Streamline Compositional Simulation of Gas Injections

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Abstract

When reservoir temperatures are lower than 120^{o}F and pressure is lower than 1500psia, gas injections, especially when injectants include CO_2, can result in four phases: water, oil, gas, and a second non-aqueous liquid. No commercial simulators can handle four phases. Although UTCOMP, an academic simulator, can handle four phases, it was built with the finite-difference method. It is so time-consuming to conduct compositional simulations with finite-difference simulators that people tend to use fewer components, or fewer grid blocks, or both; however, the use of fewer components leads to inaccurate phase behavior, while application of fewer grid blocks causes larger numerical dispersions. A streamlined simulation was incorporated into UTCOMP to tackle water flood and a streamline simulator, Strator, was developed. In this study, Strator was expanded to handle gas injections and found to be able to model gas injections involving four phases. For a gas injection case, the speed of streamline simulation is 43 times that of a finite-difference simulation. In addition, viscous fingering can be sharply caught by streamline simulation. Flood fronts from the streamline method are more clear-cut than their counterparts from the finite-difference method, owing to large numerical dispersions in the latter method, acting like physical dispersions. The streamline simulator can be used for gas injection problems involving up to four phases.

Introduction

It is well-known that it is extremely time-consuming to run compositional simulations with finite-difference simulators. Sometimes, people in industry submit compositional simulation jobs to computing clusters, go for a vacation for a couple of weeks, and then come back to collect simulation results. Compositional simulations are so prohibitively expensive that people tend to use fewer components, or fewer grid blocks, or both. However, the use of fewer components leads to inaccurate phase behavior while application of fewer grid blocks causes larger numerical dispersions [1].

When reservoir temperatures are lower than 120^{o}F and pressure is lower than 1500psia, gas injections, especially when injectants include CO_2, can result in four phases: water, oil, gas, and a second non-aqueous liquid [2]-[4]. Unfortunately, commercial simulators, such as Eclipse and VIP, cannot handle four phases. In order to accurately describe phase behavior, it is better to use an academic compositional simulator, for example, UTCOMP [5], which can handle four phases. Efforts [4] were made to simulate enhanced oil recovery processes by using UTCOMP. Like most simulators, UTCOMP is a finite-difference simulator and it is time-consuming when used for compositional simulations. A streamlined method was incorporated into UTCOMP for flood water and a streamline simulator, Strator [6], was developed. It was confirmed that the streamline method was much faster than conventional finite-difference methods. For a flood-water case, simulation speed with the streamline method was 23.71 times [6] the simulation speed of the finite-difference method.

Flood water alone is not effective in recovering Shrader oil [4] due to high viscosity of the oil. Slim-tube experiments carried out by Mohanty et al. [2] and Khataniar et al. [3] showed that solvent flooding was effective because certain solvents were miscible with the viscous oil, thus reducing oil viscosity. In this study, the streamline simulator, Strator, was expanded to handle gas injections. After being tested for a synthetic case, Strator was used to perform compositional simulations on a miscible gas injection to the viscous Shrader oil. Simulation results from the streamline method was analyzed and compared with their counterparts from the finite-difference method.

Approach

The streamline method for compositional simulation was described by Thiele et al. [7], and Jessen & Orr [1]. In this current study, the authors used an analytical streamline method for gas injections. Instead of mapping water saturation from 1D solution for flood water [6], the authors mapped overall compositions of hydrocarbon components and Strator was extended to model gas injections as shown in Figure 1 [8]. The true time step will be derived in the next several paragraphs.

Let $N_{i,I}^{n}$ be the total cumulative injection of component *i* at the nth time step (T), $N_{i,p}^{n}$ the total cumulative production of component *i* at the nth time step, $N_{i,ini}$ the initial amount of component *i*, and $N_{i,r}^{n}$ the total amount of component *i* still remaining in the reservoir at the nth time step. The total accumulation of component *i* can be calculated as $N_{i,I}^{n} - N_{i,p}^{n}$, or $N_{i,r}^{n} - N_{i,ini}$. These two numbers are equal to each other, thus yielding

$$N_{i,I}^{n} - N_{i,p}^{n} = N_{i,r}^{n} - N_{i,ini}. \qquad (1)$$

Therefore, at T (the nth time step), the total cumulative injection of component *i* is

$$N_{i,I}^{n} = N_{i,p}^{n} + N_{i,r}^{n} - N_{i,ini}. \qquad (2)$$

Similarly, for the (n+1)th time step, we have

$$N_{i,I}^{n+1} = N_{i,p}^{n+1} + N_{i,r}^{n+1} - N_{i,ini}. \qquad (3)$$

The total cumulative injection of component *i* at the (n+1)th time step, $N_{i,I}^{n+1}$, can be written as

$$N_{i,I}^{n+1} = N_{i,I}^{n} + Q_{I}^{n+1} z_{i,I} \Delta T^{n+1}, \qquad (4)$$

where Q_{I}^{n+1} is the solvent injection rate at the (n+1)th time step, $z_{i,I}$ is the overall composition of component *i* in the solvent, and ΔT^{n+1} is the true time step at the (n+1) time step.

The total cumulative production of component i at the (n+1)th time step, $N_{i,p}^{n+1}$, can be found as

$$N_{i,p}^{n+1} = N_{i,p}^{n} + Q_{p}^{n+1} \sum_{j=2}^{4} x_{i,j,p} \left(\frac{f_{j,p}^{n} + f_{j,p}^{n+1}}{2} \right) \Delta T^{n+1}, \qquad (5)$$

where $f_{j,p}^{n}$ is the production fractional flow of phase *j* at the nth time step, $f_{j,p}^{n+1}$ is the production fractional flow of phase *j* at the (n+1)th time step, Q_{p}^{n+1} is the production rate at the (n+1)th time step, and $x_{i,j,p}$ is the composition of component *i* in phase *j* in the production fluid. So, from equations (3) - (5), we get

$$\Delta T^{n+1} = \frac{N_{i,init} - N_{i,r}^{n+1} + N_{i,I}^{n} - N_{i,P}^{n}}{Q_{I}^{n+1} z_{i,I} - Q_{p}^{n+1} \sum_{j=2}^{4} x_{i,j,p} \left(\frac{f_{j,p}^{n} + f_{j,p}^{n+1}}{2} \right)}. \qquad (6)$$

These equations are implemented in the coding.

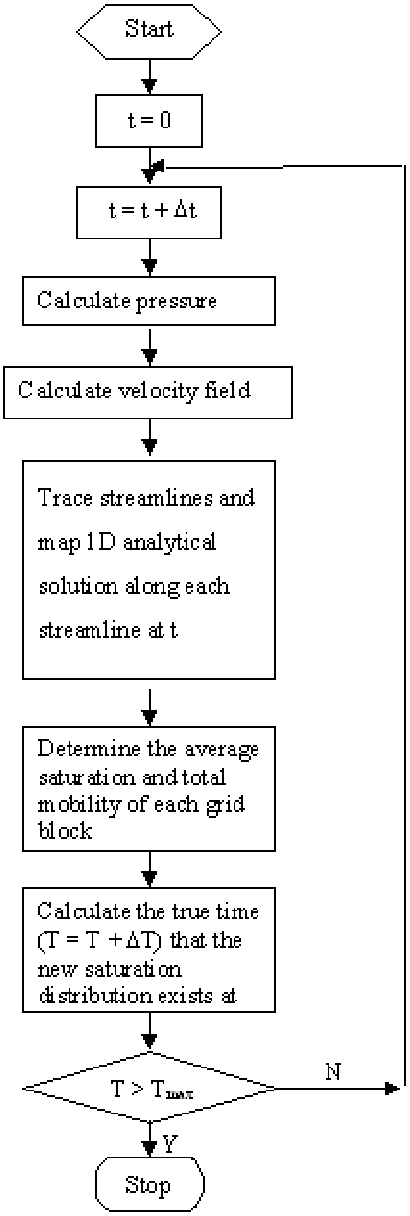

Figure 1. Flow chart of streamline simulation for gas injection [8]

Results and Discussions

Based on the equations shown in the previous section and the flow chart shown in Figure 1, some subroutines were built with the programming language FORTRAN, and incorporated into Strator. After Strator was extended for gas injections, a simple case was used to test the code. Commercial software such as Eclipse and VIP cannot handle four phases, while Strator can because it has been built on UTCOMP, which is capable of handling four phases. At 700 psi and 69.38°F, CO_2 was injected into a homogeneous reservoir with C_{16}. The reservoir was a quarter of a five-spot pattern shown in Figure 2. Simulations were run by using 20 x 20 grid blocks. At 0.28 pore volume injection (PVI) of CO_2, values of oil saturation obtained from Strator and UTCOMP are listed in Tables 1 and 2, respectively.

Table 3 shows some properties for this synthetic case, such as permeability, porosity, and temperature. In addition, the authors compared the saturation profiles in Figures 3 and 4, which show that the flood front generated by using Strator was more clear-cut than that using UTCOMP. Therefore, numerical dispersions from Strator are smaller than those from UTCOMP. Because solution from Strator is closer to the true solution, the solution from Strator was used as a reference to calculate the error from UTCOMP.

Based on the data in Tables 1 and 2, the average front oil saturation from Strator was found to be 0.5125, while its counterpart from UTCOMP was 0.5849. So, the relative error of UTCOMP for the front oil saturation was

$$(0.5849-0.5125)/0.5125\times100\% = 14\% \qquad (7)$$

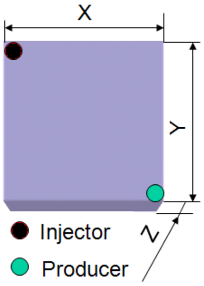

Figure 2. Schematic for the reservoir

Comparing Figures 3 and 4 further shows the speed of the solvent movement in the diagonal direction predicted by using Strator was faster than its counterpart UTCOMP. The numerical dispersions from UTCOMP were quite significant and they acted like real physical dispersions. Thus, slower movement of the solvent front predicted by UTCOMP than was observed by its counterpart Strator.

Table 1 Oil Saturation from Strator at 0.28 PV Injection of CO_2 into C_{16}

0.2274	0.2271	0.2372	0.2523	0.2743	0.2983	0.3197	0.3393	0.3586	0.3752	0.3910	0.4044	0.4180	0.4312	0.4549	0.8000	0.8000	0.8000	0.8000	0.8000
0.2271	0.2310	0.2412	0.2567	0.2790	0.3015	0.3223	0.3412	0.3597	0.3761	0.3917	0.4053	0.4182	0.4312	0.4879	0.8000	0.8000	0.8000	0.8000	0.8000
0.2372	0.2412	0.2516	0.2679	0.2886	0.3090	0.3286	0.3463	0.3632	0.3794	0.3940	0.4068	0.4194	0.4323	0.5002	0.8000	0.8000	0.8000	0.8000	0.8000
0.2523	0.2567	0.2679	0.2843	0.3018	0.3192	0.3361	0.3531	0.3680	0.3835	0.3975	0.4100	0.4214	0.4332	0.5387	0.8000	0.8000	0.8000	0.8000	0.8000
0.2743	0.2790	0.2886	0.3018	0.3164	0.3312	0.3460	0.3608	0.3747	0.3882	0.4009	0.4135	0.4238	0.4349	0.6781	0.8000	0.8000	0.8000	0.8000	0.8000
0.2983	0.3015	0.3090	0.3192	0.3312	0.3437	0.3569	0.3690	0.3824	0.3942	0.4047	0.4165	0.4265	0.4376	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3197	0.3223	0.3286	0.3361	0.3460	0.3569	0.3673	0.3788	0.3895	0.4002	0.4104	0.4192	0.4289	0.4408	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3393	0.3412	0.3463	0.3531	0.3608	0.3690	0.3788	0.3881	0.3979	0.4055	0.4158	0.4236	0.4323	0.4459	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3586	0.3597	0.3632	0.3680	0.3747	0.3824	0.3895	0.3979	0.4045	0.4135	0.4196	0.4274	0.4353	0.4647	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3752	0.3761	0.3794	0.3835	0.3882	0.3942	0.4002	0.4055	0.4135	0.4184	0.4257	0.4320	0.4401	0.5616	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3910	0.3917	0.3940	0.3975	0.4009	0.4047	0.4104	0.4158	0.4196	0.4257	0.4307	0.4363	0.4472	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.4044	0.4053	0.4068	0.4100	0.4135	0.4165	0.4192	0.4236	0.4274	0.4320	0.4363	0.4440	0.4951	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.4180	0.4182	0.4194	0.4214	0.4238	0.4265	0.4289	0.4323	0.4353	0.4401	0.4472	0.4951	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.4312	0.4312	0.4323	0.4332	0.4349	0.4376	0.4408	0.4459	0.4647	0.5616	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.4549	0.4879	0.5002	0.5387	0.6781	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000

Table 2 Oil Saturation from UTCOMP at 0.28 PV Injection of CO_2 into C_{16}

0.0000	0.0000	0.2101	0.2388	0.2676	0.2860	0.3058	0.3303	0.3542	0.3747	0.3935	0.4308	0.6071	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.0000	0.2128	0.2312	0.2531	0.2738	0.2902	0.3091	0.3321	0.3551	0.3749	0.3940	0.4309	0.6232	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.2101	0.2312	0.2564	0.2780	0.2970	0.3126	0.3265	0.3415	0.3593	0.3767	0.3956	0.4342	0.6713	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.2388	0.2531	0.2780	0.3055	0.3283	0.3448	0.3557	0.3636	0.3722	0.3842	0.4017	0.4486	0.7529	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.2676	0.2738	0.2970	0.3283	0.3563	0.3748	0.3838	0.3873	0.3901	0.3956	0.4110	0.4762	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.2860	0.2902	0.3126	0.3448	0.3748	0.3984	0.4049	0.4053	0.4057	0.4090	0.4257	0.6292	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3058	0.3091	0.3265	0.3557	0.3838	0.4049	0.4137	0.4151	0.4165	0.4192	0.4858	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3303	0.3321	0.3415	0.3636	0.3873	0.4053	0.4151	0.4199	0.4280	0.4672	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3542	0.3551	0.3593	0.3722	0.3901	0.4057	0.4165	0.4280	0.4651	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3747	0.3749	0.3767	0.3842	0.3956	0.4090	0.4192	0.4672	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.3935	0.3940	0.3956	0.4017	0.4110	0.4257	0.4858	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.4308	0.4309	0.4342	0.4486	0.4762	0.6292	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.6071	0.6232	0.6713	0.7529	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000
0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000	0.8000

Table 3. Properties for the Synthetic Case

Parameter	Value	Unit
Outlet Pressure	700	Psi
Temperature	69	^{o}F
Permeability	5	Darcy
Porosity	0.352	none
Reservoir Length	10	ft
Reservoir Width	10	ft
Reservoir Thickness	1	ft
Injection Rate	99	Mole/d

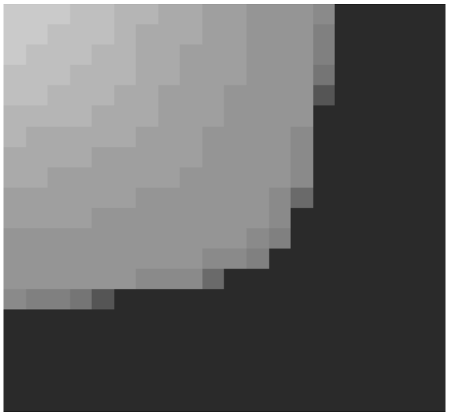

Figure 3. Oil saturation from Strator at 0.28 PV injection of CO2 into C16

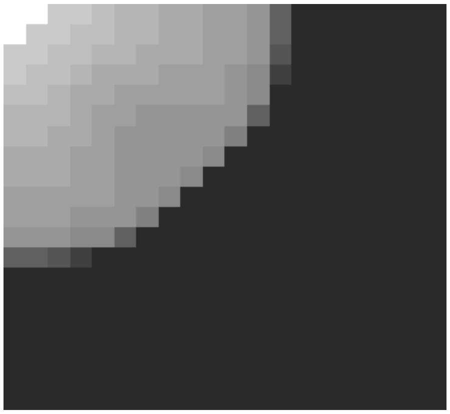

Figure 4. Oil saturation from UTCOMP at 0.28 PV injection of CO2 into C16

In order to improve the resolution of the saturation profiles and show fingering, streamline simulations were run with 70 x 70 grid blocks for the above case. Oil saturation at 0.47 PVI is shown in Figure 5, which demonstrates a lot of viscous fingers and fingering can be shown clearly with the streamline method. If the reservoir is heterogeneous, fingering will be more severe.

From both experimental [3] and simulation [4] studies, it was found that in the mixed injectant of Prudhoe Bay Gas (PBG) and Natural Gas Liquid (NGL), when the proportion of NGL is higher than 40%, the injectant reached good miscibility with viscous Shrader oil. The author then chose a mixture of 50% PBG and 50% NGL as the gas injectant.

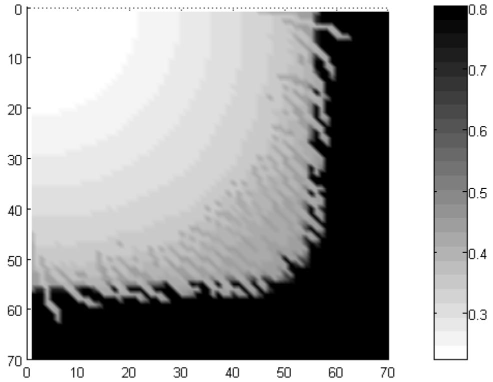

Figure 5. Oil Saturation at 0.47 PVI

While water was assumed to be immobile, simulations were run using Strator and UTCOMP for the gas injection into a reservoir with viscous Shrader oil. The mixture was injected into a quarter of a five-spot pattern reservoir shown in Figure 2. Table 4 shows the properties, such as permeability, porosity, and temperature. The injection resulted in four phases in the reservoir: water, oil, gas, and the second non-aqueous liquid. After 0.33 pore volume (PV) of gas injection, oil, gas, and the second non-aqueous liquid saturations obtained, respectively, from Strator and UTCOMP are shown in Figures 6-11, which indicate that fingering can be illustrated better by using Strator. Efforts will be made in the future to increase the resolution of saturation profiles by increasing the number of grid blocks. It took a 366-MHz Pentium II computer 5 minutes and 21 seconds to simulate a 1.2-PV injection by using Strator and about two hours to simulate a 0.6-PV injection using UTCOMP before it was bogged down. Therefore, the speedup factor is about 43.

Table 4. Properties for the Shrader Case

Parameter	Value	Unit
Outlet Pressure	1300	Psi
Temperature	82	^{o}F
Permeability	5	Darcy
Porosity	0.352	none
Reservoir Length	10	ft
Reservoir Width	10	ft
Reservoir Thickness	1	ft
Injection Rate	2	Mole/d

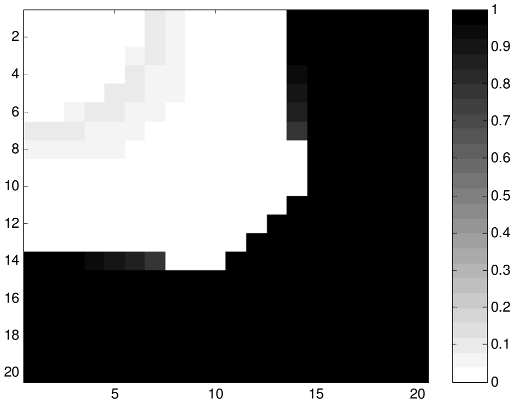

Figure 6. Oil saturation from Strator at 0.33 PV of gas injection into Shrader oil

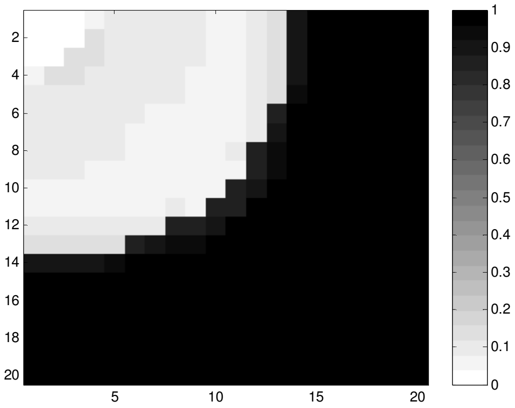

Figure 7. Oil saturation from UTCOMP at 0.33 PV of gas injection into Shrader oil

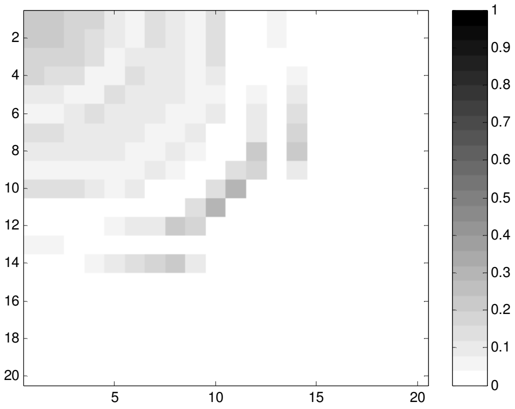

Figure 8. Gas saturation from Strator at 0.33 PV of gas injection into Shrader oil

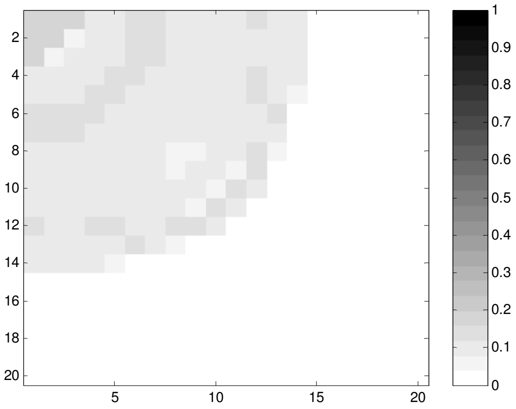

Figure 9. Gas saturation from UTCOMP at 0.33 PV of gas injection into Shrader oil

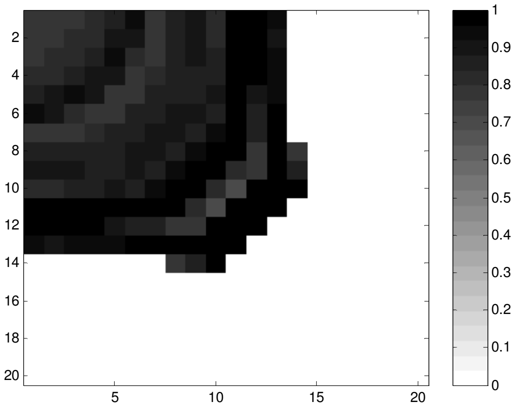

Figure 10. Second non-aqueous liquid saturation from Strator at 0.33 PV of gas injection into Shrader oil

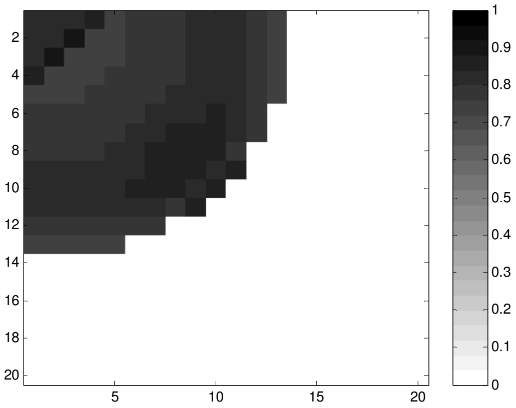

Figure 11. Second non-aqueous liquid saturation from UTCOMP at 0.33 PV of gas injection into Shrader oil

The bogging down of UTCOMP during the simulation process might be due to severe fingering; however, Strator is more resilient in handling fingering.

Conclusions

Several conclusions can be reached for this work:

1. Strator was expanded to model gas injections by using the analytical streamline method. Strator can handle gas injections involving up to four phases.
2. The streamline method leads to smaller numerical dispersions than the finite-difference method.
3. Large numerical dispersions in the finite-difference method, acting like physical dispersions, causes blurry flood fronts, while smaller numerical dispersions in the streamline method result in clear-cut flood fronts.
4. Viscous fingering can be shown well by using the streamline method.
5. Compared with the finite-difference method, the streamline method is much faster. A speed-up factor as high as 43 was achieved.

Acknowledgements

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Nomenclature

English Symbols

delta = Δ
dt = Δt
ER = oil recovery, fraction
f = fractional flow, fraction
k = permeability, L^2
M = reciprocal of the standard definition of mobility ratio, dimensionless
n = the nth time step
N = amount
PV = pore volume
PVI = pore volume injected
Q = injection rate, L^3/T
S = water saturation
t = nominal time, T
T = true time, T
TD = dimensionless time
W = Water amount, L^3

Greek Symbols

Δ = difference
Δ = nominal time step
t
Δ = true time step
T
τ = time of flight
$\bar{\tau}$ = average time of flight

Subscripts

gb = grid block
i = component index
I = injection
ini = initial
j = phase index
o = oil
P = production
r = remaining
sl = streamline
w = water

Superscripts

n = the nth time step
n+1 = the $(n+1)^{th}$ time step
sl = streamline

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Biography

DACUN LI was featured in *Who's Who in America 2011 (65th Edition)*, Dr. Dacun Li is an assistant professor of petroleum technology at the University of Texas of the Permian Basin and Editorial Review Committee member of the Society of Petroleum Engineers (SPE). Holding three degrees respectively in three different areas (a Bachelor's degree in Aerospace Engineering, a Master's degree in Health Physics, and a Ph.D. in Petroleum Engineering), he has international, academic, and industrial work experiences. He was one of the main characters in the TV documentary titled *Red Capitalism* (1994 Canada's Golden Sheaf Award winner), produced by Canadian Broadcasting Corporation (CBC) in July 1993. With a personable character, Dr. Li likes singing, dancing, photographing, practicing calligraphy, sledding, jogging, playing table tennis, and traveling. li_d@utpb.edu