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On the importance of the thermosiphon effect in CPG (CO_2 plume geothermal) power systems

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ABSTRACT

CPG (CO_2 Plume Geothermal) energy systems use CO_2 to extract thermal energy from naturally permeable geologic formations at depth. CO_2 has advantages over brine: high mobility, low solubility of amorphous silica, and higher density sensitivity to temperature. The density of CO_2 changes substantially between geothermal reservoir and surface plant, resulting in a buoyancy-driven convective current – a thermosiphon – that reduces or eliminates pumping requirements. We estimated and compared the strength of this thermosiphon for CO_2 and for 20 weight percent NaCl brine for reservoir depths up to 5 km and geothermal gradients of 20, 35, and 50 °C/km. We found that through the reservoir, CO_2 has a pressure drop approximately 3–12 times less than brine at the same mass flowrate, making the CO_2 thermosiphon sufficient to produce power using reservoirs as shallow as 0.5 km. At 2.5 km depth with a 35 °C/km gradient – the approximate western U.S. continental mean – the CO_2 thermosiphon converted approximately 10% of the energy extracted from the reservoir to fluid circulation, compared to less than 1% with brine, where additional mechanical pumping is necessary. We found CO_2 is a particularly advantageous working fluid at depths between 0.5 km and 3 km.

1. Introduction

Geothermal power plants use the temperature difference between the Earth's hot subsurface rock and the cooler surface to generate electricity. Such systems transport thermal energy from underground to the surface using a working fluid, and in a power plant at the surface, a portion of the fluid's thermal energy is converted into electricity. The cooled working fluid is then typically reinjected into a subsurface reservoir. Conventional geothermal (hydrothermal) energy technology uses hot brine as the working fluid that is circulated through geologic formations. Moreover, these power plants are often situated in tectonically and/or volcanologically active regions where reservoir temperatures are unusually high near the Earth's surface [1]. However, these unique thermal resources are limited in size and location. New technology must be developed in order to harness the estimated 200,000 EJ (exajoules) of thermal energy that may be extractable from the Earth's crust in the United States alone [2]. This resource is much greater than the 540 EJ of primary energy that was consumed worldwide in 2011 [3] and is renewable on human, rather than geologic, time scales. Furthermore, compared to most other renewable energy resources, geothermal energy is continuously available and, thus, can serve as a baseload or dispatchable power resource without requiring energy storage.

To access the high geothermal energy potential for human use, approaches have been suggested to initiate and/or widen fractures within hot, dry, low-permeability, crystalline basement rocks, thereby creating relatively small, artificial geothermal reservoirs that can support fluid flow and heat extraction [4,5]. These EGS (Enhanced or Engineered Geothermal Systems) typically use water for both fracturing and advective heat energy extraction, but CO_2 (carbon dioxide) has also been proposed as the working fluid [6,7]. While EGS has the potential to increase access to the geothermal resource base, significant technological gains are needed before EGS will be capable of extracting more than small amounts of energy [2].

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Recently, CO_2 has been proposed as the subsurface working fluid for geothermal energy extraction in sedimentary basins that host natural, large-scale, high-permeability reservoirs that are overlain by, and often inter-layered with, low-permeability cap rocks [8,9]. To distinguish it from EGS using CO_2, this approach has been termed a CPG (CO_2 Plume Geothermal) energy system. As shown in Table 1, CPG differs from conventional hydrothermal and EGS approaches in two important ways: (1) CO_2 is used as the primary working fluid instead of water or brine, and (2) the CO_2 is circulated through naturally-permeable formations, resulting in a large-scale CO_2 plume. Compared to the deep formations targeted for EGS, CPG reservoirs are typically shallower (1–4 km instead of 4–7 km deep) and, hence, cooler. However, the large size and high permeability of sedimentary basins allow for much higher fluid flow and advective heat transfer rates. Importantly, the CPG approach avoids reservoir-scale hydraulic fracturing and fault shearing/dilation, which may induce seismicity [10]. In addition, CPG reduces or eliminates the need for the expensive deep drilling that is typically required in EGS, and instead employs well-established drilling techniques developed by the oil and gas industry for sedimentary basins.

The sedimentary basins in which these saline aquifers reside are ubiquitous throughout the world [11] and underlie more than half of North America [12]. The salinity of such formations is high (TDS (total dissolved solids) > 10,000 PPM, i.e., far saltier than seawater), so they are unlikely to be considered a potable, or even industrial, water resource. Because CO_2 is less dense than the surrounding pore fluids (e.g., brine), CPG sites must be located where vertical migration of the buoyant CO_2 is impeded by low-permeability or impervious caprock layers overlying the permeable reservoir.

CPG can be combined with a CCS (CO_2 Capture and Storage) site to produce electricity and/or heat from places where CO_2 is injected into sedimentary basins as an approach to climate change mitigation [13]. This technology is an example of CCUS (Carbon Capture Utilization and Storage), because the coupled operation can leverage the injected CO_2 to produce electricity that can be used onsite and/or sold to offset the costs associated with CCS. In addition, extraction of heat from the reservoir during CPG operations reduces reservoir over-pressurization caused by CO_2 injection during CCS [14], helping to ensure reservoir integrity and decreasing monitoring requirements. In addition, strategically producing brine and/or CO_2 from a GCS (geologic CO_2 storage) site and its associated reduction in over-pressurization reduces the likelihood of inducing seismicity and can provide brine at the surface for potential use as potable or process resources [15]. CPG may also be implemented in (partially) depleted hydrocarbon fields alongside EOR (enhanced oil recovery) operations [16,17] and offset the hydrocarbon fuels used to power such sites.

The surface plant that produces electricity from geothermal energy can have two basic configurations: direct and indirect (binary). In an indirect system, heat is extracted from the primary subsurface working fluid to drive a secondary Rankine cycle. An indirect system is desirable when the pressure difference between primary fluid production and injection wellheads is small and the temperature difference between the fluid leaving the production well and the ambient at the surface is high. In contrast, a direct system typically expands the primary working fluid through a piece of turbomachinery in order to generate electricity, and is therefore desirable when the pressure difference between the production and injection wellheads is large. This latter condition – high pressure difference – occurs when CO_2 is used as the primary working fluid (even at low reservoir temperatures of <100 °C) and at relatively rare, high temperature (>200 °C) hydrothermal sites. In this paper, we exclusively model indirect geothermal systems.

Systems using CO_2 as the subsurface working fluid develop a buoyancy-driven thermosiphon, which occurs because of the differences in CO_2 density between the injection and production wells upon even a small amount of heating in the reservoir [18,19] and because the high mobility (inverse kinematic viscosity) of CO_2 in the reservoir facilitates fluid flow. The thermosiphon can eliminate parasitic, and thus costly, pumping requirements necessary in conventional hydrothermal installations.

In this paper, we estimate the strength of this thermosiphon effect using idealized reservoir and surface plant parameters to compare the strengths of thermosiphons generated by indirect CO_2 and existing "state-of-the-art" 20 wt% NaCl brine indirect geothermal power systems for depths up to 5 km and geothermal gradients of 20, 35, and 50 °C km^{-1}. From these idealized cases, we draw a number of conclusions about the relative strengths of thermosiphons for subsurface systems (reservoirs) composed purely of CO_2 and purely of brine.

1.1. The thermosiphon effect in geothermal power systems

The driving force of the thermosiphon is generated by the density difference of the CO_2 between injection and production wells. The phase of the fluid is relevant to the extent to which it affects its compressibility—supercritical CO_2, which typically exists throughout the subsurface portion of a CPG system, has a large variability in density, despite having liquid-like density and gas-like dynamic viscosity. When fluid flows upward in a production well, the pressure decreases because the increase in elevation reduces the hydrostatic pressure of the fluid and pressure losses accumulate due to friction with the pipe wall. For a static fluid, the pressure losses are zero and the change in pressure can be calculated from the Bernoulli equation:

$$\int_1^2 \frac{\mathrm{d}P}{\rho} = g(z_2 - z_1) \tag{1}$$

When the density of the fluid is nearly constant with changes in temperature and pressure (e.g., with liquid brine), the integral in Equation (1) can be eliminated and the pressure change, ΔP, becomes the product of fluid density, ρ, the Earth's gravitational acceleration constant, g, and the change in elevation, $z_2 - z_1$, between the surface, z_2, and the reservoir, z_1. Thus, for conventional hydrothermal systems, the pressure changes in the production and injection wells roughly offset each other. Consequently, the pressure

Table 1
The four types of geothermal systems considered.

Type of reservoir	Energy extraction working fluid: Water	Energy extraction working fluid: CO_2
Sedimentary basin (large-scale, naturally permeable, typically lower temperature)	Conventional Hydrothermal System	CO_2-Plume Geothermal (CPG) System
Enhanced Geothermal System (EGS) (small-scale, relatively impermeable prior to stimulation, typically higher temperature)	Conventional EGS	CO_2-based EGS

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