Gas Phase Appearance and Disappearance in Fully Implicit Black Oil Simulation

P. Forsyth Jr., SPE, Computer Modelling Group
P.H. Sammon, SPE, Computer Modelling Group

#11757

Abstract

This paper describes the pseudogas and variable substitution methods for handling gas phase appearance/disappearance in fully implicit black oil simulation. The results of several test runs indicate that there is virtually no difference between these two methods in terms of efficiency. The pseudogas method is easier to program than variable substitution but requires some crucial reallocations of saturations and shows greater material balance errors.

Introduction

One of the major difficulties arising in fully implicit black oil or thermal simulation occurs during phase appearance or disappearance.[1,2] Usually, variable or equation substitution is used to circumvent this problem.[3] Another approach, which uses pseudo K-values, originally was suggested by Crookston *et al.*[2] Essentially, this method prevents phase disappearance by altering the K values so that a small amount of the phase in question remains in the system. This approach also can be used in black oil systems, where a small amount of free gas (pseudogas) is always present.[4] It is clear that the pseudogas method is easier to code than the variable substitution method. However, the small amount of pseudogas may lead to an inaccurate solution or less efficiency than variable substitution. The objective of this paper is to compare the pseudogas and variable substitution methods for fully implicit black oil simulations.

Formulation

In the following, our discussion is restricted to variable bubblepoint, three-phase black oil problems. The three equations, which represent the conservation of gas, oil, and water[1] must be solved at all times.

Consider first the variable substitution method. If free gas is present, the variable set (p, S_o, S_w) is used with the constraints:

$$S_g = 1 - S_o - S_w \quad \ldots\ldots (1)$$

and

$$R_s = R_{st}(p), \quad \ldots\ldots (2)$$

where R_{st} is the table value of R_s values, assuming an unlimited supply of free gas. If there is no free gas present, the independent variables are p, S_o, and R_s, with the constraint:

$$S_w = 1 - S_o. \quad \ldots\ldots (3)$$

Note that R_s is no longer equal to $R_{st}(p)$. The switching criteria are

$$S_g < 0 \quad \ldots\ldots (4)$$

for gas approaching no gas and

$$R_s > R_{st}(p) \quad \ldots\ldots (5)$$

for no gas approaching gas.

In steam simulation, it has been found that the convergence of the Newtonian iteration can be accelerated after phase appearance/disappearance if the constraint equation is added to the basic equation set.[5] However, in practice $R_{st}(p)$ is an almost linear function of p over the entire range, and linear interpolation is used between table values. This implies that the derivative of $R_{st}(p)$ with respect to p is virtually constant. Consequently, the constraint equations (Eqs. 1, 2, and 3) are linear in the independent variables, and hence it is pointless to add these equations to the basic equation set. (They are eliminated analytically.)

The pseudogas formulation always uses the variable set (p, S_o, S_w) with the constraints:

$$S_g = 1 - S_o - S_w \quad \ldots\ldots (6)$$

and

$$R_s = \phi(S_g) R_{st}(p), \quad \ldots\ldots (7)$$

where

$$\phi(S_g) = 1 \quad \ldots\ldots (8)$$

when $S_g > \epsilon$, and

$$\phi(S_g) = \frac{S_g}{\epsilon} \quad \ldots\ldots (9)$$

0197-7520/84/0101-1757$00.25

TABLE 1—COMPARISON OF PSEUDOGAS AND VARIABLE SUBSTITUTION ON PROBLEM 1

	Timesteps	Newtonian Iterations	Timesteps Cuts	Maximum Material Balance Error
Pseudogas	43	129	0	2×10^{-2}
Variable substitution	43	131	0	$<5\times10^{-6}$

when $0<S_g<\epsilon$. Here ϵ is of the order of 10^{-4}. If $S_g>\epsilon$, the variable set and constraint equations are the same as in the variable substitution formulation. When $S_g<\epsilon$, S_g assumes the character of R_s in that a small change in S_g in the range $(0, \epsilon)$ will change R_s in the range $(0, R_{st})$. If, during the course of the Newtonian iteration, $S_g>\epsilon$ on one iteration and $S_g<\epsilon$ on the next iteration, then S_g is set as

$$S_g=\epsilon-\delta, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where $\delta\ll\epsilon$. This gives a reasonable first guess for R_s of $R_s\sim R_{st}$. A similar first guess can be used in the variable substitution formulation.

Test Problems

To test the variable substitution and pseudogas formulation, the 10×15 coning problem used for the second comparative solution project was considered.[6] Problem 1 was reported by Chappelear and Nolen.[6] Free gas is initially present only in the top two layers of the reservoir and appears in almost all the cells soon after the well is opened.

Problem 2 uses the same reservoir and properties data as in Problem 1. The initial well data are the same to 10 days, but from 10 to 100 days 200 B/D [31.8 m^3/d] of dead oil is injected into the reservoir. The simulation is halted at 100 days. At the end of 100 days, all the gas has gone back into solution except in the gas cap. Almost every timestep of Problem 2 has free gas appearing/disappearing, so that this problem provides a severe test of the phase disappearance formulations.

Results

The results for Problem 1 are shown in Table 1. Since the computational cost of either formulation is essentially the same per Newtonian iteration, the CPU time is proportional to the number of Newtonian iterations.

Both methods used the same number of timesteps with virtually the same number of Newtonian iterations. The material balance of any component was computed with error equal to 1−(initial mass+injection−production−calculated mass)/max (injection, production). The material balance error of the variable substitution method was correct to the number of figures printed (five), while there was an error in the pseudogas formulation. This is to be expected because of the presence of the pseudogas itself. On the whole, both runs were remarkably similar. At 900 days, the differences in the cumulative gas, oil, and water production were in the fourth decimal place. Both methods agreed with the published runs.[6]

Table 2 shows the results obtained for Problem 2. Again the material balance error for the pseudogas method is larger than for the variable substitution formulation. However, the pseudogas method was approximately 6% faster than variable substitution in terms of Newtonian iterations. On any given timestep, there was no definite trend as to which method required fewer Newtonian iterations. Sometimes the pseudogas formulation required fewer iterations, sometimes more than variable substitution. Note that the pseudogas method requires a reallocation after gas phase disappearance (Eq. 10). This is not required for variable substitution. It may be that Eq. 10 provides a good first estimate for S_o, S_w on some timesteps. We attempted to verify this by using a similar reallocation scheme in the variable substitution formulation, but it did not make any noticeable difference.

There seems to be an inherent material balance error associated with the pseudogas formulation. The size of the material balance error is clearly dependent on ϵ. However, ϵ cannot be made arbitrarily small because this would lead to numerical difficulties.

Conclusions

The results indicate that there is little difference in efficiency between the variable substitution and pseudogas formulation. This conclusion is supported by other runs on several different problems that we have tried. One of the problems observed with the pseudogas method occurs during the initialization of the reservoir. The phases must be allocated carefully (i.e., by Eq. 7) to ensure rapid convergence. The pseudogas formulation also has an inherent material balance error, but in most cases it is within acceptable limits. In spite of these difficulties, the pseudogas formulation offers a reasonable alternative to variable substitution.

Nomenclature

p = pressure, m/Lt^2
R_s = solution GOR

TABLE 2—COMPARISON OF PSEUDOGAS AND VARIABLE SUBSTITUTION ON PROBLEM 2

	Timesteps	Newtonian Iterations	Timesteps Cuts	Maximum Material Balance Error
Pseudogas	20	64	0	2×10^{-3}
Variable substitution	20	68	0	$<5\times10^{-6}$

R_{st} = solution GOR, assuming unlimited supply of free gas
S = saturation
ϵ = pseudogas threshold

Subscripts

g = gas
o = oil
w = water

Acknowledgments

This research was supported by the associated members of CMG and by the Alberta/Canada Energy Resources Research Fund administered by the Dept. of Energy and Natural Resources of Alberta. We thank Anthony Au for many useful discussions.

References

1. Aziz, K. and Settari, A.: *Petroleum Reservoir Simulation*, Applied Science, London (1979).
2. Crookston, R.B. *et al.*: "A Numerical Simulation Model for Thermal Recovery Processes," *Soc. Pet. Eng. J.* (Feb. 1979) 37–58; *Trans.*, AIME, **267**.
3. Coats, K.H.: "A Highly Implicit Steamflood Model," *Soc. Pet. Eng. J.* (Oct. 1978) 369–83.
4. Au, A.D.K., *et al.*: "Techniques for Fully Implicit Reservoir Simulation," paper SPE 9302 presented at the 1980 SPE Annual Technical Conference and Exhibition, Dallas, Sept. 21–24.
5. Forsyth, P., Rubin, B., and Vinsome, P.K.W.: "The Elimination of the Constraint Equation and Modelling of Problems with a Noncondensable Gas in Steam Simulation," *J. Can. Pet. Tech.* (Oct.–Dec. 1981) 63–68.
6. Chappelear, J.E. and Nolen, J.S.: "Second Comparative Solution Project: A Three-Phase Coning Study," paper SPE 10489 presented at the 1982 SPE Reservoir Simulation Symposium, New Orleans, Feb. 20–23.

SPEJ

Original manuscript (SPE 11757) received in the Society of Petroleum Engineers office Dec. 1, 1982. Paper accepted for publication June 20, 1983. Revised manuscript received Dec. 12, 1983.