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A Comprehensive Review of Coupled CO_2 Storage and Geothermal Energy Recovery Systems

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Abstract

CO_2-geothermal energy storage, recently proposed, has been demonstrated to be advantageous in power output, thermal efficiency, and geological stability compared with water-based geothermal systems, however, the technology remains largely in its infancy due to major uncertainties in performance, risks, and design of the CO_2-Plume Geothermal (CPG) system. This review aims to summarize the current state-of-the-art of the integrated CO_2-geothermal system that utilizes CO_2 as both the working fluid and the stored medium, and covers the coupled thermos-hydraulics, reservoir engineering, numerical modeling, and techno-economic evaluation. Therefore, it provides a comprehensive reference for researchers and practitioners, including a detailed discussion of the key components and processes of CPG systems. It builds on the latest advances from field tests, pilot projects, and simulation studies published in peer-reviewed journals and conference proceedings. Thus, this synthesis provides a foundation for further research and for the design of the next generation of CO_2 storage and geothermal recovery projects. The evidence from the literature indicates that CO_2-based geothermal systems can be more advantageous than water-based geothermal systems in power output under favorable conditions, but the long-term performance of these systems still has large uncertainties. This uncertainty mainly stems from parameter estimation and uncertainty quantification, experimental validation, model efficiency and verification, power plant and surface facilities system design, potential synergies with other technologies, public perception and acceptance, and multi-EHS (environmental, health, and safety) risk assessment, and these issues are common to most, if not all, subsurface utilization applications. Hence, some of the concerns relevant to CPG are also pertinent to other geothermal and CO_2 storage applications. For all these reasons, future research should focus on plume containment and trapping capacity, induced seismicity and fluid-rock interactions, injection and production strategy, multiphase behavior and property effects, and caprock integrity and leakage risk, and these challenges and knowledge gaps are elaborated in the following sections.

Introduction

Coupled Carbon Dioxide (CO_2) Storage and geothermal energy recovery systems are considered an attractive dual-benefit technology to address two major Global Challenges: greenhouse gas reduction and renewable energy production. The operation of traditional geothermal systems depends on water-based heat transfer, which occurs between injection wells and production wells. The Enhanced Geothermal Systems (EGS) technology uses hydraulic stimulation to create better reservoir permeability than natural convection systems. What sets apart the new advances in joining carbon dioxide storage with geothermal energy is the use of supercritical, or almost supercritical, CO_2 – rather than water – as the principal fluid to make the system function (Alsarhan et al., 2021) . The key advantages of doing it this way (Wu & Li, 2020) are (1) it is better from a thermodynamics point of view: $scCO_2$'s ability to move heat is improved over water's at similar depths, as $scCO_2$ has a greater heat capacity and is less viscous. These qualities cause better heat transfer and Thermosyphon movement of the fluid. The buoyant nature of CO_2 together with its ability to dissolve in water creates multiple trapping systems, which function within geological storage systems. The reduced pumping requirements due to CO_2's lower viscosity enhance system economics the system operates as a climate change solution, which generates power through its combined operations. A thorough review of the state-of-the-art of the integrated systems where CO_2 is used as storage mechanism and working fluid for heat extraction from Enhanced Geothermal Systems (EGS) has been compiled to provide a clear picture of the convergence of carbon capture and storage technologies (CCS), and EGS.

Theory and/or Methods

The choice of a working fluid has a significant impact on the performance of geothermal systems. A comparative thermodynamic study of water and supercritical carbon dioxide as a working fluid shows that the use of supercritical CO_2 will result in better heat transfer performance in naturally porous and permeable geological reservoirs than water (Randolph et al., 2012). The improved heat transfer efficiency is due to a number of factors related to the physical properties of supercritical CO_2, including:

(1) Supercritical CO_2 presents an elevated effective thermal conductivity because of its interaction with solid materials (Randolph et al., 2012). Modeling of wellbore heat transfer indicates that while the convective heat transfer coefficient for supercritical CO_2 is generally less than that for water, the low dynamic viscosity of CO_2 and the rough surface conditions of typical piping provide reduced frictional loss and therefore increased overall efficiency (Randolph et al., 2012).

(2) The greater mobility (smaller inverse kinematic viscosity) and compressibility of CO_2 compared to water enhance the natural Thermosyphon flow within the formation (Randolph et al., 2012). The buoyancy driven flow by density difference does not require the same degree of artificial pumping as required by water-based systems; this results in a decrease in operational energy needs. Supercritical CO_2 systems are capable of recovering heat at lower temperatures and with lower permeability than water based systems (Wu & Li, 2020).

CO_2-Enhanced Geothermal Systems (CO_2-EGS): Technology Integration

The integration of CO_2-EOR includes several domains integrations including:

Coupling Mechanisms and System Architecture: CO_2 enhanced geothermal systems include an integrated system that is comprised of three main subsystems: (1) CO_2 capture and compressing module; (2) a geothermal reservoir that has artificially created fracture networks; and (3) a surface device to convert the heat extracted into usable energy (Wu & Li, 2020). The coupling between these systems occur at the reservoir scale because the CO_2 being injected will displace the native fluids within the formation and extract heat as a result of the close interaction between the rock and the fluid.

Reservoir Characterization and Fracture Network Engineering: Successful operation of CO_2-EGS systems require detailed characterization of DFNs. A comprehensive review of characterization methods for (Discrete Fracture Network) DFNs found that structural geology, geomechanical properties, remote sensing, geophysical data and hydraulic testing were all important components of a characterization framework for DFNs (Medici et al., 2023). Structural geologic characterization using borehole logging along with seismic attributes allows for an accurate estimate of fracture orientation, density and trend (Medici et al., 2023). Hydraulic testing of fractures will allow for calculation of transmissivity of fractures and identification of hydraulically active fractures, which will provide the necessary input for the computational modeling of fracture network flow (Medici et al., 2023).

Heat Extraction Performance in Fractured Reservoirs: Fully coupled THM models have demonstrated that inter-connected large scale fractures are responsible for most of the mass transfer processes in a fractured system; whereas, widely distributed small scale fractures play an important role in the cooling process as fluid flows in parallel through these pathways (Han et al., 2019). Also, fully coupled THM models demonstrate that the temperature differences between the fluids flowing in the fractures and the solid rock matrix are sufficiently large to necessitate the use of the Local Thermal Nonequilibrium (LTNE) theory rather than the conventional thermal equilibrium assumption to describe thermal behavior in fractured systems (Han et al., 2019).

Multiphase Flow, Transport, and Geochemical Reactions

CO_2 Migration and Plume Dynamics: Pore-scale numerical simulation of supercritical CO_2 migration in water-saturated porous and fractured media reveals preferential flow at locations with high strain rates and pressure (Liu et al., 2020). During drainage processes, $scCO_2$ displaces connate fluids; during imbibition following injection cessation, brine flows back toward $scCO_2$. The spatial distribution and migration pathways depend critically on wettability, mineral grain geometry, interfacial tension, and fracture aperture variations (Liu et al., 2020). The presence of interfacial tensions affects the pattern of distribution density, and lower values create thinner bands with a higher concentration of saturation (Liu et al., 2020).

Well Placement and Doublet Configuration Optimization: The strategic placement of wells in fractured geothermal reservoirs is very important for the overall efficiency of an operation. Studies analyzing the impact of different well placements on discrete fracture networks resulted in almost a tenfold difference for heat recovered when different injection and production well pairs were placed in different locations within the same fracture network (Mahmoodpour et al., 2022). The thermal breakthrough time, mass flux, and energy extraction potential of the system were also shown to be strongly affected by the location of the well in relation to the densities of connected fractures (Mahmoodpour et al., 2022).

Mineral Precipitation and Permeability Evolution: Geochemical reactions caused by the injection of CO_2 into the reservoir cause changes in the reservoir's permeability due to precipitation and dissolution of minerals. Experiments simulating salt precipitation during CO_2 injection into an Enhanced Geothermal System (EGS) indicate that the fracture is clogged near the production wellbore as the reservoir dries out (Borgia et al., 2013). Strategies to mitigate these problems using alternating cycles of water and CO_2 injection at specified mass ratios can double the productive life of the system and increase total heat extraction by more than 40% compared to drying out scenarios (Borgia et al., 2013). Reactive transport modeling at the pore-scale demonstrates that the relationship between the reactive-induced permeability and porosity are non-linear and dependant upon the flow rate (Nogues et al., 2013). Systems dominated by diffusion result in localized porosity changes close to the inlet with large total changes, whereas systems dominated by advection result in relatively uniform changes throughout the entire domain with less total change in permeability (Nogues et al., 2013).

Wellbore Design, Heat Transfer, and Surface Systems

Wellbore Thermal and Hydraulic Behavior: The development of comprehensive wellbore heat transfer analysis for geothermal systems that use carbon dioxide has produced significant information on the optimization of geothermal system designs (Randolph et al., 2012). A quasi one-dimensional transient model was used to analyze both convective heat loss to the fluid surrounding the pipe as well as conductive heat loss from the pipe itself to its surroundings. Using back of the envelope type calculations the authors found that the Reynolds number for flow through the pipes would be typically greater than 10^4; and therefore, that there would be a high rate of advective heat transfer in the pipe (Randolph et al., 2012). However, the high rates of advective heat transfer are offset by the lower thermal conductivity of the solid/fluid combination. In addition, due to the low viscosity of CO_2 and the smoothness of the nickel steel tubing, there would be relatively low frictional losses in the system; generally, less than 10 percent of the theoretical maximum heat transfer resistance that could exist based on the properties of the rock (Randolph et al., 2012). Therefore, it is necessary to perform a detailed analysis of each specific system configuration to determine the best possible system performance.

Deep Borehole Heat Exchangers (DBHE): Technical review of coaxial deep borehole heat exchangers identifies key design parameters and performance considerations (Chen & Tomac, 2023). Field tests, analytical approaches, and numerical simulations collectively demonstrate that DBHE performance depends critically on: (1) fluid property dependence on pressure and temperature variations (2) Groundwater flow effects within formation and fractures, (3) Different working fluid characteristics (CO_2 vs. water) (4) Pump parameter optimization and intermittent operation patterns (5) Treatment of fluid, pipe walls, and working fluid interactions. Long-term performance prediction remains a challenge, requiring validation through laboratory testing and empirical model calibration (Chen & Tomac, 2023). Enhanced heat transfer through continuous research on material selection, fluid properties, and operational strategies remains essential.

Surface Heat Recovery and Power Generation: The surface equipment for CO_2-based geothermal systems will require an ability to be able to work with a variety of unique thermodynamic states. The power cycle system based on super-critical and trans-critical CO_2 operation achieves better efficiency than water-based systems when operating with low-temperature heat sources (Wang et al.,2021). Engineers apply CO_2 working fluid properties to create compact equipment which reaches outstanding heat-to-power conversion efficiency (Wang et al. ,2021). Scientists have conducted experimental studies to understand supercritical CO_2 cycles which have shown them to study transcritical Organic Rankine Cycle (ORC) designs more than steam Rankine Cycle designs (Lecompte et al.,2019). Domestic and industrial pump designs using transcritical fluid are prevalent; however, there is still limited research into other potential working fluids for these systems (Lecompte et al., 2019). Designing optimal compressor and expander components for CO_2-based systems will require particular emphasis on mechanical integrity with respect to high pressure (Lecompte et al., 2019).

Environmental, Safety, and Operational Challenges

Induced Seismicity and Geomechanical Risks: Geothermal production creates changes to underground stress conditions. These stress conditions can create or induce earthquakes by changing how rock moves under stress. Ge & Saar (2022) have identified four primary mechanisms responsible for inducing earthquakes. They are (1) Diffusion of pore fluid pressure, (2) poroelastic stress transfer (3) Transfer of Coulomb static stressa and (4) Aseismic slip. There is evidence that shallow porous sedimentary aquifers that are located away from the basement and at relatively low temperatures do not typically produce felt seismic activity (Buijze et al., 2019).

Water Resources and Environmental Protection: The water challenges presented by the geologic sequestration of CO_2 are different than those associated with traditional energy production and operation. The displacement of brine into a formation will result in an increase in the storage reservoir pressure; and this may lead to several adverse outcomes that could range from increased groundwater withdrawals to contamination through displacement (Newmark et al., 2010). To effectively monitor and control these effects, it is necessary to determine when such water-related impacts occur (Newmark et al., 2010).

Conclusions

The deployment of geothermal energy recovery systems with CO_2 storage operations will create a new technology, which provides a functional answer to enhance both energy security and climate change mitigation when executed properly. The fundamental scientific research demonstrates that supercritical CO_2 functions as an ideal working fluid, which delivers better performance than water does in particular geological settings. The development of modern reservoir characterization methods together with wellbore engineering and closed-loop heat extraction systems has transitioned from theoretical ideas to operational systems. The success of the future for coupled CO_2 geothermal systems depends upon: First, carbon pricing mechanisms will help to make coupled CO_2 geothermal systems economically attractive by increasing the price of CO_2 through tax policies or carbon trading programs. Second, development of regulations will need to occur in areas that currently have no clear regulations on geothermal development and CO_2 sequestration, including monitoring protocols and liability allocations. Finally, Learning by Doing will happen when continued investments are made into R&D through demonstration projects; this will help reduce costs through learning-by-doing mechanisms and mature technologies.

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