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Keeping inventory of carbon dioxide in liquid dominated geothermal reservoirs

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ABSTRACT

Carbon dioxide can have a significant effect on the production performance of geothermal reservoirs. The main impact is on the flashing point of water – carbon dioxide mixtures. Even small amounts of carbon dioxide can significantly increase the flashing point considerably. Hence at relatively high values of pressure, a gas phase could form during production either in the well or sometimes in the reservoir. When modeling geothermal systems with carbon dioxide it becomes crucial to include the effects of carbon dioxide in the model. Therefore it is very important to be able to keep track of the inventory of carbon dioxide. During production/re-injection operations the amount of carbon dioxide could change. This change in carbon dioxide should be modeled accurately to be able to make accurate future performance predictions. Even if two phase conditions never occur in the reservoir, it is still very important to account for the change in carbon dioxide due to the wellbore. The changes in carbon dioxide significantly affect the flashing point depth and the wellhead pressure. High wellhead pressures are necessary for keeping power plants operational and maintaining high production flow rates.

In this study we present a new analytical model that give the amount of carbon dioxide as a function of time and amounts of production, re-injection and recharge for liquid dominated reservoirs. The analytical approach presented in this study is an original contribution to the literature. The model is first verified using a method listed in the literature. Then various synthetic cases that demonstrate the effects of various parameters on the change of carbon dioxide in the reservoir are presented.

1. Introduction

The use of geothermal energy is increasing every day because of its cleanliness and sustainability. In order to make future performance predictions, geothermal reservoir simulations must be made. Early reservoir simulations considered the geothermal water to be pure water. However, geothermal waters may contain significant amounts of non-condensable gasses such as carbon dioxide. In some cases the amount of carbon dioxide may be as high as 5% by mass. The Kızıldere field in Turkey has around 1.5% (by mass) of carbon dioxide dissolved in the water. This value increases up to 3% by mass in deeper zones (Satman et al., 2005). Similarly, the Germencik field in Turkey has an average of 2.1% (by mass) of carbon dioxide dissolved in the geothermal water (Tureyen et al., 2014).

Geothermal models (numerical simulators, lumped parameter models and etc.) must take into account the effects of carbon dioxide. The presence of carbon dioxide affects the major thermodynamic properties of the geothermal fluid such as density, viscosity, the flashing point, pressure, and the effective compressibility. The changing mass fraction of carbon dioxide particularly affects the pressure and temperature behavior. The flashing point of geothermal systems with carbon dioxide are considerably higher than those with pure water.

From a sustainability point of view, carbon dioxide plays an extremely important role. Usually, during production in liquid dominated geothermal reservoirs, the flashing point is reached within the well. The existence of carbon dioxide causes the flashing point to be higher. Hence, a gas phase is formed inside the wells during production at relatively high pressures. It is the relatively high partial pressure of carbon dioxide that causes this phenomenon. Due to this high partial pressure, high flowing well head pressures can be achieved. Well head pressures must remain above a certain threshold for power production since the fluid must be able to flow through a turbine. Carbon dioxide aids in achieving this goal because of the high partial pressure. When making future performance predictions, the change in the carbon dioxide must be taken into account. Otherwise, if not considered, wrong predictions for the well head pressures could be made leading to unsustainable

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Nomenclature

c	Compressibility (bar^{-1})
f	Mass fraction of carbon dioxide (fraction)
m	Mass (kg)
p	Pressure (bar)
t	Time (s)
V	Volume (m^3)
w	Mass rate (kg/m^3)

Greek

β	Ratio of injected to produced carbon dioxide mass fractions (fraction)
Δ	Difference operator
ρ	Density (kg/m^3)
μ	Viscosity (bar s)
ϕ	Porosity (fraction)
Ψ	Recharge index used in the model of (Hosgor et al., 2015) (m^3)

Subscripts

0	Initial condition
b	Bulk
i	Initial
inj	Injection
n	Net
p	Production
r	Rock
re	Recharge
t	Total

management. This is why a good inventory of carbon dioxide must be kept. Hence a mathematical model is necessary to do so.

Modeling the effects of carbon dioxide has been considered by many authors in the literature. Zyvolosky and O'Sullivan (1980) have modeled the transport of carbon dioxide numerically. They provide a detailed description of the equations used for the simulation. Three conservation equations are considered; a mass balance on water, a mass balance on the carbon dioxide and overall energy balance. Their model clearly demonstrates the significance of carbon dioxide on the transient behavior of pressure.

The modeling of the Bagnore field which has considerable amounts of carbon dioxide was performed by Atkinson et al. (1980) using a lumped parameter model. Since the initial conditions of the Bagnore field was two phase, the authors have used a two tank model for representing the field. An upper tank used for modeling the gas phase and a lower tank model for modeling the liquid phase.

The simulation of geothermal systems where phase changes occur needs special attention in handling of primary variables. O'Sullivan et al. (1985) have provided in detail how these primary variables should be handled. The approach presented by the authors are still in use today in many of the simulators used for geothermal simulations.

Whiting and Ramey (1969) presented one of the first lumped parameter models that was capable of modeling pure water systems. Later Alkan and Satman (1990) developed the model to include for the effects of carbon dioxide by way of introducing a thermodynamic package describing the behavior of water – carbon dioxide systems. The model of Alkan and Satman (1990) was used to model the Cerro Prieto, Ohaaki, Bagnore and Kizildere fields.

Satman and Ugur (2002) have modeled the two phase compressibility at the flashing point pressure of water – carbon dioxide systems. Using this definition of compressibility together with a simple mass balance, information could be obtained regarding the

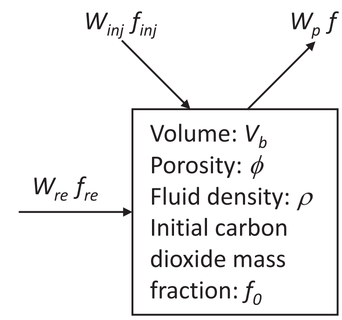

Fig. 1. Schematic of the control volume.

overall size of the geothermal reservoir. The developed model is used for modeling the Cerro Prieto, Ohaaki, and Kizildere fields.

Kaya et al. (2005) have used the simulator TOUGH 2 for analyzing the behavior of geothermal reservoirs with carbon dioxide for various different partial pressures of carbon dioxide. The analysis is performed for both single phase and two phase systems.

Hosgor et al. (2015) have presented a lumped parameter model capable of modeling water – carbon dioxide geothermal systems. They have adopted the approach of O'Sullivan et al. (1985) on a tank in lumped parameter modeling. They have analyzed various effects of parameters such as the initial amount of carbon dioxide, production rate, and re-injection rate on the performance of pressure, temperature, saturation and carbon dioxide amount both in the liquid and gas phases.

Garg et al. (2015) presented results of a model to describe the change of mass fraction of carbon dioxide for the Kizildere Geothermal Field. The model used in this study was a numerical model.

Ellis and Golding (1963) presented studies regarding the thermodynamic behavior of water – carbon dioxide mixtures. Sutton (1976) also studied this subject. Specifically Sutton (1976) presents relations about how the Henry's constant changes as a function of temperature. Other relationships regarding Henry's constant are given by Cramer (1982) and Upton and Santoyo (2002).

2. The mathematical model

In this section we present the details of the analytical equations derived in this study. The analytical equations model the change of carbon dioxide with time given a specific production/re-injection scheme. The basis of the model is application of mass balance on carbon dioxide over any tank (control volume). The tank is illustrated in Fig. 1. It is assumed that the tank has a bulk volume V_b, a porosity ϕ and an initial mass fraction of carbon dioxide in the reservoir f_0. It is also assumed that the tank contains water with a density of ρ. The mass fraction of carbon dioxide is denoted by f. Three sources of carbon dioxide are considered:

- Carbon dioxide extraction due to production.
- Carbon dioxide contribution due to re-injection.
- Carbon dioxide to/from the recharge.

The mass balance on the tank can be stated as shown in Eq. (1).

$$\begin{pmatrix}\text{The rate of}\\ \text{accumulation}\\ \text{of carbon dioxide}\end{pmatrix} = \begin{pmatrix}\text{Mass rate of}\\ \text{carbon dioxide}\\ \text{re-injected}\end{pmatrix} + \begin{pmatrix}\text{Mass rate of}\\ \text{carbon dioxide}\\ \text{from recharge}\end{pmatrix} - \begin{pmatrix}\text{Mass rate of}\\ \text{carbon dioxide}\\ \text{extracted due to}\\ \text{production}\end{pmatrix} \quad (1)$$