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RESERVOIR ENGINEERING

Calculation of Gas Recovery Upon Ultimate Depletion of Aquifer Storage

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Abstract

The recovery of cushion gas upon ultimate depletion of an aquifer storage reservoir is dependent upon reservoir heterogeneity, aquifer strength, production rate, and fluid and rock properties. This study illustrates the use of multi-dimensional, two-phase, compressible fluid flow calculations to simulate the depletion. Results that illustrate the non-exhaustive examination of the effects of heterogeneity, aquifer strength, and gas production rate are presented. The study indicates a strong dependence of recovery upon reservoir heterogeneity. The multi-dimensional type of calculation employed appears necessary to reliably estimate recoverable cushion gas for any particular reservoir.

Introduction

When the use of aquifer storage for natural gas is contemplated, the capital cost of such a venture must be closely estimated to evaluate properly the feasibility of such a proposal. It is relatively simple to account for lease acquisition, drilling, well completion and surface facility costs. Determining the cost of the unrecoverable cushion gas is difficult, and this portion of the investment can be the largest item in the total required to develop an aquifer storage field. This paper describes a study made at Northern Natural Gas Co. to evaluate a technique that has application to this problem.

Two basic factors determine the percentage of nonrecoverable cushion gas: water invasion efficiency and average pressure level at abandonment. Invasion efficiency is defined here as the average water saturation in the reservoir at time of abandonment. This efficiency is dependent upon reservoir heterogeneity, gas production rate, and fluid and rock properties such as density, viscosity, relative permeability, capillary pressure and residual gas saturation — the lowest saturation at which gas will flow under a potential gradient during displacement by water.

Earlier work related to this problem of gas recovery treated the effects of aquifer strength, production rate, and several other factors on ultimate recovery from gas producing fields.[1] In that work the reservoir was assumed to be homogeneous with uniform pressure, and water invasion efficiency was assumed.

In this paper a computerized model is described and applied to simulate the displacement of gas by water during ultimate storage field depletion. This simulation yields unsteady-state pressure and saturation distributions throughout the reservoir during depletion. These distributions give water invasion efficiency and average pressure level, which in turn determine the percentag of cushion gas not recoverable at abandonment. The calculations simulate multi-dimensional, two-phase, compressible fluid flow and account for effects of reservoir heterogeneity, production rate, aquifer strength, well completion interval and fluid and rock properties.

Three hypothetical reservoirs of different heterogeneities are treated, including one considered representative of a zone in the Redfield Storage field. For each reservoir, results are presented as percentage of cushion gas recovered for various aquifer strengths and gas production rates.

The Simulation Model

A calculational technique described by Douglas, Peaceman and Rachford[2] was applied recently by Coats and Richardson[3] to the problem of water displacement by gas during initial growth of an aquifer storage reservoir. The technique simulates two-dimensional, two-phase, incompressible fluid flow in reservoirs. A similar method was used in this study to simulate the two-dimensional, compressible gas-water displacement during ultimate depletion of an aquifer storage field.

The calculations are based on continuity equations for both fluid phases and Darcy's law including relative permeability. These are combined to give the basic equations of flow, Eqs. 1a and 1b.

$$\nabla \cdot \frac{k\, k_{rw}}{\mu_w} \rho_w{}^2\, \nabla \Phi_w + q_w = \phi \frac{\partial}{\partial t} (\rho_w S_w) \quad . \quad (1a)$$

$$\nabla \cdot \frac{k\, k_{rg}}{\mu_g} \rho_g{}^2\, \nabla \Phi_g + q_g = \phi \frac{\partial}{\partial t} (\rho_g S_g) \quad . \quad . \quad (1b)$$

These equationse are expressed in a finite difference form and simultaneously solved using an alternating direction

[1]References given at end of paper.

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implicit procedure.[2] In this model study, fluid viscosities are treated as constants and fluid densities are functions of phase pressure.

Some experimental verification of these multi-dimensional, two-phase flow calculations is given in Refs. 2 and 4.

Displacement Studies

The investigation consisted of simulating three different radial cross-sections for various aquifer strengths and gas production rates. A completely homogeneous cross-section and a heterogeneous, non-communicating, layered cross-section were the reservoir description extremes. An intermediate case considered was a heterogeneous cross-section with vertical communication. This cross-section approximates one of the storage zones in the Redfield Storage field. The permeability and porosity data were obtained from core data and are considered only approximately characteristic of Redfield since a history match of this reservoir to validate the description has not been completed. The homogeneous cross-section had the same flow capacity (md-ft product), thickness and pore volume as the heterogeneous reservoir. The two heterogeneous reservoirs are identical except for the zero vertical permeability in one of them. In all runs, the abandonment criterion was either water-gas ratio greater than 60 bbl/MMcf, or pressure in the producing blocks lower than 200 psia.

Tables 1 and 2 give the formation volume factor, capillary pressure, relative permeability and other pertinent data used for all systems. Note that residual gas saturation is 30 percent; i. e., gas relative permeability is zero at a water saturation of 0.7. Fig. 1 schematically illustrates the heterogeneous reservoir. For clarity, vertical grid lines have been omitted from all reservoir figures.

Aquifer Definition

The aquifer description used in this study is a zero dimensional representation that does not consider the effects of transient flow in the aquifer, which is treated as a "pot" lying just outside the reservoir. The aquifer is capable of delivering a fixed number of barrels of water for each unit of potential drop in the outer block of the reservoir. This type of aquifer was chosen instead of aquifer influence functions because of simplicity. It is felt, however, that this characterization of aquifer behavior is adequate for the purposes of this type of study. A comparison of the behavior of this system with a completely sealed

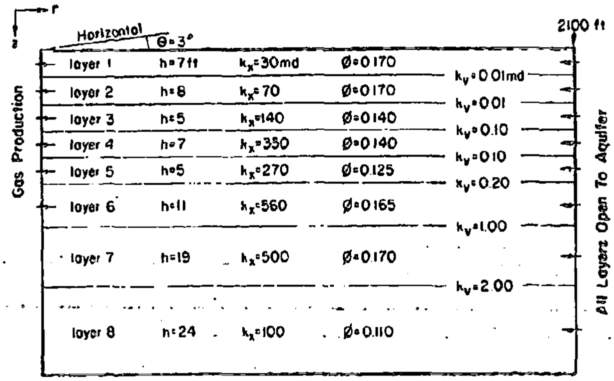

Fig. 1 — *Schematic heterogeneous reservoir representation.*

system with additional, large, water-filled blocks demonstrated that the flow gradients and saturations within the radius of gas bubble were virtually identical.

Computing Times

The numerical system of these studies consisted of 8 blocks in the z-direction and 19 in the x-direction. As an example of the computing time required, the heterogeneous system with vertical communication, gas flow rate of 2 MMcf/D and aquifer strength of 1 million bbl of influx/D/psi pressure drop required about 20 minutes of processor time on a Burroughs B-5500 to carry the run through 301 days.

Results of Radial, Cross-Sectional, Unsteady-State Studies

As shown in Fig. 2, the initial saturation distributions were identical for all cases. Fig. 3 presents a comparison of the watered-out area of the homogeneous reservoir with the heterogeneous reservoir (Fig. 1). Both reservoirs have identical flow capacities. The aquifer strength was 10^6 B/D/psi and the gas flow rate was 4 MMcf/D. The profiles are drawn for an identical time of 352 days at 0.70 water saturation. In the homogeneous case a nearly piston-

TABLE 1

RESERVOIR DATA

Density of water at 1,000 psia, lb/cu ft	62.4
Density of gas at 1,000 psia, lb/cu ft	8.89
Sine of dip angle	0.05
Gas viscosity (constant), cp	0.017
Water viscosity (constant), cp	1.0
Initial gas in place, Bcf	3.3

FORMATION VOLUME FACTOR DATA

Pressure (psia)	Water Formation Volume Factor (res. bbl/STB)	Gas Formation Volume Factor (res. bbl/Mcf)
200	1.0000	13.17
400	0.9988	6.36
600	0.9976	4.10
800	0.9964	2.97
1000	0.9952	2.29

TABLE 2 — CAPILLARY PRESSURE — RELATIVE PERMEABILITY DATA

Water Saturation (fraction)	Capillary Pressure* (psi)	Water Relative Permeability (fraction)	Gas Relative Permeability (fraction)
0.20	200.0	0.000	0.270
0.205	60.0	0.001	0.262
0.21	30.0	0.002	0.254
0.215	15.0	0.003	0.247
0.22	12.0	0.004	0.240
0.25	8.5	0.010	0.204
0.30	7.0	0.020	0.158
0.35	6.0	0.030	0.125
0.40	5.0	0.042	0.100
0.45	4.5	0.058	0.070
0.50	4.0	0.077	0.045
0.55	3.5	0.100	0.020
0.60	3.0	0.123	0.005
0.70	2.5	0.196	0.0
0.80	2.0	0.340	0.0
0.90	1.5	0.580	0.0
1.00	1.0	1.000	0.0

*These are capillary pressure data for layer 5. For other layers, capillary pressures were obtained by assuming that P_c is proportional to $\sqrt{\phi/k_x}$.

TABLE 3 — COMPARISON OF GAS RECOVERIES
(Initial gas in place = 3.3 Bcf)

Case	Reservoir Description	Production Rate (MMcf/D)	Pot Aquifer Strength (B/D/psi)	Percent of Initial (Cushion) Gas Recovered at Abandonment[*]
1	Homogeneous	4	10^6	62.5[w]
2	Heterogeneous (Fig. 1)	2	10^3	75.7[p]
3	Heterogeneous	2	10^4	51.4[w]
4	Heterogeneous	2	10^6	38.9[w]
5	Heterogeneous	4	10^3	69.6[p]
6	Heterogeneous	4	10^4	53.5[w]
7	Heterogeneous	4	10^6	42.9[w]
8	Heterogeneous (No vertical communication)	2	10^6	18.3[w]
9	Heterogeneous (No vertical communication)	4	10^6	20.6[w]

[*] Abandonment criterion was well pressure <200 psia or a produced water cut > 60 bbl/MMcf, whichever occurred first.

[w] Abandonment criterion of water cut was exercised.

[p] Abandonment criterion of well pressure was exercised.

like edge-water drive developed. The lower part of the heterogeneous reservoir has been watered out by a more rapid advance of the water caused by the heterogeneities. At abandonment conditions, the homogeneous reservoir recovered 62.5 percent of the cushion gas compared with 42.9 percent for the heterogeneous reservoir. The abandonment condition in each case was excessive water-gas ratio.

Fig. 4 compares the heterogeneous system with a system with no vertical flow. The recovery from the no-vertical-flow system is only 20.6 percent of initial gas in place. A water finger developed in the high permeability zone and caused early watering-out of the producing well.

Fig. 5 illustrates saturation profiles for the three different aquifer strengths in the heterogeneous reservoir for a 4 MMcf/D gas production rate. The profiles are at approximately equal time and show that the stronger the aquifer, the farther the water front advanced into the reservoir. In these and other runs, stronger aquifers decreased gas recovery due to the combined effects of earlier watering-out of the well and higher pressure at abandonment.

Table 2 gives the percentage of cushion gas recovered in the runs discussed above and in several additional cases. Cases 2 through 7 of this table pertain to the heterogeneous reservoir (with vertical communication) of Fig. 1. These six cases show that, given a significantly strong aquifer, cushion gas recovery increases as gas production rate increases. For example, at an aquifer strength of 10^6 B/D/psi the percentage of cushion gas recovered increased from 38.9 to 42.9 percent as gas production rate increased from 2 to 4 MMcf/D (cases 4 and 7). The reduction in gas recovery with increased production rate for the low aquifer strength of 10^3 B/D/psi is due to the near absence of water influx and the 200 psia well pressure abandonment criterion.

Discussion of Results

Table 3 shows a strong dependence of cushion gas re-

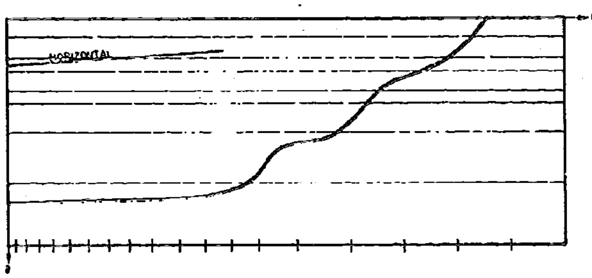

Fig. 2 — *Initial S_w = 0.70 contour, all cases.*

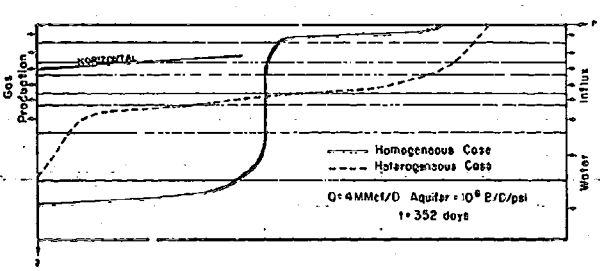

Fig. 3 — *Comparison of watered-out area, homogeneous vs heterogeneous. Contoured on S_w = 0.70.*

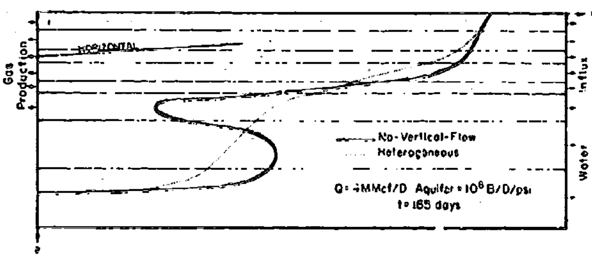

Fig. 4 — *Comparison of watered-out area, heterogeneous and no-vertical-flow. Contoured on S_w = 0.70.*

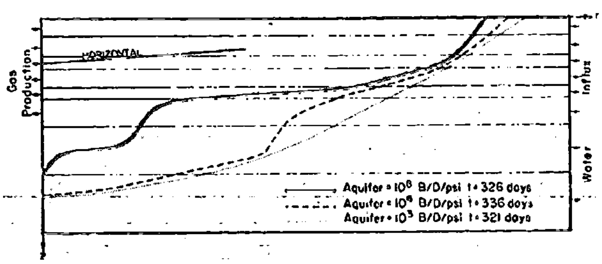

Fig. 5 — *Comparison of watered-out area for three aquifers; production rate = 4 MMcf/D. Contoured on S_w = 0.70.*

covery upon reservoir heterogeneity. The recovery percentages for the three different reservoirs at a 4 MMcf/D production rate were 62.5 (homogeneous), 42.9 (heterogeneous with vertical communication) and 20.6 (heterogeneous with no vertical communication). This variation with heterogeneity indicates the difficulty inherent in attempts to derive general figures or correlations for recoverable gas. However, a calculational method of the type employed here is capable of estimating recovery for any particular field.

Table 3 also shows that cushion gas recovery decreased with increased aquifer strength and increased (except in the case of the very weak aquifer) with increased gas production rate. This behavior agrees with that noted earlier by Agarwal *et al.*[1]

The absolute levels of the recoveries are not so meaningful as the variation with reservoir heterogeneity, etc. The reason for this is that several factors or parameters not varied in this work also affect recovery. For example, reservoir size and initial pressure, the number and location of wells, and reservoir geometry all affect the nature of the water-gas displacement and, hence, affect recovery.

Conclusions

Two-dimensional, two-phase flow calculations indicate a significant variation of cushion gas recovery with reservoir heterogeneity. This indicates that the effects of heterogeneity as well as effects of production rate, aquifer strength and fluid and rock properties must be considered when estimating the investment represented by non-recoverable cushion gas. These effects can be accounted for through simulation of multi-dimensional, two-phase flow.

Calculations showed that cushion gas recovery increased with decreasing aquifer strength and increasing production rate. These results agree with those of previous work.

Nomenclature

g = acceleration of gravity, ft/sec^2
g_c = gravitational constant, 32.17 ft-lb$_m$/lb$_f$ – sec^2
h = elevation (vertical position), measured positively downward, ft
k = absolute permeability, md × .00633
k_r = relative permeability
p = pressure, psi
q = injection rate, lb$_m$/cu ft/D
S_w = water saturation
t = time, days
μ = viscosity, cp
ρ = density, lb$_m$/cu ft
ϕ = porosity

$$\Phi = \text{potential}, \int^{p} \frac{dp}{\rho} - \frac{g}{144 g_c} h$$

Subscripts

w = water
g = gas

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