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How to sustain a CO_2-thermosiphon in a partially saturated geothermal reservoir: Lessons learned from field experiment and numerical modeling

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ABSTRACT

CO_2 has been proposed as a working fluid for geothermal energy production because of its ability to establish a self-sustaining CO_2 thermosiphon, taking advantage of the strong temperature dependence of CO_2 density. To test the concept of CO_2 heat extraction, in January 2015 a CO_2 thermosiphon was operated at the SECARB Cranfield Site, Cranfield, Mississippi, where a brine-saturated sand at a depth of 3.2 km has been under near continuous CO_2 flood since December 2009 as part of a U.S. Department of Energy demonstration of CO_2 sequestration, resulting in a partially saturated reservoir surrounding a well pair. The lateral distance between the producer and injector was 112 m at reservoir depth, a distance considered pre-commercial in scale, but great enough that thermal breakthrough was still not significant after several years of injection. Instead of producing power with a turbine, heat was extracted heat from recirculated fluid using a heat exchanger and portable chiller. The well field and surface equipment were instrumented to compare field observations with predicted responses from numerical models. Thermosiphon flow could be initiated by venting, but thereafter flow rate steadily declined, indicating that the thermosiphon was not sustainable. To model the system, the capability of T2Well, a fully coupled wellbore/reservoir numerical simulator, was expanded to enable simulation of the entire loop of fluid circulation in the fully-coupled system consisting of the injection/production wells, the reservoir, and the surface devices (heat exchanger, flow-rate regulator etc.). Combined with the newly developed TOUGH2 equation of state module called EOS7CMA, the enhanced T2Well was used prior to the field experiment to simulate the circulation of a CO_2-H_2O-CH_4 mixture in a model geothermal system patterned after the Cranfield demonstration test. The model predicted that a sustainable thermosiphon could be achieved. After the field thermosiphon did not achieve the pre-test prediction of flow rates and thermosiphon sustainability, the numerical model was modified to improve realism and calibrate certain processes; it was then able to reproduce the major phenomena observed in the field. In a series of sensitivity studies, many factors were found that could potentially contribute to the failing of a sustainable thermosiphon. These factors could be categorized as two types: factors that increase the resistance to flow and factors that increase heat loss of the working fluid. The lessons learned can be applied to both future modeling and to achieving CO_2-based geothermal reservoir exploitation.

1. Introduction

Brown (2000) first proposed using CO_2 in place of water as the working fluid for extracting geothermal heat. Replacing water with CO_2 is hampered by the scarsity of naturally occurring CO_2 sourcesHowever, the widespread adoption of geologic carbon sequestration (GCS), where CO_2 from point sources such as power plants, oil refineries, and ethanol processing facilities is captured and stored underground, will drastically increase the availability of CO_2. Coupling GCS with geothermal energy production can offset some of the incremental costs associated with carbon capture, and end up benefitting both industries (Randolph and Saar, 2011).

The primary benefits cited for using CO_2 as a replacement for water are: (1) its large compressibility and expansivity, which can lead to creation of a natural thermosiphon, wherein CO_2 circulates without the need for external pumping; (2) lower viscosity; and (3) reduced chemical interaction with rock minerals. While CO_2 has a smaller heat capacity than water, when considered in light of its lower viscosity, the greater mobility leads to a net overall increase in efficiency (Pruess, 2006). Pan et al. (2015a) performed coupled wellbore/reservoir numerical simulations to investigate the efficiency of an all-CO_2 system. including heat transfer between the wells and the surrounding formation, and frictional and inertial forces within the wells. However, a

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Nomenclature

A	Wellbore cross-sectional area m^2
b	Formation thickness m
C_0	Shape factor –
C	Heat capacity $J\,kg^{-1}\,K^{-1}$
$\mathbf{g}$	Acceleration of gravity vector $m\,s^{-2}$
E	Energy J
$\mathbf{F}$	Mass flux vector $kg\,m^2\,s^{-1}$
f	Apparent friction coefficient –
H	Enthalpy J
h	Specific enthalpy $J\,kg^{-1}$
k	Permeability m^2
k_r	Relative permeability –
m	Mass kg
$\mathbf{n}$	Outward unit normal vector –
P	Total pressure Pa
q_v	Volumetric source term $kg\,m^{-3}\,s^{-1}$
R	Radial coordinate, gas constant m, $J\,kg^{-1}\,mol^{-1}$
S	Saturation, storativity –, m^{-1}
t	Time s
T	Temperature °C
$\mathbf{u}$	*Darcy* velocity $m\,s^{-1}$
u_G, u_L	Phase velocity of gas and liquid in the well $m\,s^{-1}$
U	Internal energy $J\,kg^{-1}$
v	Velocity $m\,s^{-1}$
V	Volume m^3
W	Work J
X	Mass fraction w/phase subscript and component superscript
z	z-coordinate (positive upward) m

Greek symbols

α	Heat exchange coefficient per length of pipe W/°C/m
Γ	Perimeter of wellbore m
γ	Phase interaction term $kg\,m^{-1}\,s^{-1}$
θ	Angle between wellbore and the vertical °
κ	Mass components (superscript) –
λ	Thermal conductivity of fluid-rock composite $J\,m^{-1}\,s^{-1}\,K^{-1}$
μ	Dynamic viscosity $kg\,m^{-1}\,s^{-1}$
ρ	Density $kg\,m^{-3}$
τ	Tortuosity –
ϕ	Porosity –

Subscripts and superscripts

β	Phase index
cap	*capillary*
d	Drift
G	Gas
κ	Component index
l	Liquid residual
L	Liquid
m	Mixture
NK1	Energy component
0	Reference value
r	Relative
R	Rock
res	Bulk reservoir

more realistic situation is that of a partially saturated reservoir containing both mobile water and CO_2, which complicates the fluid flow process (Pruess, 2006). Under such conditions, the produced fluid may be a mixture of water and CO_2 instead of pure CO_2, which could hurt the performance of the CO_2-based thermal system. For example, the natural thermosiphon, the primary benefit of a CO_2-based system, may not be sustainable because of interference by water in both the well and the reservoir, which could greatly limit the potential for using CO_2 as a working fluid for geothermal energy production. Therefore, the objective of this study is to investigate the sustainability of a thermosiphon in a partially saturated reservoir and identify possible factors that impact sustainability, through a combined approach of field scale experiment and numerical simulations.

The field experiment (Cranfield Test) was conducted at the SECARB Cranfield CFU31 site, the location of a previous U.S. Department of Energy project to demonstrate GCS in a saline aquifer (Hovorka et al., 2013), operated by the South Eastern Regional Partnership for Carbon Sequestration (SECARB). The well site consists of three wells: an

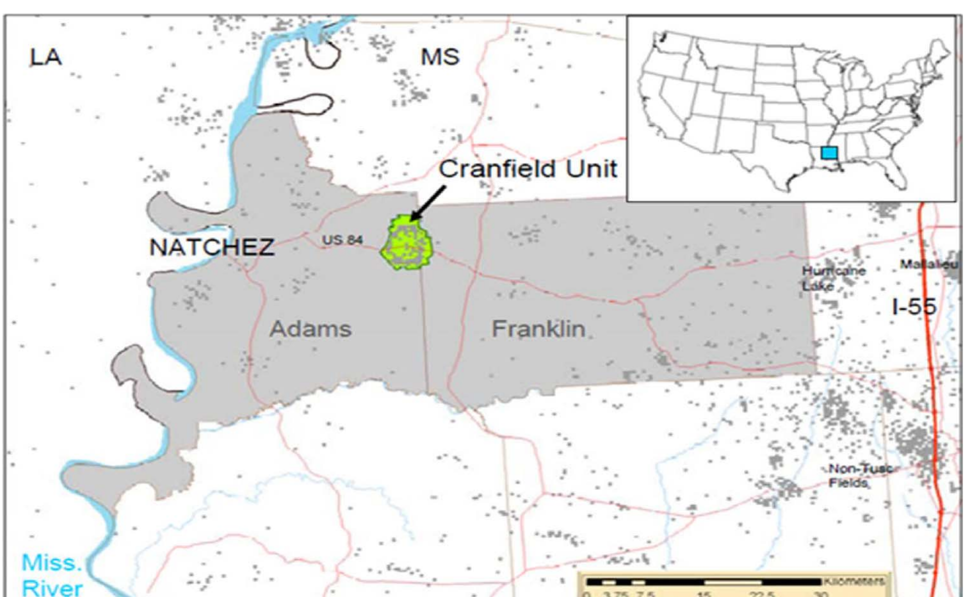

Fig. 1. Location of the Cranfield site at the border of Adams and Franklin County, MS.