Modifications improve waterflood performance model

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Modifications to the Craig-Geffen-Morse (CGM) waterflooding model improve reservoir performance predictions and allow for the inclusion of pressure drop variations with time.

The modified model was validated against numerical simulation results.

Waterflooding

Waterflooding increases production rates and improves ultimate oil recovery from a variety of reservoirs.

Over the years, many waterflood performance prediction methods[1] have been developed. Among these methods, the CGM[2] model seems to be the best simple method for five-spot reservoirs. One advantage is that calculations can be done by hand.

However, this method is limited because it involves many assumptions that are rarely met in field applications. Investigators[3] [4] have shown that matching field data with this simple model is often difficult.

Wu[5] modified this method for rectangular patterns. In this article, two additional modifications enable the CGM model to be applied in other realistic applications.

CGM model

The CGM model was developed in 1955. The model is based on the Buckley-Leverett[6] and Welge[7] solution of the fractional-flow equation. It accounts for areal sweep efficiency based on correlations developed in the laboratory. It also takes into account variations in the mobility ratio after water breakthrough.

Water injection rate is corrected based on the conductance ratio correlation developed by Caudle and Witte.[8] This model assumes incompressible fluids and homogeneous five-spot patterns. Also, it ignores gravity effects and capillary pressure.

Fig. 1

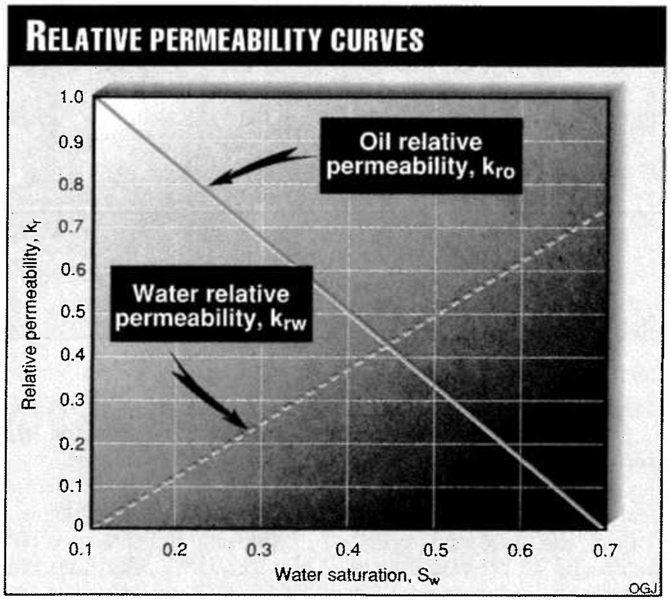
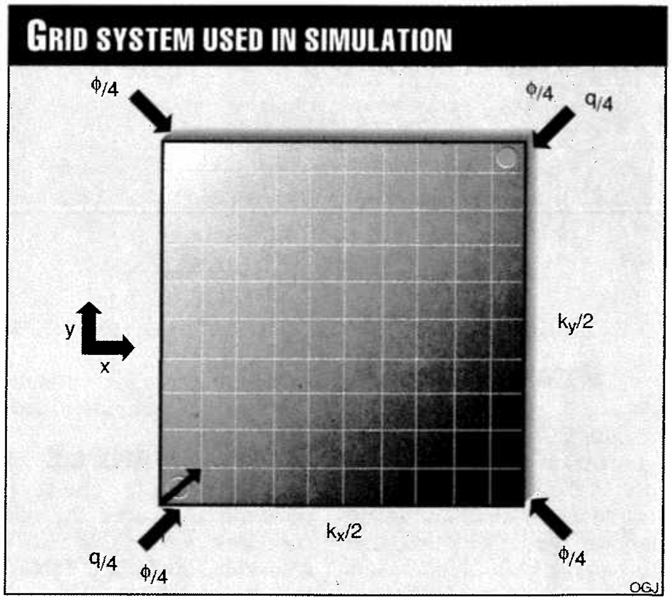

RELATIVE PERMEABILITY CURVES

Fig. 2


GRID SYSTEM USED IN SIMULATION

EQUATIONS

$$j^2p = \frac{\phi\mu c_t}{k} \frac{\partial p}{\partial t} \quad (1)$$

$$i_{base} = \frac{3.541 \times 10^{-3}\, hk\, k_{ro}\, \Delta p}{\mu_o\left(\ln \frac{d}{r_w} - 0.619\right)} \quad (2)$$

$$S_{wbt} = S_{wc} + \frac{(S_{wf} - S_{wc}) \times (1 - f_{Swc})}{(f_{wf} - f_{Swc})} \quad (3)$$

$$\lambda_o = \frac{k_{ro}\,|_{Swc}}{\mu_o} \quad (4)$$

$$\lambda_w = \frac{k_{rw}\,|_{Sor}}{\mu_w} \quad (5)$$

$$S_{om} = (1 - S_{wc}) - S_{or} \quad (6)$$

$$S_{wm} = S_{wc} - S_{wir} \quad (7)$$

$$frac_o = \left(\frac{S_{om}}{S_{om} + S_{wm}}\right) \times \left(\frac{\lambda_o}{\lambda_o + \lambda_w}\right) \quad (8)$$

$$frac_w = \left(\frac{S_{wm}}{S_{om} + S_{wm}}\right) \times \left(\frac{\lambda_w}{\lambda_o + \lambda_w}\right) \quad (9)$$

$$q_{oi} = \frac{i_i \times frac_o}{(frac_o + frac_w) \times B_o} \quad (10)$$

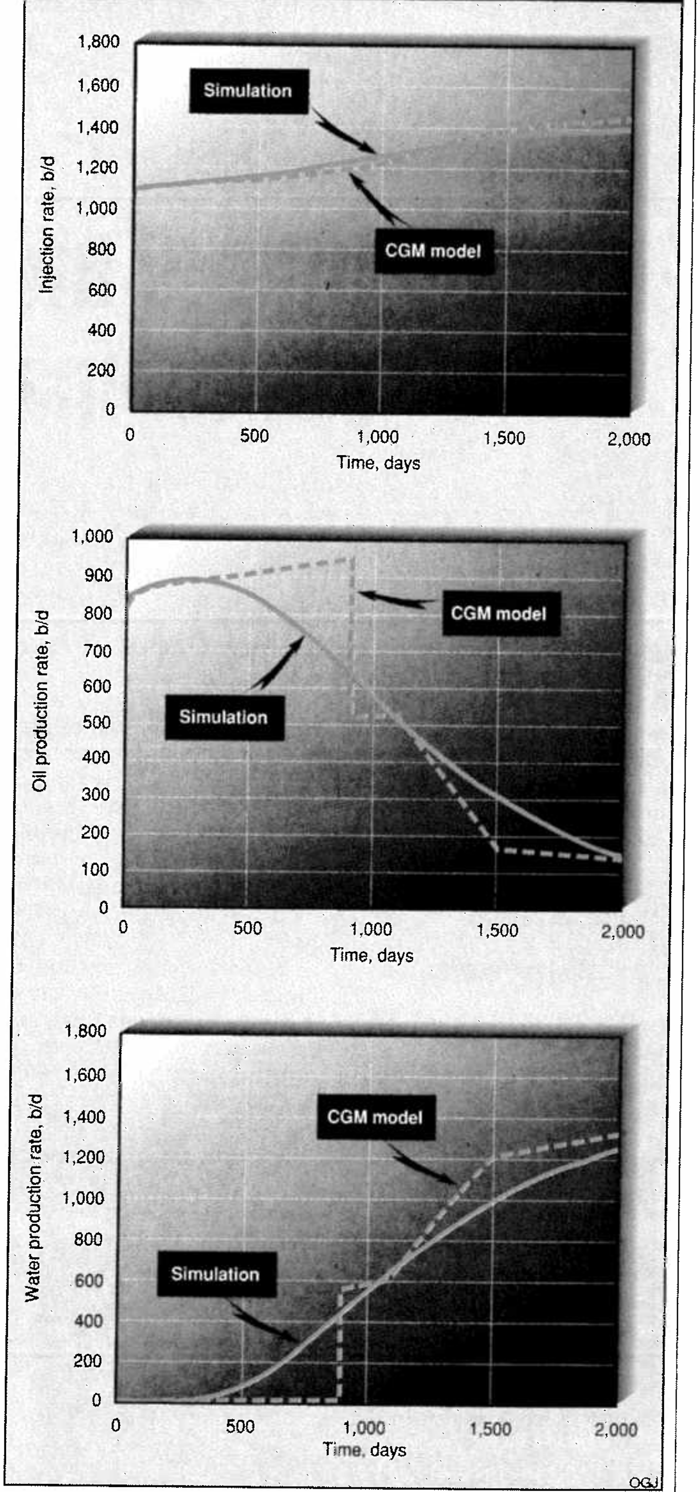
$$q_{wi} = \frac{i_i \times frac_w}{(frac_o + frac_w) \times B_w} \quad (11)$$

NOMENCLATURE

B_o = Oil formation volume factor
B_w = Water formation volume factor
c_t = Total compressibility, 1/psi
d = Distance between injector and producer
f_{wf} = Fractional flow at the flood front
f_{Swc} = Fractional flow at connate water saturation
$frac_o$, = Fraction of water injection causing oil production
$frac_w$ = Fraction of water injection causing water production
h = Formation thickness, ft
i_{base} = Base water injection rate
i_i = Water injection rate at ith time step
k = Formation permeability, md
k_{ro} = Oil relative permeability
q_{oi} = Oil production rate at ith time step
q_{wi} = Water production rate at ith time step
r_w = Well radius, ft
S_{wf} = Water saturation at the flood front
S_{om} = Mobile oil saturation
S_{wm} = Mobile water saturation
λ = Formation porosity
λ_o = End-point mobility to oil
λ_w = End-point mobility to water
Δp = Pressure drop between injector and producer
λ_o = Oil viscosity, cp

Fig. 3

COMPARISON WITH ORIGINAL CGM MODEL



Model validation

The CGM computer program used in this work had been validated against different data sets[1] and hand calculations. But when compared to reservoir simulations several problem areas with the CGM model were identified.

Hypothetical data set

A five-spot, one-layer reservoir compared the performance of the CGM with a reservoir simulation. Table 1 presents the reservoir and fluid data.

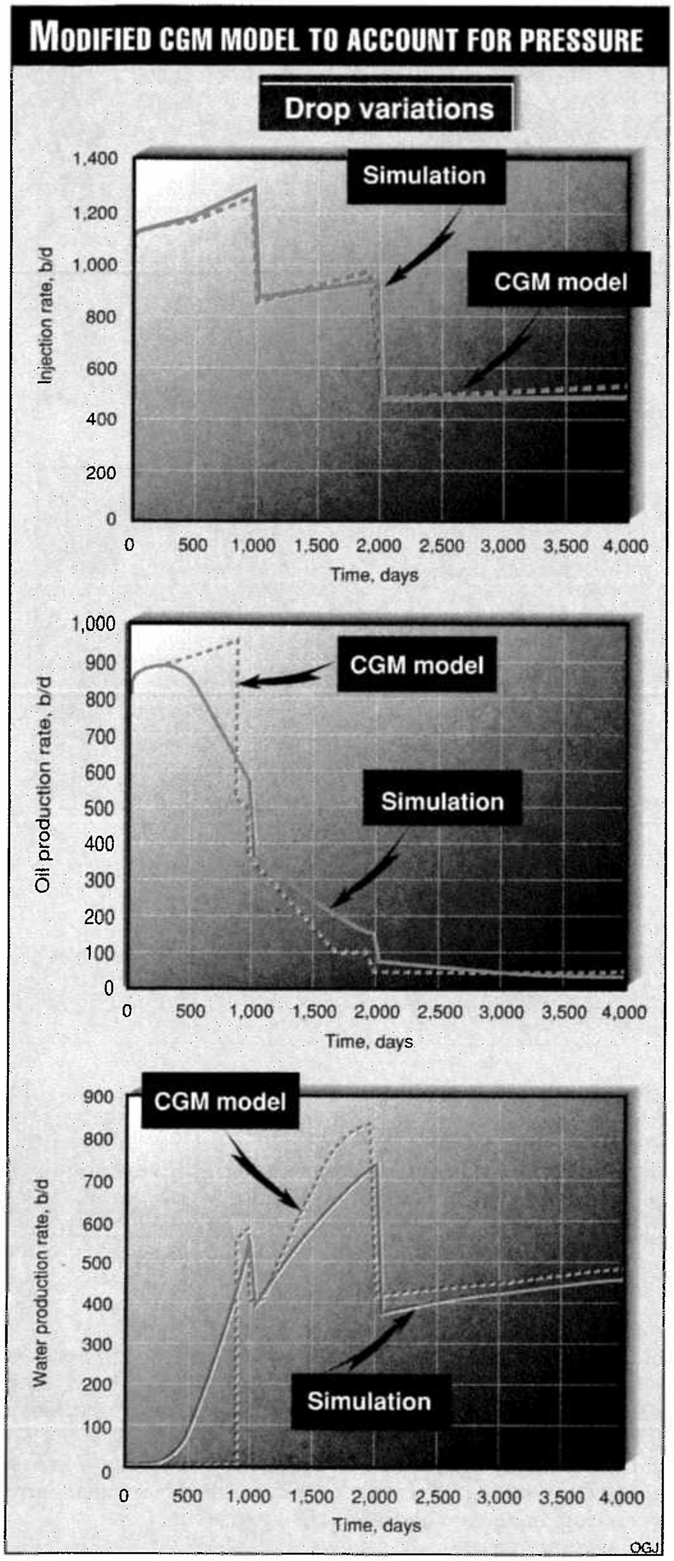
To compare the analytical solution of two-phase (Buckley-Leverett) with the numerical solution (reservoir simulation), the reservoir was chosen to be an oil-water reservoir system.

Fig. 1 shows the relative permeability data for the hypothetical reservoir.

Simulation technique

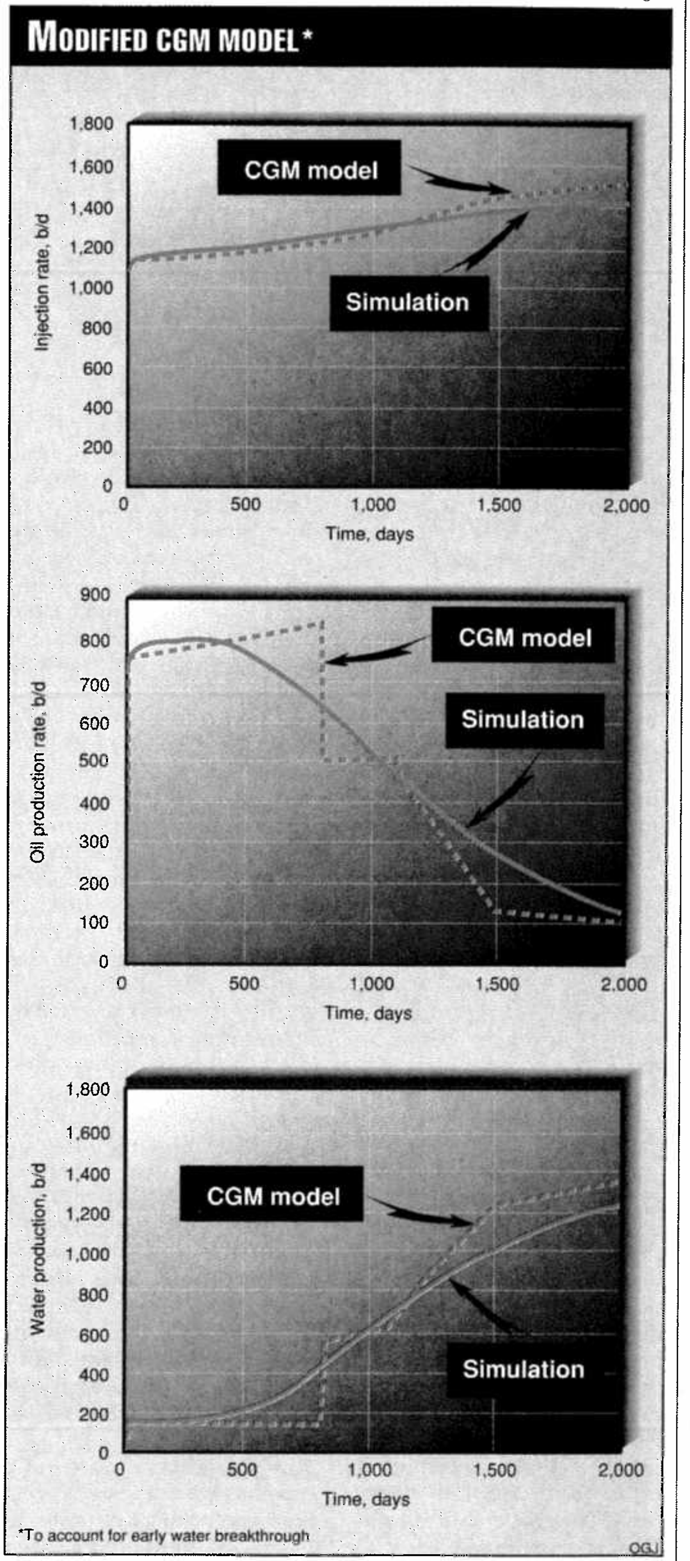
Because the five-spot pattern can be divided into four

Fig. 4



MODIFIED CGM MODEL TO ACCOUNT FOR PRESSURE

Fig. 5



MODIFIED CGM MODEL*

*To account for early water breakthrough

symmetrical parts, to save time, only one quadrant with a producer and an injector in opposite corners was simulated.

The data were manipulation to adjust for using only one quadrant of the five-spot. In this case, porosity in the corner cells was reduced to one fourth of the pattern porosity. Likewise, on the sides, porosity was reduced to half its value.

Also in the flow direction, the X and Y permeabilities in side cells were reduced by half. Then, the rates were multiplied by four to obtain the full pattern rates.

The grid system for all simulation runs consisted of a 10 x 10 grid with equal dimensions of 66 ft, as represented in Fig. 2.

The fractional-flow solution (Buckley-Leverett) assumes that neither the rock nor the fluids have any compressibility. This means that the right-hand side of the diffusivity equation is zero.

Table 1

RESERVOIR AND FLUID PROPERTIES FOR A HYPOTHETICAL FIVE SPOT

Number of layers	=	1
Pattern area, acres	=	40
Pressure drop between injector and producer, psi	=	3,000
Oil viscosity, cp	=	1.0
Water viscosity, cp	=	0.5
Well radius, ft	=	0.25
Oil formation volume factor, res. bbl/st-tk bbl	=	1.29
Water formation volume factor, res. bbl/st-tk bbl	=	1.0
Oil specific gravity, fraction	=	0.8
Reservoir porosity, %	=	20
Thickness, ft	=	50
Reservoir permeability, md	=	10
Connate water saturation, %	=	10

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The diffusivity equation describes fluid flow in porous media and is given by Equation 1 (see equation box) for a horizontal reservoir with no capillary pressure.

The numerical solution of such an equation with zero compressibility is not as easy as the solution of compressible systems. Moreover, abrupt saturation changes, which happen in displacement processes, may cause instability in the solution.

Therefore, fully implicit formulation of equations is needed to model such a process. Consequently, we used a two-dimensional, three-phase, fully implicit, finite-difference reservoir simulator to generate waterflood data for comparison.

Comparisons

The hypothetical five-spot reservoir was used to compare the results of both the CGM model and simulation. This step provided an understanding of the CGM model before and after breakthrough and identified problem areas.

Fig. 3 shows this comparison for injection rates and oil and water production rates. The match between the CGM model and simulation is considered good in most of the time periods. However, the match around the breakthrough time is not as close. Also, numerical simulation cannot depict the sharp increase in water production at water breakthrough.

Several reasons explain the poor agreement of the results at the breakthrough.

- The numerical dispersion[9] problem inherent in the numerical simulation causes no sharp saturation change. As a result, no sharp front can be obtained from the numerical simulation. It may be important to note that numerical dispersion is more severe in the fully implicit formulation used in the reservoir simulator.
- The grid orientation[9] affects the breakthrough time. By grid orientation, we mean that the fluid flow between cells depends on how the grids are oriented. This causes some doubt as to when breakthrough occurs. Also, Grid orientation is more of a problem for the adverse mobility ratio cases that were compared.
- A flaw in the CGM model is believed to be due to the areal sweep calculation. The CGM method assumes that areal sweep is calculated from a laboratory correlation. The laboratory correlation considered only miscible displacement and, therefore, the mobility ratio was actually a viscosity ratio rather than a mobility ratio.
- The conductance ratio correlation used to correct the water injection rate in the CGM method is based on laboratory experiments. In these experiments, the saturation gradients found in the displacement processes were totally absent.

The difference in computer time between reservoir simulation and CGM calculations was large. Each simulation run took almost 30 min for a quadrant of the five-spot compared to less than 30 sec on the same computer for CGM calculations.

Modifications

One limiting assumption of the CGM model is the production against constant pressure drop between the injector and producer for the entire reservoir life. In actual field operations, this pressure drop changes with time for several reasons. Therefore, the model was modified to allow for the pressure drop to change with time. This feature should help the engineer in either history matching or planning a waterflood.

The second modification concerns water production before breakthrough. In many reservoirs, water production occurs early in the reservoir life and sometimes even before any water injection. This water production may be due to connate water saturation, S_{wc}, being higher than irreducible water saturation, S_{wir}.

It could also happen if the well is completed in a transition zone between water and oil. This transition zone is often formed because of the action of capillary pressure.

Pressure drop variation

The injectivity equation (Equation 2) assumes water is injected against constant pressure drop, Δp.

It also assumes unit mobility ratio between oil

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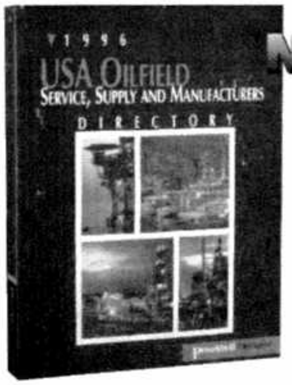

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and water, but this assumption is accounted for in the CGM model by using the conductance ratio correlation.[8] In the program we developed to do the CGM calculations, the user is allowed to input different pressure drops with time cards. After each time step, the program checks if the pressure drop has changed or not and uses the new value if it has.

A case with variable pressure drop was simulated with the reservoir simulator described earlier and with the CGM program we developed. The data set for the five-spot, single-layer reservoir (Table 1) was modified to include pressure changes.

The pressure drop between the injector and the producer was taken to be 3,000 psi for the first 1,000 days, changed to 2,000 psi for the following 1,000 days, and finally kept at 1,000 psi for the rest of the run.

The simulation results are plotted along with the modified CGM model in Fig. 4 for injection and oil and water production rates.

Considering the factors that reduce the match between numerical simulation and laboratory scaled models such as the CGM model, the agreement between the two is considered very good. This agreement shows the feasibility of the proposed modification.

Water production

To account for water production before breakthrough, another modification of the CGM model was introduced. Before explaining the modification, several terms need to be defined.

Connate water saturation, S_{wc}, is the initial water saturation in the reservoir at the time waterflooding starts.

Irreducible water saturation, S_{wir}, is the water saturation at which the water becomes totally immobile.

The Buckley-Leverett[6] solution of flow equations can handle the case where the connate water saturation is higher than S_{wbt}. In this case, the tangent to the fractional-flow curve, needed to determine the average water saturation behind the flood front at the breakthrough, S_{wbt}, is simply drawn from S_{wc} instead of S_{wir}. Mathematically, Equation 3 can represent S_{wbt}.

However, the CGM model assumes no water production before breakthrough. In our solution, we allow the CGM program to produce water before breakthrough.

Equations 4 and 5 are used to calculate the water and oil mobilities at the end points, such as water mobility at residual oil saturation and oil mobility at connate water saturation.

Those mobilities along with the mobile saturations of each phase are used as weighting factors for determining production of each phase before breakthrough. The calculation procedure is as follows:

- First, the end-point mobilities, are calculated by Equations 4 and 5.
- Then the mobile saturations are determined from Equations 6 and 7.
- Water injection in every time step is calculated by the normal CGM calculations, and the injection water fraction responsible for oil production before breakthrough is calculated from Equation 8.
- Likewise, the fraction of water injection rate responsible for water production before breakthrough is obtained with Equation 9.
- The oil and water production rates are then determined by Equations 10 and 11.

The same data set used previously was simulated with a numerical simulator and our modified CGM program. The only modification to the data was that the connate water saturation was assumed to be 15%. The irreducible water saturation determined from relative permeability data remained at 10%.

Fig. 5 shows the match between the numerical simulation and the modified CGM method. In spite of the fact that around the breakthrough time the match is not perfect, the agreement between the overall performance is sufficiently accurate.

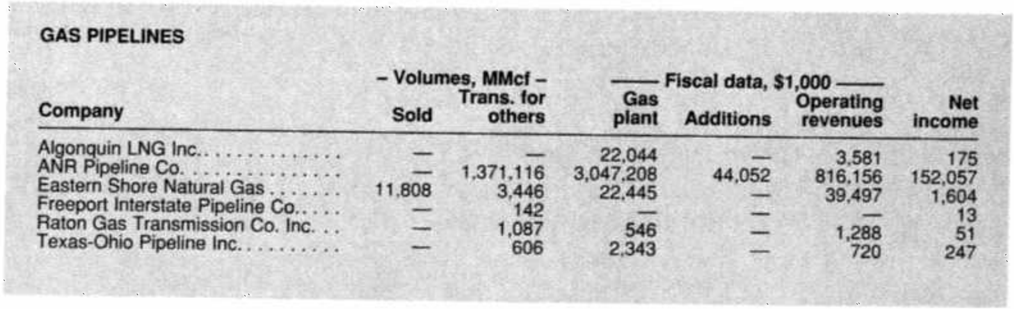
More importantly, water production before breakthrough (Fig. 11) was modeled with the modified CGM program. Without the proposed modification, the CGM model could not match this water production.

References

1. Craig, F.F. Jr., The Reservoir Aspects of Waterflooding, Monograph Series, SPE, 1971.
2. Craig, F.F., Geffen, T.M., and Morse, R.A, "Oil Recovery Performance of Pattern Gas or Water Injection Operations From Model Tests," Trans. AIME, Vol. 204, 1955, p. 715.
3. Willhite, G.P., Waterflooding, Textbook Series, SPE, 1986.
4. Timmerman, E.H., Practical Reservoir Engineering, PennWell Publishing Co., 1982, pp. 161-97.
5. Wu, C.H, "Waterflood Performance Projection Using Classical Waterflood Models," Paper No. SPE 18597, SPE Production Technology Symposium, Hobbs, N.M., Nov. 7-8, 1988.
6. Buckley, S.E., and Leverett, M.C., "Mechanism of fluid Displacement in Sands," Trans. AIME, Vol. 146, 1942, pp. 107-16.
7. Welge, H.J., "A Simplified Method for Computing Oil Recoveries by Gas or Water Drive," Trans. AIME, Vol. 195, pp. 91-98.
8. Caudle, B.H., and Witte, M.D., "Production Potential Changes During Sweep-Out in a Five-spot System," Trans. AIME, Vol. 216, 1959.
9. Mattax, C.C., and Dalton, R.L., Reservoir Simulation, Monograph Series, Vol. 13, SPE, 1990.

Correction

A software printing problem caused data from FERC annual reports of six natural-gas pipelines to be incorrectly published in the "GAS PIPELINES" table of OGJ's annual Pipeline Economics Report (Nov. 27,1995, p. 56). The table's totals are correct. Here are the correct company data:



GAS PIPELINES

Company	– Volumes, MMcf – Sold	Trans. for others	—— Fiscal data, $1,000 —— Gas plant	Additions	Operating revenues	Net income
Algonquin LNG Inc.	—	—	22,044	—	3,581	175
ANR Pipeline Co.	—	1,371,116	3,047,208	44,052	816,156	152,057
Eastern Shore Natural Gas	11,808	3,446	22,445	—	39,497	1,604
Freeport Interstate Pipeline Co.	—	142	—	—	—	13
Raton Gas Transmission Co. Inc.	—	1,087	546	—	1,288	51
Texas-Ohio Pipeline Inc.	—	606	2,343	—	720	247