

SIMULATION OF THE BROADLANDS GEOTHERMAL FIELD, NEW ZEALAND

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Abstract

The governing equations for a two phase geothermal reservoir are presented for the case when a substantial amount of carbon dioxide is present. Sample results for a model reservoir based on the Broadlands geothermal field are given.

Introduction

The Broadlands geothermal field is the next field in New Zealand which will be extensively developed. Like the Bagnore field in Italy and the Ngawha field in New Zealand, the Broadlands field is characterized by a relatively high (2-4% by mass) content of carbon dioxide. The presence of carbon dioxide has depressed the boiling surface sufficiently deep to make the production zone two phase. Because of the importance of the gas content in influencing the design of geothermal energy conversion systems it is important to understand and to predict the behaviour of carbon dioxide in the reservoir.

Lumped parameter models of gassy (carbon dioxide) geothermal reservoirs have recently been studied.^{1,2,3} They have shown that the reservoir properties are sensitive to changes in the carbon dioxide content. This report presents some of the initial results of a simulation of the behaviour of a multi-dimensional carbon dioxide dominated reservoir.

Basic Field Equations

A thorough discussion of the governing equations for the carbon dioxide water geothermal system is given by Zylvolski and O'Sullivan.⁴ Here we present only the final results (see notation section).

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Conservation of mass:

$$\Delta \cdot (D_m \nabla p) - q_m - \frac{m}{t} = 0 \quad (1)$$

Conservation of energy:

$$\nabla \cdot (D_e \nabla p) - q_e - \frac{\partial A_e}{\partial t} = 0 \quad (2)$$

Conservation of carbon-dioxide:

$$\nabla \cdot (D_c \nabla p) - q_c - \frac{\partial A_c}{\partial t} = 0 \quad (3)$$

where

$$A_m = \phi (S_v \rho_v + S_l \rho_l)$$

$$A_e = (1-\phi) \rho_r U_r + \phi (S_v \rho_v U_v + S_l \rho_l U_l)$$

$$A_c = \phi (S_v \rho_v n_v + S_l \rho_l n_l)$$

The transmissibilities D_m , D_e , and D_c are given by

$$D_m = D_{mv} + D_{ml}$$

$$D_e = H_v D_{mv} + H_l D_{ml}$$

$$D_c = n_v D_{mv} + n_l D_{ml}$$

with

$$D_{mv} = \frac{kR_v \rho_v}{\mu_v}, \quad D_{ml} = \frac{kR_l \rho_l}{\mu_l}$$

We note here that in equations (1), (2) and (3), use was made of Darcy's law. The forms of the relative permeabilities are those suggested by Corey.⁵

The independent variables used are the total pressure p , the mixture enthalpy H and the temperature T . The variables H and T do not appear explicitly in equations (1), (2), and (3) but the variables D_α , A_α ($\alpha = m, e, c$) depend on them.

The mixture enthalpy is defined by

$$H = (\rho_l H_l S_l + \rho_v H_v S_v) / (\rho_l S_l + \rho_v S_v)$$

This equation is used to solve for S_v ($S_l = 1 - S_v$) in terms of other quantities which depend only on p and T .

Thermodynamics

The thermodynamics formulae used are similar to those used by Sutton and McNabb⁶, Grant¹, Zyvoloski and O'Sullivan⁴, Atkinson et al³, and Mercer and Faust⁷ and are not reproduced here.

The sink terms q_e and q_c are calculated from the prescribed mass withdrawal q_m using the formulae

$$q_e = q_v H_v + q_l H_l$$

$$q_c = q_v n_v + q_l n_l$$

Here q_v and q_l , the mass withdrawals of vapour and liquid respectively, are calculated using the equations below (Mercer and Faust⁷)

$$q_v = \sigma q_m \quad q_e = (1 - \sigma) q_m$$

with

$$\sigma = 1 / (1 - \rho_l R_l \mu_v / \rho_v R_v \mu_l)$$

For a presentation of the numerical procedures used the reader is referred to Zyvoloski and O'Sullivan.⁴

RESULTS

Two examples were chosen to investigate the effect of the presence of carbon dioxide on reservoir behaviour. The first is a hypothetical two-phase, two-dimensional reservoir with field properties similar to those found in the Broadlands (New Zealand) geothermal field. The data for the problem are given in Table 1. The problem is similar to one considered previously for a pure water field by Faust and Mercer⁷, Toronyi and Farouq Ali⁸ and Thomas and Pierson⁹. The results in Figures 1 and 2 give contours for pressure and saturation, after the field has been discharging for 500 days. The results clearly show that the pressure changes are propagated more rapidly across the field when carbon dioxide is present corresponding to a decrease in the compressibility of the fluid.

The second example considered was designed to test the effect of carbon dioxide on the short term transient behaviour of a geothermal aquifer. The data for the problem are given in Table 2. Two initial liquid saturations of 0.99, 0.2 and three initial carbon dioxide contents are considered. The pressure of the wellbore as a function of time for these six cases is shown in Figures 3 and 4. The qualitative difference between the behaviour at high saturation (Figure 3) and low saturation (Figure 4) can be explained in terms of the carbon dioxide content. With a high liquid saturation there is a very small amount of carbon dioxide in the discharge (see equation 18) because the discharge is mainly from the liquid phase in which the carbon dioxide content is small. In this situation the carbon dioxide primarily affects the system by decreasing the compressibility of the two-phase fluid. At the low liquid saturation the discharge comes mainly from the vapour phase and is rich in carbon dioxide. This removal of carbon dioxide, or "de-gassing", dominates the pressure response and consequently the pressure drops significantly as a result of the decrease of the partial pressure of carbon dioxide in the vapour. Figures 5 and 6 show the radial pressure profiles at the different saturations. The compressibility and de-gassing effects are evident.

CONCLUSIONS

The spatial behaviour of gas-dominated reservoirs is substantially different from pure water reservoirs. The qualitative behaviour of the pressure transients is affected by the saturation and the presence of carbon dioxide. Careful monitoring of the gas content in the discharge may be required to allow correct interpretation of pressure transients in gassy geothermal fields.

Nomenclature and Notation

A	-	Accumulation term
D	-	Transmissibility
H	-	Enthalpy
k	-	Field permeability
n	-	Mass fraction carbon dioxide
P	-	Field pressure
4	-	Sink
R	-	Relative permeability
S	-	Saturation
T	-	Temperature
t	-	Time
U	-	Specific internal energy
ϕ	-	Field porosity
ρ	-	Density
μ	-	Viscosity

Subscripts

c	-	carbon dioxide
m	-	mass
e	-	energy
l	-	liquid phase
v	-	vapour phase
r	-	rock

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TABLE 1 - A MODEL TEST TWO-PHASE RESERVOIR

Permeability	$k = 3(10^{-14}) \text{ m}^2$
Porosity	$\phi = 0.20$
Thermal conductivity	$K = 2.5 \text{ W/m.K}$
Rock density	$\rho_r = 2500 \text{ kg/m}^3$
Rock specific heat	$C_r = 1.0 \text{ kJ/kg.K}$
Aquifer dimensions:	Length = 1760 m
	Width = 880 m
	Thickness = 250 m
Number of blocks	$NX \times NY = 11 \times 11$
Time step	$\Delta t = 10 \text{ days}$
Production rate	$q_m = 80 \text{ kg/sec}$
Initial pressure	$p_{i,j}^0 = 62 \text{ bars}$
Initial liquid saturation	$S_{li,j}^0 = 0.85$
Initial partial pressure of CO ₂	$p_{ci,j}^0 = 0.0 \text{ or } 15.0 \text{ bars}$

TABLE 2 - RADIAL PRESSURE TRANSIENT TEST

Permeability	$k = 6(10^{-14}) \text{ m}^2$
Porosity	$\phi = 0.2$
Thermal conductivity	$K = 2.5 \text{ W/m.k}$
Rock density	$\rho_r = 2500 \text{ kg/m}^3$
Rock specific heat	$C_r = 1.0 \text{ kJ/kg.K}$
Aquifer radius	$= 12 \text{ m}$
Aquifer thickness	$= 100 \text{ m}$
Number of blocks	$= 35$
Time step	$\Delta t = 43.2 \text{ s}$
Discharge rate	$q_m = 16.7 \text{ kg/s}$
Initial pressure	$p_{i,j}^0 = 50 \text{ bars}$
Initial liquid saturation	$S_{li,j}^0 = 0.2 \text{ or } 0.99$
Initial partial pressure of CO_2	$p_{ci,j}^0 = 0.0, 4.0 \text{ or } 12.0 \text{ bars}$

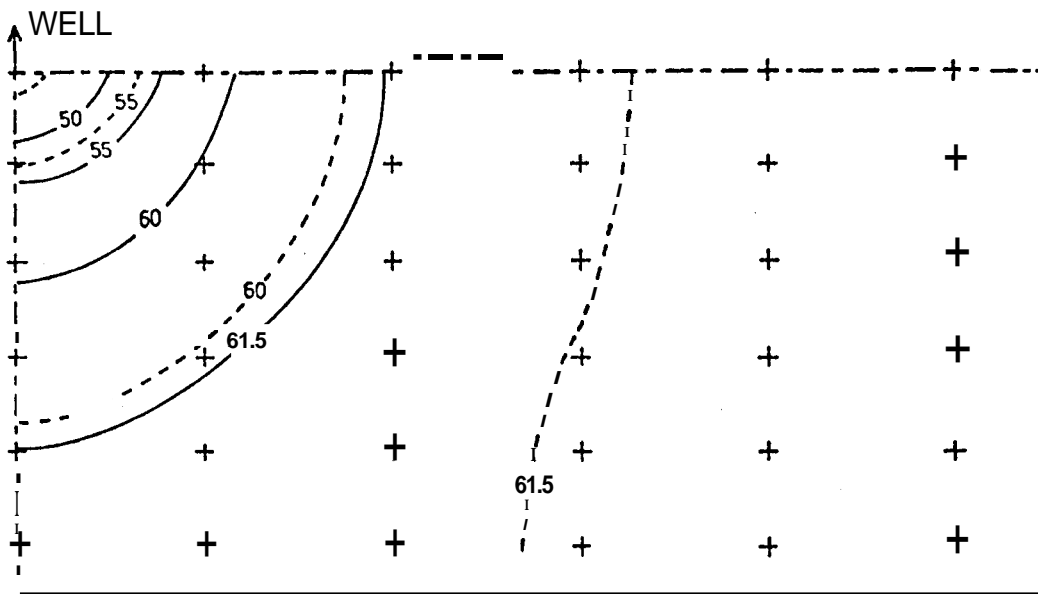


Figure 1. Pressure contours in the model reservoir after 200 days.
 _____ no CO₂, - - - - - 15 bar initial partial pressure of CO₂.

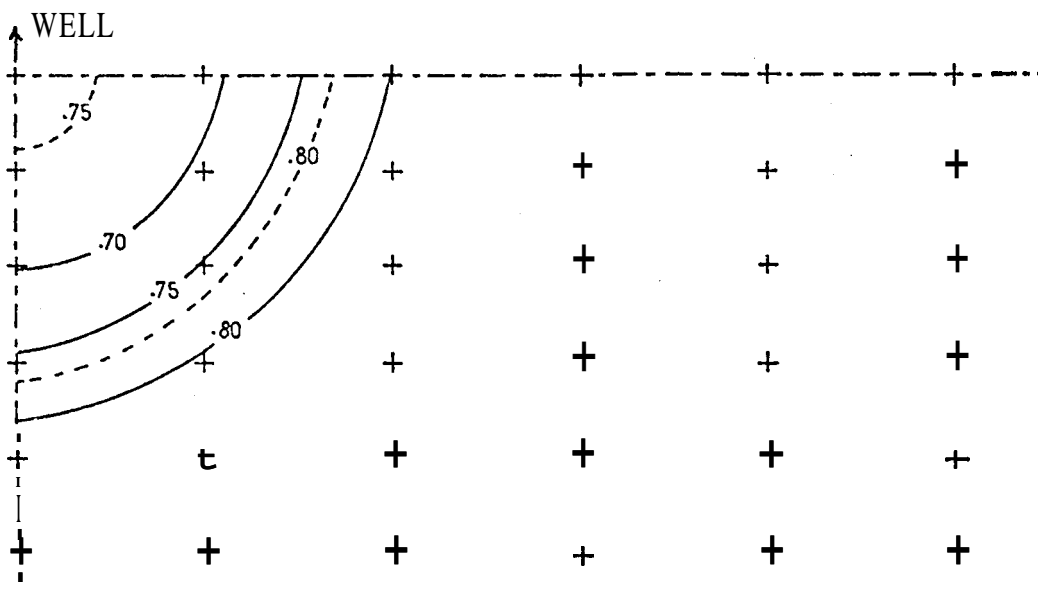


Figure 2. Liquid saturation contours in the model reservoir after 200 days.
 _____ no CO₂, - - - - - 15 bar initial partial pressure of CO₂.

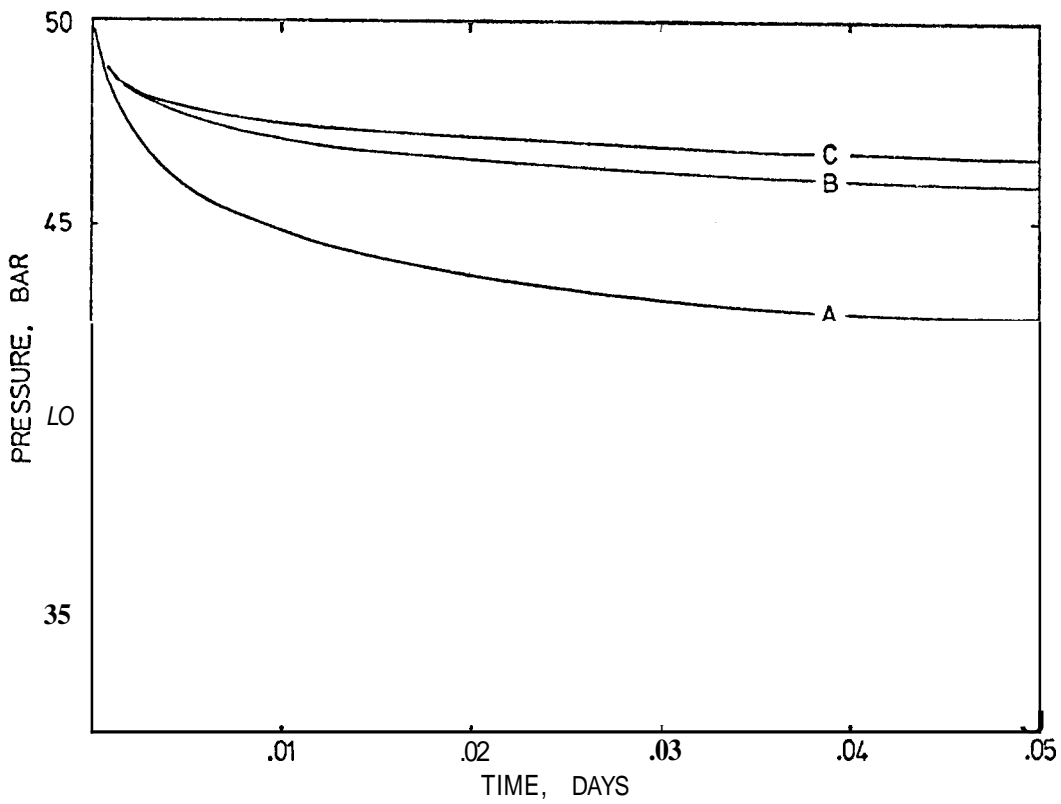


Figure 3. Transient pressure response of a model aquifer with an initial liquid saturation of 0.99 and varying CO₂ concentrations A - no CO₂, B - 4 bar CO₂, C - 12 bar CO₂.

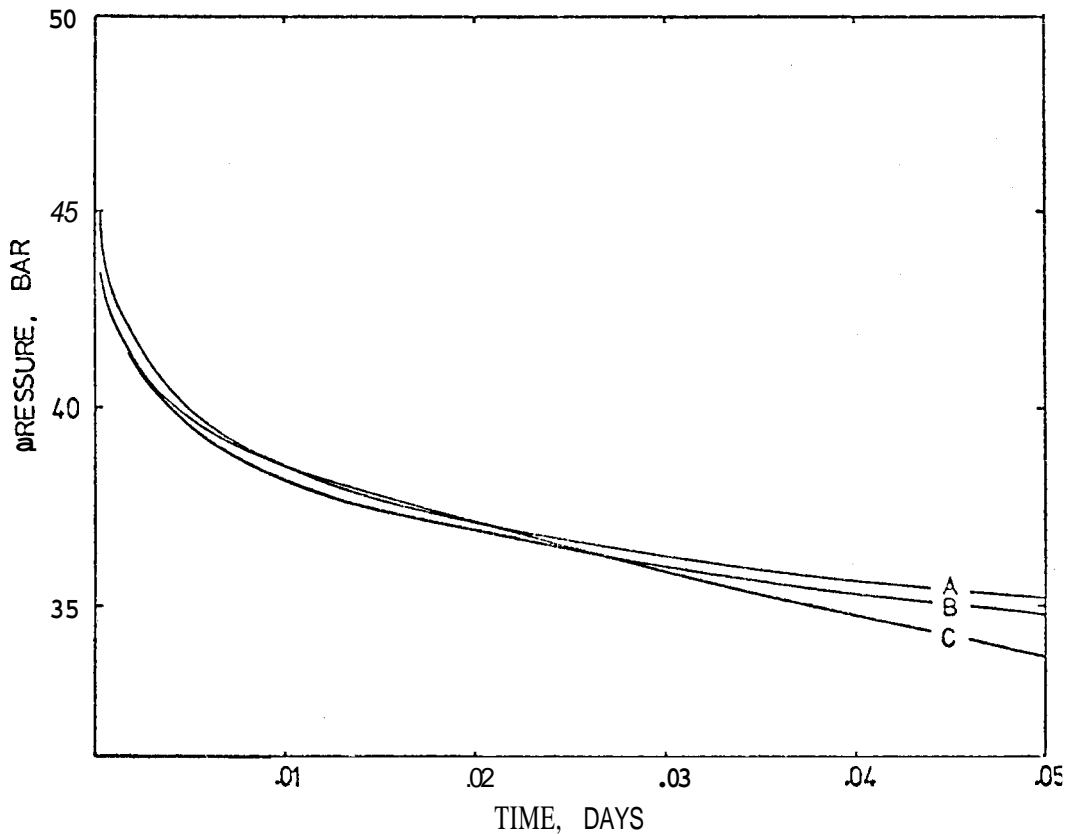


Figure 4. Transient pressure response of a model aquifer with an initial saturation of 0.20 and varying CO₂ concentrations. A - no CO₂, B - 4 bar CO₂, C - 12 bar CO₂.

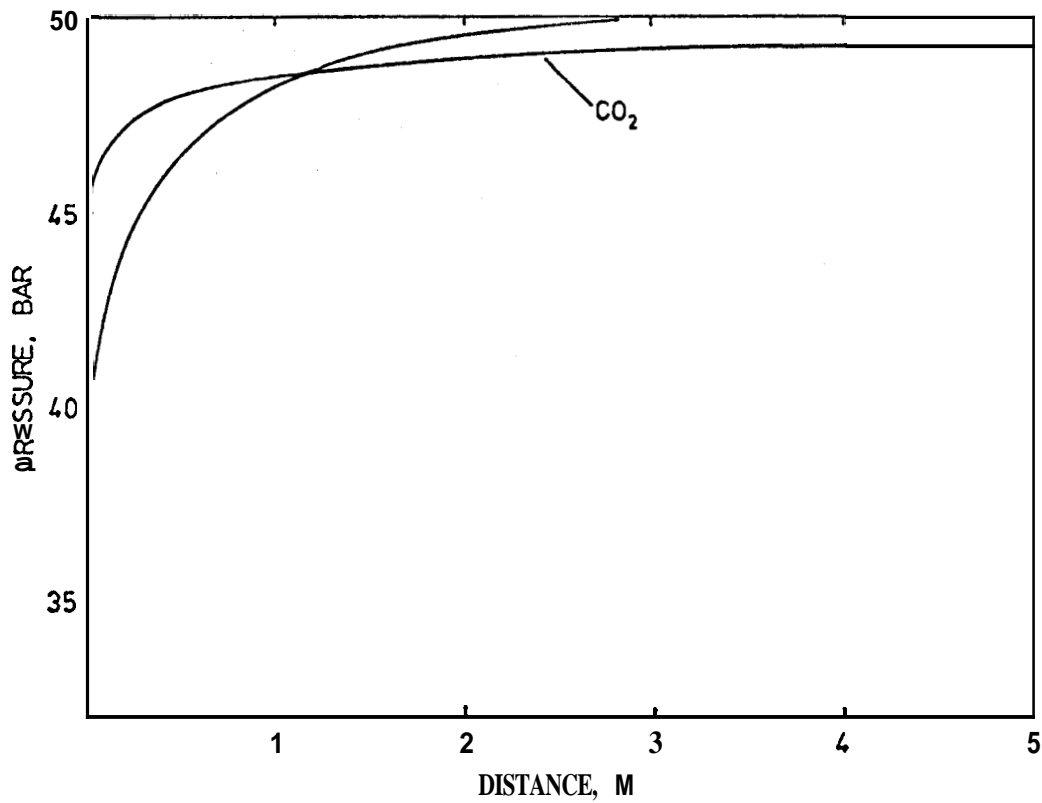


Figure 5. Pressure profiles in a model aquifer after 0.050 days. Initial liquid saturation 0.99. No CO, and 12 bars initial partial pressure of CO₂ respectively.

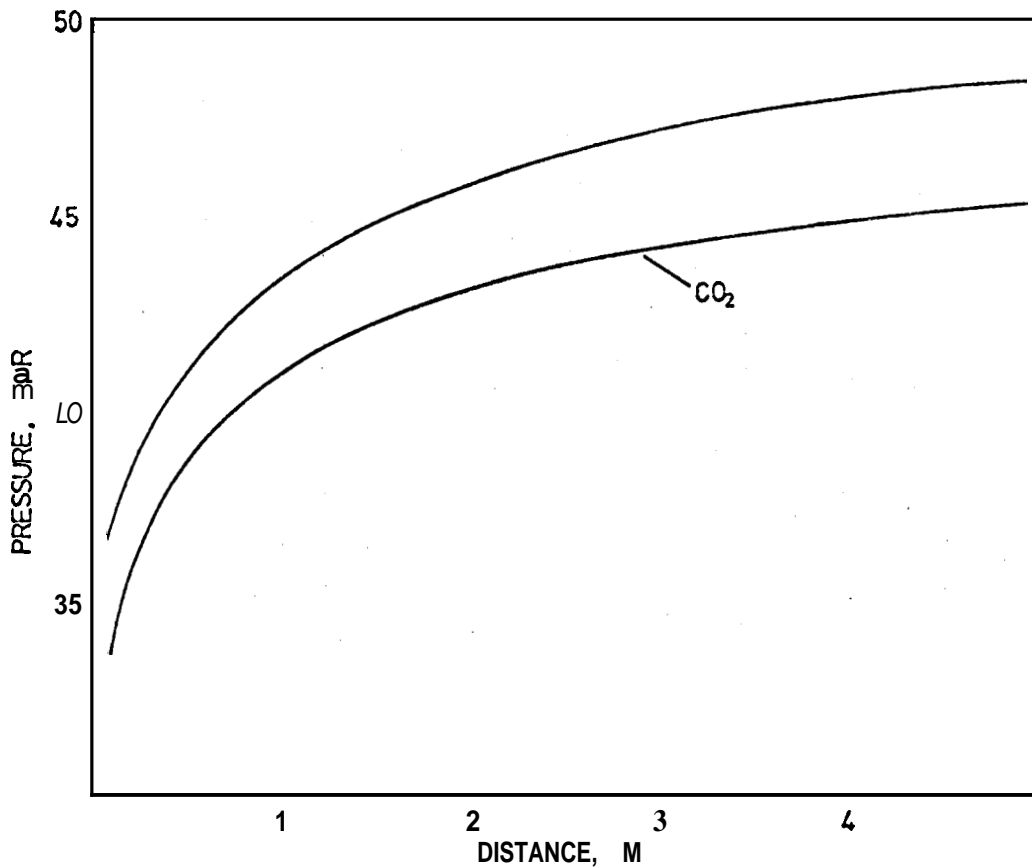


Figure 6. Pressure profiles in a model aquifer after 0.050 days. Initial liquid saturation 0.20. No CO, and 12 bars initial partial pressure of CO₂ respectively.