of components. This requires the development of faster simulation techniques than those currently available in commercial simulators.

The fully implicit (FIM) model, the implicit pressure and explicit saturations (IMPES) model and the adaptive implicit (AIM) model are the traditional approaches. The IMPSAT (implicit pressure and saturations and explicit component mole fractions) model has been proposed in the literatures, but so far it is not considered a viable approach. This may be a result of lack of suitable stability analysis and improper implementation. Our analysis shows that the IMPSAT model is significantly more stable than the IMPES model, and in many cases substantially less expensive than the FIM model. The IMPSAT model becomes particularly attractive as the number of components becomes large. IMPSAT can also be used in an adaptive implicit approach to form various IMPSAT based adaptive implicit (IMPSAT-AIM) models.

A new General Purpose Research Simulator (GPRS) using a General Formulation Approach has been developed and tested. The General Formulation Approach used in GPRS can be used to obtain any type of model. We can easily form a model by selecting any reasonable set of primary variables and any level of implicitness from IMPES to FIM. One important subset of models that have been developed from this new approach is the IMPSAT model and the IMPSAT based AIM models.

The performance of different compositional models has been evaluated using a wide range of problems. We found that the IMPSAT model and the IMPSAT-AIM models have very good performance, and they are more efficient than the traditional models (FIM, IMPES and AIM). The IMPSAT model is generally over 50% faster than the IMPES model due to its improved stability. For problems that are not very hard, the IMPSAT model is cheaper to run than the FIM model since it reduces the number of unknowns that have to be solved implicitly. The IMPSAT-AIM models are more flexible, more stable and with appropriate linear solvers have the potential to be less expensive in terms of CPU time than the traditional AIM model.

Introduction

For isothermal compositional models, the implicit level (number of implicit variables per gridblock) ranges from 1 in the IMPES model to number of components (n_c) in the FIM model. With the increase of implicit level, stability increases, and we can use larger timestep size with fewer Newton iterations. However with the increase in number of implicit variables, the computational cost per Newton iteration also increases dramatically. In the IMPES model, the cost of each linear solve is fixed relative to n_c, because we always solve for one variable (pressure) per gridblock, but in the FIM model, the cost of each linear solve increases in $O(n_c^{1.1\sim 1.2})$. The question here is how to balance these two factors, and select a suitable implicit level that is fast enough and stable enough.

To make a simulation run fast, we need to reduce the number of implicit unknowns per gridblock from n_c. This number is minimum for the IMPES model and maximum for the FIM model. We also like a model to only solve for a fixed number (relative to n_c) of unknowns per gridblock as is the case for the IMPES model. Under these constraints, implicit pressure and implicit saturations appear to be desirable, because both variables are independent of the number of components. Here we propose an IMPSAT model[1,2], where only pressure and saturations are treated implicitly, and all of the component mole fractions are treated explicitly. Since one of the saturations can be removed using the saturation constraint equation, we are left with as many unknowns per gridblock as the number of phases (n_p). Since typically we have two or three phases, the number of unknowns per gridblock for the IMPSAT model is three or less. Compared to

n_c unknowns per gridblock for the FIM model, the IMPSAT model has the potential to yield big savings in computational cost per linear solve, especially for problems with large number of components.

In fact, the IMPSAT model is not new, Quandalle and Savary[1] and Branco and Rodriguez[2] also proposed similar ideas. In Quandalle and Savary's paper[1], it was called IMPIMS (implicit pressure and implicit saturations) model, and they used it to simulate a laboratory experiment. In Branco and Rodriguez's paper[2], it was called semi-implicit model, and several small test problems were used to validate the model. Neither paper provided a detailed analysis of the model, no stability criteria and no comparisons with the IMPES and FIM models were provided. Furthermore all of the tests were on small simple problems. In order to prove that the IMPSAT model works in practice, more work was needed in all of these areas. As a matter of fact the IMPSAT model is an option in at least one of the commercial simulators, but so far it has not worked properly. In this paper we will show that when properly implemented, the IMPSAT model works very well for most cases. Hopefully this will lead to greater use of this method.

A General Purpose Research Simulator (GPRS)[3] is developed and used in this study. GPRS uses a General Formulation Approach[3] to generate all of the compositional models. This approach can be used to obtain any desired formulation, regardless of the type of model, type of variables and level of implicitness. All of the operations are performed on individual gridblocks, so the extension to the use of different implicit levels for different gridblocks (Adaptive Implicit Method, AIM) is straightforward. The cost of this approach is of first order to the number of gridblocks. Within this approach we can treat each part (phase mobility, phase density and component mole fraction) of the transmissibility term differently, by either fixing a part at the old time level or updating it iteration by iteration.

IMPSAT model

In reservoir simulations, all variables are coupled from gridblock to gridblock due to the flux between two gridblocks and the upstream weighting of transmissibility terms. Consequently it is desirable to solve for all of the variables together, as is the case for the FIM model. But in reality the strength of coupling for each variable is different, pressure is always strongly coupled from gridblock to gridblock, while saturations and component mole fractions are less strongly coupled from gridblock to gridblock. The IMPES model is based on this observation, it ignores the coupling of saturations and component mole fractions between gridblocks by treating the transmissibilities explicitly. Once this is done, pressures are decoupled and can be computed implicitly followed by explicit updating of saturations and component mole fractions gridblock by gridblock.

Here we make a new claim: the coupling between component mole fractions is even weaker than the coupling between saturations[3]. Based on this, we propose the IMPSAT model, where the phase density and the component mole fraction in the transmissibility part are treated explicitly. Once this is done, both pressure and saturations are simultaneously solved for first, then component mole fractions are updated explicitly gridblock by gridblock. Since we only ignore the coupling between component mole fractions, which is generally weak, the IMPSAT model should be more stable than the IMPES model. Hopefully this improved stability will allow timesteps that are of the same order as in the FIM model.

In the General Purpose Research Simulator (GPRS), the following stability criterion is used for the explicit treatment of saturations, which is suitable for two-phase (gas/oil) flow without capillary pressure.

$$CFL_S = \frac{\Delta t}{V\phi} \cdot \frac{\frac{\lambda_o}{\lambda_g}\frac{d\lambda_g}{dS_g} q_g - \frac{\lambda_g}{\lambda_o}\frac{d\lambda_o}{dS_g} q_o}{\lambda_o + \lambda_g} \le 1 \quad \text{……………..(1)}$$

where Δt is the timestep size, V is the cell volume, ϕ is the porosity, λ_g and λ_o are the gas and oil phase mobilities, q_g and q_o are the gas and oil phase volumetric flow rates. Coats[4] derived the general stability criterion for multi-dimensional three-phase flow, including both gravity and capillary pressure. All of the compositional problems used in this study are two-phase (gas/oil) flow without capillary pressure, and at that condition, the general stability criterion[4] can be reduced to Eq. 1. The stability criterion for the explicit treatment of component mole fractions for three-phase flow is[3]

$$CFL_X = \frac{\Delta t}{V\phi} \frac{\rho_o q_o x_c + \rho_g q_g y_c + \rho_w q_w \omega_c}{\rho_o S_o x_c + \rho_g S_g y_c + \rho_w S_w \omega_c} \le 1 \quad \text{….(2)}$$

where y_c, x_c and ω_c are the component mole fractions in the gas, oil and water phases, ρ_g, ρ_o and ρ_w are the gas, oil and water phase densities. If we assume that the water component is completely separated from the hydrocarbon components, then ω_c will be constants ($\omega_w = 1$ and $\omega_c = 0, c \ne w$), and we only need stability criterion for y_c and x_c. Eq. 2 can be simplified as

$$CFL_X = \frac{\Delta t}{V\phi} \frac{\rho_o q_o x_c + \rho_g q_g y_c}{\rho_o S_o x_c + \rho_g S_g y_c} \le 1,\ c \ne w \quad \text{…...(3)}$$

Note that CFL_S and CFL_X are different, Eq. 1 is the saturation based CFL number and Eq. 2 and Eq. 3 are the component mole fraction based CFL numbers, and for the same CFL numbers, the stable timestep sizes will be different for the two methods.

In the IMPES model, both the saturations and the component mole fractions are treated explicitly, so it needs to satisfy both Eq. 1 and Eq. 2. While in the IMPSAT model, only the component mole fractions are treated explicitly, so it only needs to satisfy Eq. 2.

Light components cause more instability than heavy components, this is because lighter components are more likely to stay in the gas phase, which has a much higher flow rate than the oil phase due to its small viscosity. So if we include one extra variable x_l, y_l or z_l (component l is the lightest one) in the implicit variables, the new model (IMPSAT++) could be much more stable than the IMPSAT model. While GPRS allows any level of implicitness, we have not fully tested models of this type. In this paper, we will only consider the IMPSAT model.

IMPSAT-AIM models

For large and difficult problems, the stable timestep size of the IMPES model is generally too small to be practical, and for some problems even the IMPSAT model is not stable enough. While the FIM model is always stable, it is just too expensive for problems with large number of components. In such cases, we propose adding the IMPSAT model into an adaptive implicit (AIM) scheme[5], we call this new AIM model the IMPSAT based adaptive implicit (IMPSAT-AIM) model. Compared to the traditional AIM (IMPES+FIM) model, it is more flexible, more stable and less expensive. There are three variations of the new IMPSAT-AIM model:

- **IMPES+IMPSAT** Here we use the IMPSAT model to replace the FIM model, and this model is the least expensive in terms of cost per Newton iteration. However, this model is less stable than the IMPSAT model, so any problem that can not be handled by the IMPSAT model, can also not be handled by the IMPES+IMPSAT model.
- **IMPSAT+FIM** Here we use the IMPSAT model to replace the IMPES model, and this model is the most stable one of the AIM models.
- **IMPES+IMPSAT+FIM** Here we use the IMPSAT model as the third formulation in a new AIM model, and this is the most general model. Actually, the first two AIM models and the traditional AIM model are all special cases of this general AIM model.

All of these AIM models are very easy to build using the proposed General Formulation Approach[3], where all of the operations are done gridblock by gridblock, and we can control the implicit level at each gridblock separately.

Depending on problem difficulty, one of these new AIM models will outperform the traditional AIM model. For easy problems, the IMPES+IMPSAT model is the best to use, for hard problems, the IMPSAT+FIM model is a better choice. With properly tuned percentages of IMPES, IMPSAT and FIM gridblocks, the IMPES+IMPSAT+FIM model should be the most efficient model to use, especially for large field case studies.

For AIM models, there are two ways to decide the timestep size and assign implicit level for each gridblock, and they are discussed bellow:

- **Fixed timestep size** For a given timestep size, assign the implicit level for each gridblock according to the stability criteria (CFL number at that gridblock). This method is straightforward, and the percentage of gridblocks for each formulation changes from timestep to timestep.
- **Fixed percentage** For a fixed percentage of gridblocks for each formulation, first decide the maximum stable timestep size which can satisfy the given percentage, then assign the implicit level for each gridblock according to the stability criteria. This method is not straightforward, in order to decide the maximum stable timestep size for a given percentage, we need to order the gridblocks according their CFL numbers.

For AIM systems, the performance of linear solvers and preconditioners depends strongly on the percentage of gridblocks for each formulation[3]. Considering that, the fixed percentage method is used in GPRS. For all of the AIM runs performed in this study, the percentage for each formulation was given below:

- **IMPES+FIM** 90% IMPES gridblocks and 10% FIM gridblocks
- **IMPES+IMPSAT** 90% IMPES gridblocks and 10% IMPSAT gridblocks
- **IMPSAT+FIM** 90% IMPSAT gridblocks and 10% FIM gridblocks
- **IMPES+IMPSAT+FIM** 90% IMPES gridblocks, 9% IMPSAT gridblocks and 1% FIM gridblocks

In all of the AIM models, the well blocks are either FIM or IMPSAT.

Model Validation

The black-oil and the compositional models in GPRS are validated. The black-oil model results are compared with the results from Eclipse 100 (Geoquest, 2000A), and the compositional model results are compared with the results from Eclipse 300 (Geoquest, 2000A). The black-oil model is treated as a special case of the general compositional model in GPRS, where flash calculations are no longer needed.

Black-oil Model

The first problem is the first SPE comparative solution project[6]. Here a three-phase black-oil simulation of a quarter of a 5-spot is done with a 10×10×3 grid. Each layer has different properties. One gas injector is located at (1, 1, 1), and one oil producer is located at (10, 10, 3), and both wells are under constant rate control. Initially, the reservoir is full of undersaturated oil and connate water. The simulation was run to 10 years with a maximum timestep size of 180 days, and the results from GPRS are compared with the results from Eclipse 100. Compositional formulation was used to simulate this black-oil problem in GPRS, and both simulators were run in fully implicit mode. The gas was not allowed to re-dissolve.

Fig. 1 and Fig. 2 show the results from GPRS and Eclipse 100. GPRS results are shown in dots, and Eclipse 100 results are shown in solid lines. Fig. 1 shows the oil production rate, plateau production up until around 1000 days, then the producer changes to bottom hole pressure (BHP) control. Fig. 2 shows the gas oil ratio (GOR) at the producer, initially, there is no free gas, GOR is constant, after around 660 days, free gas appears, and GOR increases. Basically, the results from these two simulators are the same.

Compositional Model

This is a four-component (C1, C2, C4, C7), two-phase (gas-oil) compositional problem. The grid is 5×5×5. One producer is located at (5, 5, 1), which is under bottom hole pressure (BHP) control. The Peng-Robinson Equation of State[7] was used for flash calculations. Initially the reservoir has both the oil and gas phases. The simulations were run to 1000 days with a maximum timestep size of 30 days, and the results from GPRS are compared with the results from Eclipse 300. Both simulators were run in fully implicit mode.

Fig. 3 and Fig. 4 compare the results from GPRS with the results from Eclipse 300. Initially the reservoir was not at equilibrium, since the same initial overall composition was used for all depths. Up to 300 days gravity dominated the process, causing phase segregation, gas phase moving up and oil phase moving down. After about 400 days gravity segregation is complete and the oil phase starts to cone around the producer by moving up.

Similar to the results in Fig. 1 and Fig. 2, GPRS results are shown in dots, and Eclipse 300 results are shown in solid lines. The black lines are for producer (5,5,1), and the blue lines are for block (1,1,5). Fig. 3 shows the pressure at block (1,1,5) and at the producer (5,5,1). Fig. 4 shows the oil saturation at these two blocks. The oil saturation at the producer block from these two simulators does not match exactly, the reason is that Eclipse 300's convergence criteria (pressure and effective saturation changes)[8] are not as strict as those used in GPRS. Actually Eclipse 300 may go to the next timestep without full convergence in the current timestep. From Fig. 4 we can notice a small glitch (around 90 days) in Eclipse 300 results. By reducing the maximum timestep size from 30 days to 10 days in Eclipse 300, the results improve as shown in Fig. 5. In this case Eclipse 300 used a maximum timestep size of 10 days, and GPRS still used 30 days. Now these two results are almost the same. Hence we can conclude that the compositional model in GPRS works well, and at times it performs even better than the model in Eclipse 300.

Test Examples and Model Performance

The performance of different compositional models has been evaluated using a wide range of problems. Each problem is designed for one specific condition. These conditions include injection of components, heterogeneity, large number of components and large systems. The five compositional problems used here are discussed below:

- **Case 1** This is the same homogeneous 5×5×5 four component (C1, C2, C4, C7) two hydrocarbon phase problem that was used to validate the compositional modeling in GPRS. One bottom hole pressure (BHP) controlled producer is located at (5, 5, 1). This is a relatively easy problem, and both the IMPES and IMPSAT models should perform well.
- **Case 2** This is the same problem as in Case 1, but here an injector is added to increase the difficulty. The injector is located at (1, 1, 1). It is under bottom hole pressure control and C1 is injected. This problem is tough for the IMPSAT model, because a component is injected when the component mole fractions are treated explicitly.
- **Case 3** This is a heterogeneous problem, with four components (C1, C2, C4, C7) and two hydrocarbon phases. The grid is 24×1×25. One bottom hole pressure controlled producer is located at (1, 1, 1-3), and it penetrates only the top three layers. The permeability field is from the 9th SPE comparative project[9]. Only the top layer is used. The permeability changes over four orders of magnitude and it is correlated along the x direction. The primary objective here is to test the performance of different models on a difficult heterogeneous problem. Due to high flow rates in the high permeability regions, this problem is hard for both the IMPES and IMPSAT models.
- **Case 4** This is a nine-component problem. The fluid description is from the 3rd SPE comparative project[10], and the nine components are CO2, N2, C1, C2, C3, C4-6, $C7+_1$, $C7+_2$ and $C7+_3$. The grid is 5×5×5 with homogeneous permeability, and one bottom hole pressure controlled producer is located at (5, 5, 1). Due to the large number of components, this problem is hard for both the IMPES and IMPSAT models.
- **Case 5** This is a large homogeneous problem with 100,000 gridblocks (100×100×10) and four components (C1, C2, C4, C7). One bottom hole pressure controlled producer is located at (100, 100, 1-2), and it penetrates only the top two layers. Compared to other problems, this problem has a much smaller gridblock size (100ft×100ft×10ft compared to 1000ft×1000ft×10ft for other problems). This small gridblock size limits the maximum stable timestep size of the IMPSAT model to around 0.5 days, and it is virtually impossible to run the problem with this model. For the IMPES model, it is even worse. So for this problem, only the FIM and AIM models were used. The stability of the IMPES+IMPSAT model is even worse than the stability of the IMPSAT model, so it was also not used.

For each problem, we compare the results and the stable timestep sizes from different models. The fully implicit model is unconditionally stable, and we can have a timestep of any size. But in practice, in order to control the number of Newton iterations for each timestep, a reasonable timestep size is required, here we limit its maximum timestep size to 100 days. For models that are not fully implicit, such as the IMPES and IMPSAT models, their maximum timestep sizes are limited by their stability (maximum CFL number over all gridblock). Normally this maximum CFL number is set to 1, but in practice, we can use CFL numbers larger than 1, and larger CFL numbers mean larger timestep sizes. Note that the CFL numbers of the IMPES and IMPSAT models are calculated differently, and even for the same CFL numbers, they have different timestep sizes. We also report the total number of Newton iterations performed for each model and each problem, which should give a rough estimation of the cost of each model.

The performance of the IMPSAT (implicit pressure and implicit saturations) model is evaluated for different problems and different CFL numbers (larger CFL numbers lead to larger timestep sizes). CFL=1 is always stable, but CFL>1 may not be always stable. Fig. 6 to Fig. 9 show the timestep sizes of CFL=1 for each problem, compared with the same timestep sizes of the IMPES model. In practice, both the IMPES and IMPSAT models can use CFL numbers larger than 1. Fig. 10 to Fig. 17 show the well block oil saturations for the IMPES and IMPSAT models using larger CFL numbers. The fully implicit result (the dark solid line) for maximum timestep size of 100 days is included for comparison. In Fig. 18, we compare the total number of Newton iterations for the FIM, IMPES and IMPSAT models, which should give us a relative comparison of simulation cost. From all of these results, we observe the following points:

- The timestep sizes of CFL=1 for the IMPSAT model are quite good, ranging from 6 days to 90 days, which are 2 to 7 times larger than those for the IMPES model.
- For Case 1, 2 and 3, the IMPSAT model with CFL=4 is stable, and the IMPES model with CFL=2 is stable. But with the increase of number of components, such as in Case 4, stable timestep limits for both models are reduced. But for all cases, the IMPSAT model can use roughly two times larger CFL numbers than the IMPES model. Combining this with the fact that for a given CFL number IMPSAT timestep is larger, the IMPSAT model can use up to 10 times larger timesteps than the IMPES model.
- The results of the IMPSAT model agree well with the results of the FIM model, and both models appear to have the same level of numerical diffusions. As expected, the IMPES model has less numerical diffusion.
- Compared to the IMPES model, the IMPSAT model needs fewer (over 50%) number of Newton iterations due to its improved stability. The IMPSAT model may cost more in the linear solver part than the IMPES model, because of its increased number of implicit unknowns. But it can also save a lot in flash calculations, whose costs are directly proportional to the number of Newton iterations, and they are one of the most time consuming parts in compositional simulation. Finally, the total cost of the IMPSAT model is generally much lower than the total cost of the IMPES model, and most of the time, it can cut the running time by half compared to the IMPES model.
- For most problems, the improved stability of the IMPSAT model enables it to use the same number of timesteps and Newton iterations as the FIM model (with a maximum timestep size of 100 days). Because the IMPSAT model solves for fewer unknowns in the linear solver part, it is a cheaper alternative to the FIM model.

The performance of the traditional AIM model and three new IMPSAT-AIM models is evaluated here for different problems. The maximum timestep size was set to be 100 days. Fig. 19 to Fig. 20 show the well block oil saturation for Case 2 and Case 4, and the legend in each figure marks the model used. The fully implicit result (the dark solid line) for maximum timestep size of 100 days is included for comparison. In Fig. 21, we compare the total number of Newton iterations for each AIM model and each problem. From these results, we observe the following points:

- The results of all AIM models agree well with the results of the FIM model.
- For easy problems, such as Case 1 and 3, the IMPES+IMPSAT model is faster than the traditional AIM model, since both models use roughly the same number of Newton iterations and the IMPSAT model solves for fewer unknowns than the FIM model.
- For hard problems, such as Case 2, 4 and 5, the IMPSAT+FIM model need far fewer timesteps and Newton iterations than the traditional AIM model, due to the improved stability of the IMPSAT model. Hence for hard problems, the IMPSAT+FIM model is much faster than the traditional AIM model.
- The IMPES+IMPSAT+FIM model is the general AIM model, with proper tuning of the percentages of gridblocks for each formulation according to the difficulties for the IMPES and IMPSAT models, it should be a better choice than all of the other AIM models.

Summary

A new General Purpose Research Simulator (GPRS) has been developed. It incorporates various simulation models and techniques so that their advantages and disadvantages can be investigated in a consistent manner.

A new General Formulation Approach has been developed and implemented in GPRS to facilitate the implementation of different models. This approach can generate any model, regardless of the selection of variables and the level of implicitness. All of the operations are performed on individual gridblocks, so different implicit levels can be used in different gridblocks. This is necessary for the building of AIM models. In GPRS we can also use different variables, we found that the natural variables (pressure, saturations and component mole fractions) are good for the fully implicit model, while the overall variables (pressure, overall component mole fractions) are more efficient for the IMPES model

An extensive study has been conducted for the new IMPSAT (implicit pressure, implicit saturations and explicit mole fractions) model, which is actually a special case of the General Formulation Approach. In addition, we have proposed three new IMPSAT based AIM models, and their performance has been compared with the performance of the traditional AIM model.

Conclusions

- The IMPSAT model is much more stable than the IMPES model, due to the implicit treatment of saturations, and it can use timestep sizes of up to 10 times larger than what is possible with the IMPES model. Compared to the IMPES model, the IMPSAT model needs far fewer timesteps and Newton iterations, and generally can cut the running time by half.
- For problems that are not very hard, the improved stability of the IMPSAT model enables it to use the same number of timesteps and Newton iterations as the FIM model (with a maximum timestep size of 100 days). Because the number of unknowns to be solved is reduced, the IMPSAT model is a cheaper alternative to the FIM model. This is especially true for problems with a large number of components.
- The IMPSAT based AIM models are more flexible, more stable and less expensive to run than the traditional AIM model. With properly tuned percentages of gridblocks for each formulation, the IMPES+IMPSAT+FIM model will always outperform the traditional IMPES+FIM model.

Nomenclature

n_c = Number of components

n_p = Number of phases

q_p = Volumetric flow rate of phase *p* [SCF/Day]

S_p = Saturation of phase *p*

V = Cell volume [SCF]

x_c = Mole fraction of component *c* in the oil phase

y_c = Mole fraction of component *c* in the gas phase

ω_c = Mole fraction of component *c* in the water phase

Greek

Δ = Delta (change)

λ_p = Mobility of phase *p* [1/cp]

ρ_p = Density of phase *p* [Lbm/SCF]

ϕ = Porosity

Subscripts

p = Phase

c = Component

Acronyms

AIM = Adaptive implicit

BHP = Bottom hole pressure

GOR = Gas oil ratio

GPRS = General Purpose Research Simulator

IMPES = Implicit pressure and explicit saturations

IMPSAT =Implicit pressure and saturations

FIM = *Fully implicit*

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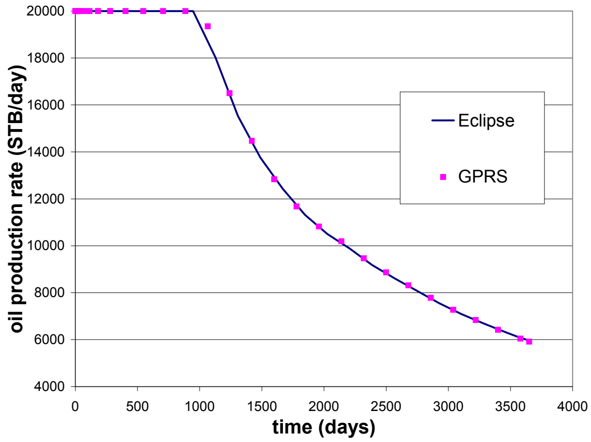

Figure 1 Oil production rate at the producer from GPRS and Eclipse 100 for a black-oil problem

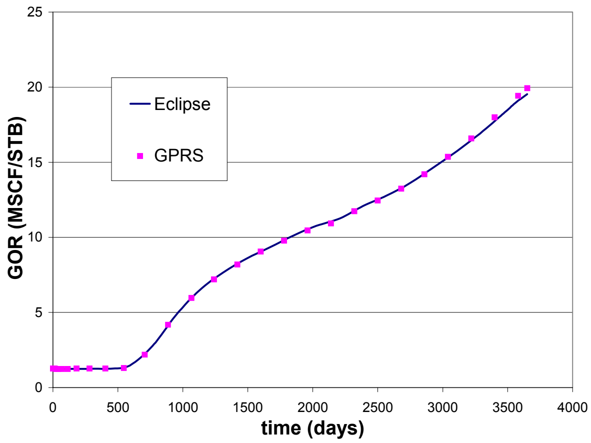

Figure 2 Gas oil ratio at the producer from GPRS and Eclipse 100 for a black-oil problem

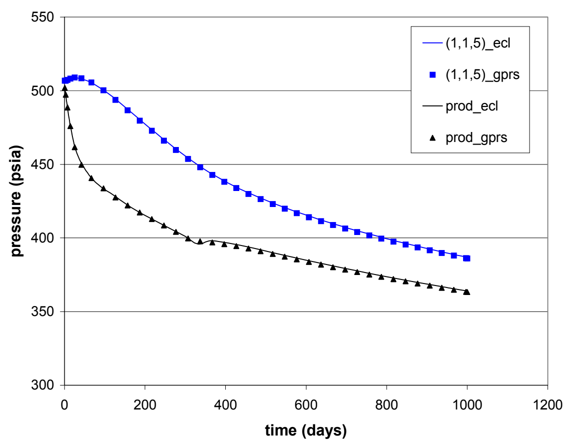

Figure 3 Well block and block (1,1,5) pressures results from GPRS and Eclipse 300 with Δt_{max}=30 days for a compositional problem

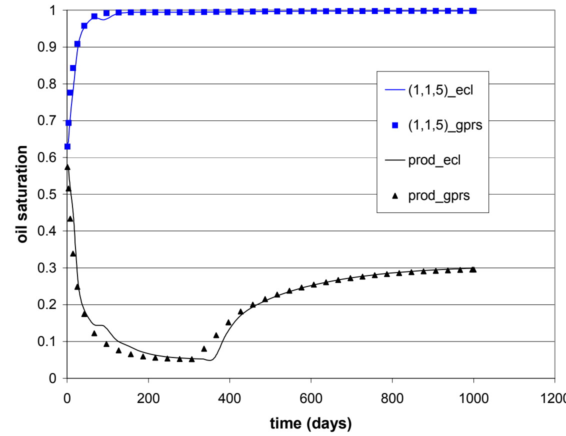

Figure 4 Well block and block (1,1,5) oil saturations results from GPRS and Eclipse 300 with Δt_{max}=30 days for a compositional problem

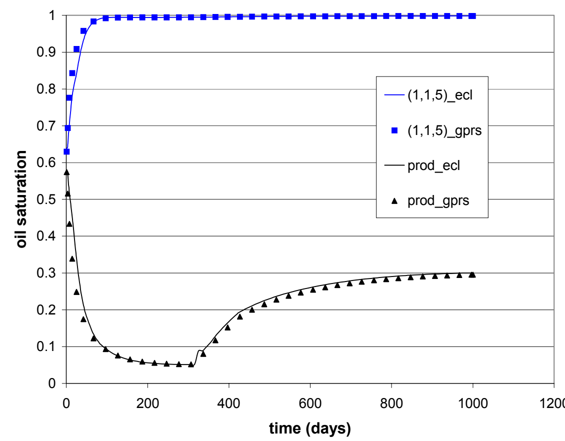

Figure 5 Well block and block (1,1,5) oil saturations results from GPRS and Eclipse 300 with Δt_{max}=30 days for GPRS and Δt_{max}=10 days for Eclipse 300 for a compositional problem

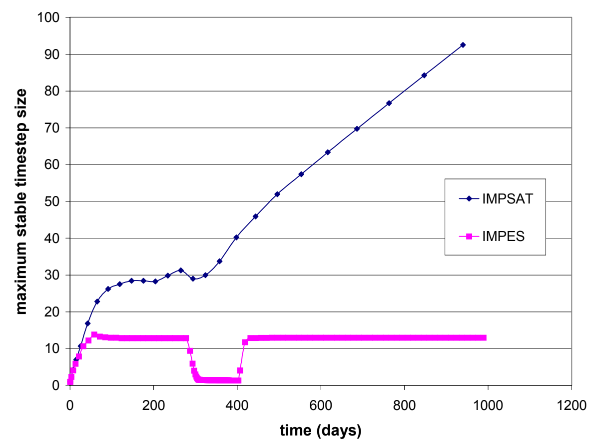

Figure 6 Timestep sizes of CFL=1 for the IMPES and IMPSAT models and Case 1 problem

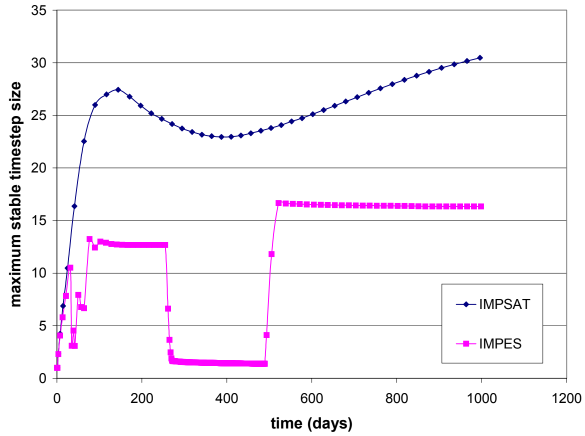

Figure 7 **Timestep sizes of CFL=1 for the IMPES and IMPSAT models and Case 2 problem**

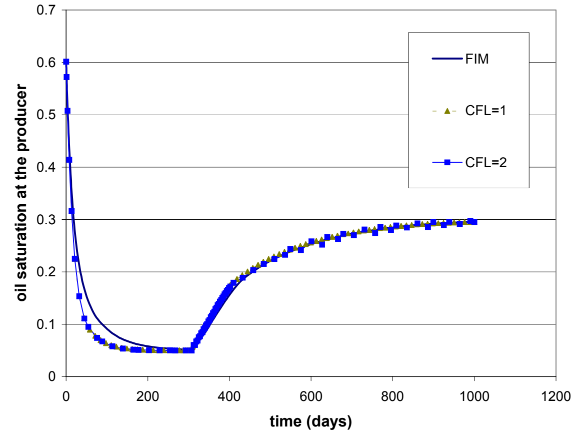

Figure 10 **Well block oil saturation comparisons for the IMPES model and Case 1 problem**

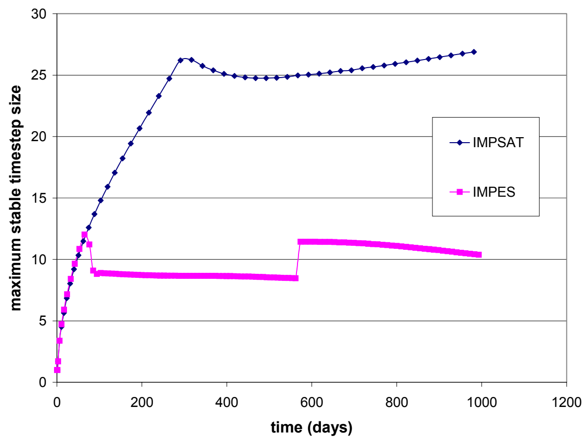

Figure 8 **Timestep sizes of CFL=1 for the IMPES and IMPSAT models and Case 3 problem**

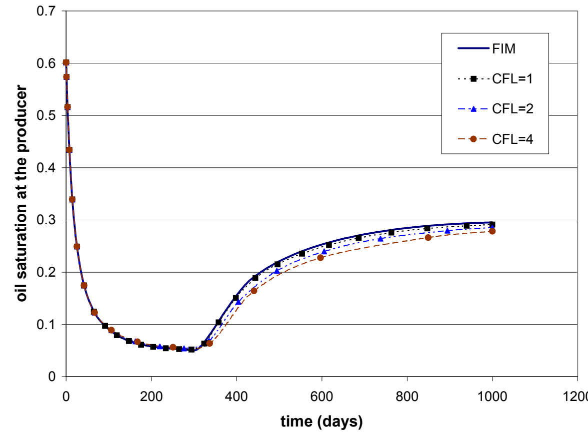

Figure 11 **Well block oil saturation comparisons for the IMPSAT model and Case 1 problem**

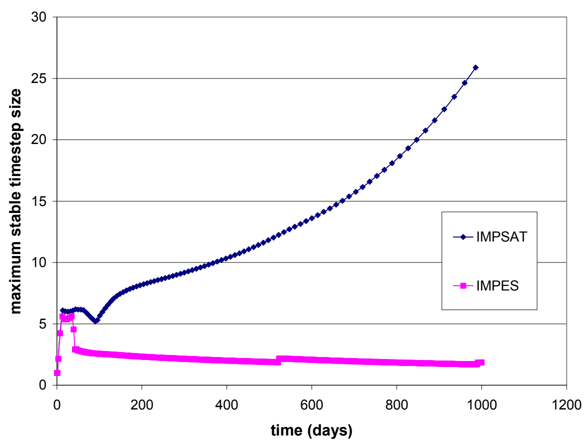

Figure 9 **Timestep sizes of CFL=1 for the IMPES and IMPSAT models and Case 4 problem**

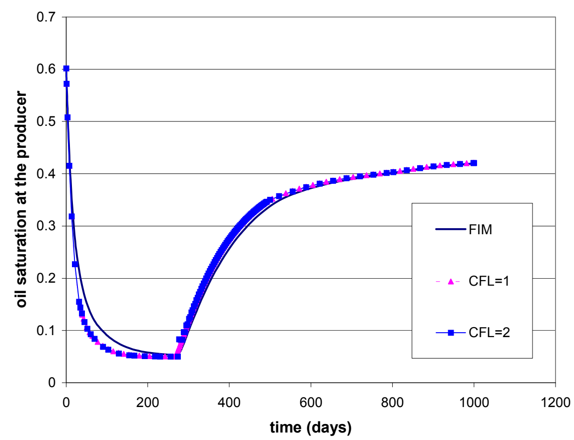

Figure 12 **Well block oil saturation comparisons for the IMPES model and Case 2 problem**

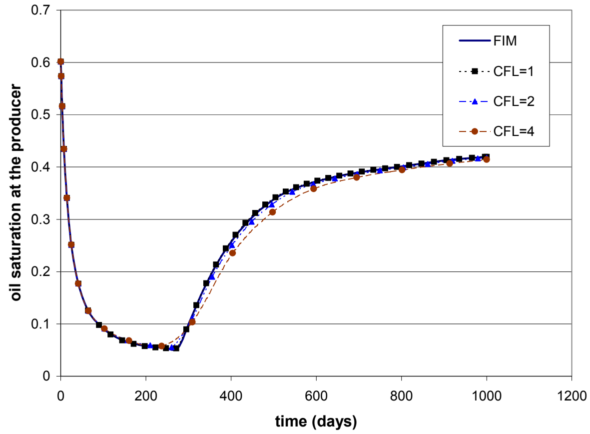

Figure 13 Well block oil saturation comparisons for the IMPSAT model and Case 2 problem

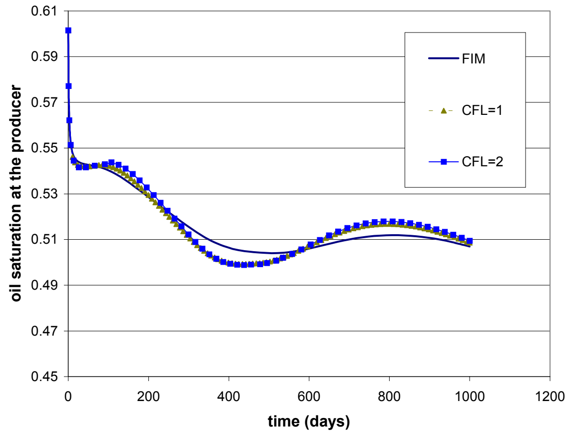

Figure 14 Well block oil saturation comparisons for the IMPES model and Case 3 problem

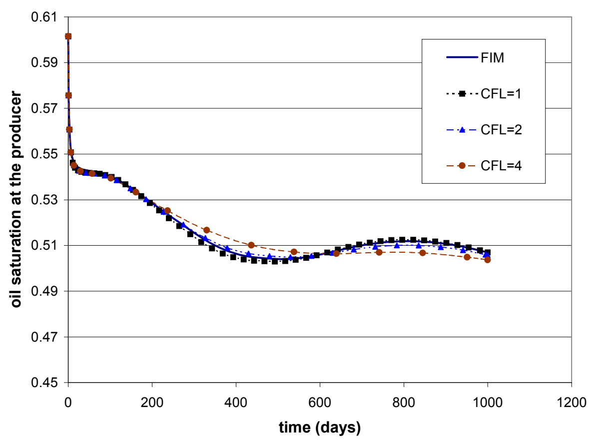

Figure 15 Well block oil saturation comparisons for the IMPSAT model and Case 3 problem

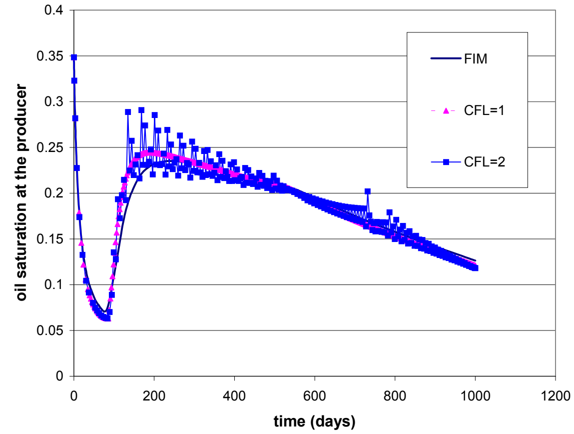

Figure 16 Well block oil saturation comparisons for the IMPES model and Case 4 problem

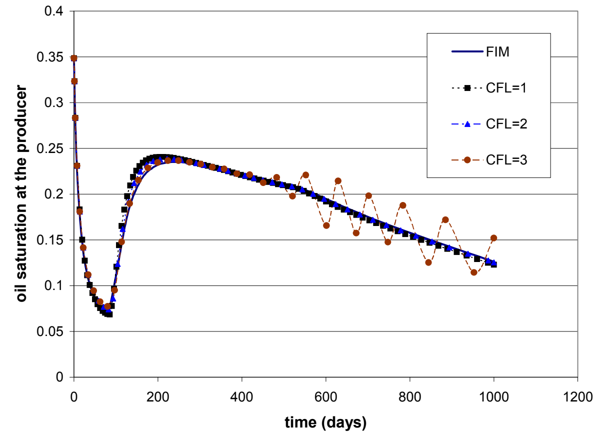

Figure 17 Well block oil saturation comparisons for the IMPSAT model and Case 4 problem

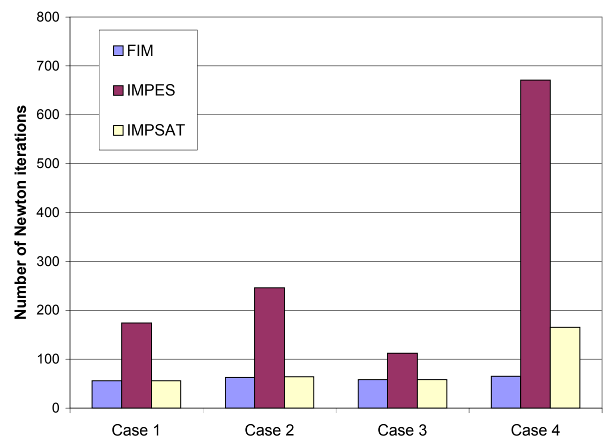

Figure 18 Total number of Newton iterations comparisons for the FIM, IMPES and IMPSAT models

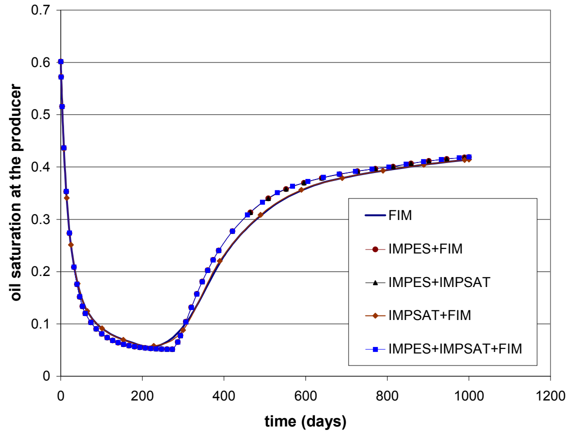

Figure 19 Well block oil saturation comparisons for the AIM models and Case 2 problem

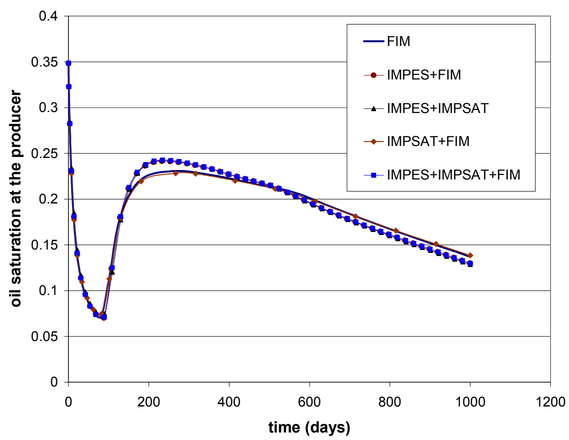

Figure 20 Well block oil saturation comparisons for the AIM models and Case 4 problem

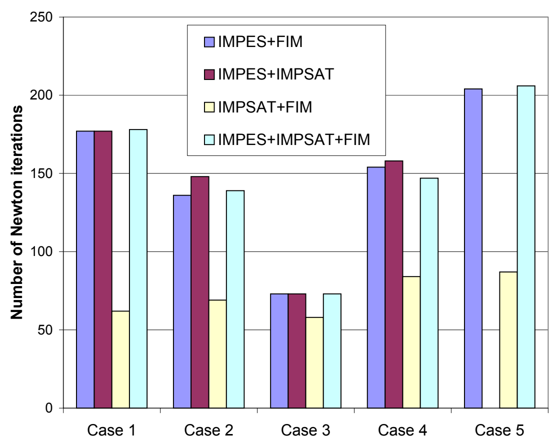

Figure 21 Total number of Newton iterations comparisons for the AIM models