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Geothermal energy production coupled with CCS: a field demonstration at the SECARB Cranfield Site, Cranfield, Mississippi, USA

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Abstract

A major global research and development effort is underway to commercialize carbon capture and storage (CCS) as a method to mitigate climate change. Recent studies have shown the potential to couple CCS with geothermal energy extraction using supercritical CO_2 ($ScCO_2$) as the working fluid. In a geothermal reservoir, the working fluid produces electricity as a byproduct of the CCS process by mining heat out of a reservoir as it is circulated between injector and producer wells. While $ScCO_2$ has lower heat capacity than water, its lower viscosity more than compensates by providing for greater fluid mobility. Furthermore, CO_2 exhibits high expansivity and compressibility, which can both help reduce parasitic loads in fluid cycling. Given the high capital costs for developing the deep well infrastructure for geologic storage of CO_2, the potential to simultaneously produce geothermal energy is an attractive method to offset some of the costs and added energy requirements for separating and transporting the waste CO_2 stream.

We present here the preliminary design and reservoir engineering associated with the development of direct-fired turbomachinery for pilot-scale deployment at the SECARB Cranfield Phase III CO_2 Storage Project, in Cranfield, Mississippi, U.S.A. The pilot-scale deployment leverages the prior investment in the Cranfield Phase III research site, providing the first ever opportunity to acquire combined CO_2 storage/geothermal energy extraction data necessary to address the uncertainties involved in this novel technique. At the SECARB Cranfield Site, our target reservoir, the Tuscaloosa Formation, lies at a depth of 3.0 km, and an initial temperature of 127 °C. A CO_2 injector well and two existing observation wells are ideally suited for establishing a CO_2 thermosiphon and monitoring the thermal and pressure evolution of the well-pair on a timescale that can help validate coupled models. It is hoped that this initial demonstration on a pre-commercial scale can accelerate commercialization of combined CCS/geothermal energy extraction by removing uncertainties in system modeling.

Keywords: geothermal systems; carbon dioxide; carbon sequestration;

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1. Introduction

The objective of our research effort is to demonstrate coupled CO_2 sequestration with geothermal energy production to validate reservoir/power plant models, which can be used in the design and operation of commercial scale systems. To accomplish this objective we have undertaken a program in which we have (1) developed a coupled reservoir-wellbore model which contains key thermophysical processes needed to accurately capture subsurface behavior, (2) designed an optimal power plant for harnessing the energy from geothermally heated CO_2, and (3) plan to fabricate and operate the geothermal heat recovery engine at the Southeast Regional Carbon Sequestration Partnership (SECARB) Cranfield CO_2 storage field site to validate the coupled models that have been developed.

Brown first proposed the novel use of CO_2 as a working fluid for geothermal energy extraction, citing CO_2's greater expansivity and compressibility as compared to water, resulting in lower parasitic energy losses, its lower viscosity, which more than offsets its reduced heat capacity in improving heat mining efficacy, and its reduced geochemical reactions with minerals, avoiding many of the scaling and pore plugging issues associated with circulating water [1]. Pruess investigated the detailed hydrological and thermodynamic behavior of a CO_2/geothermal system within a reservoir that is part of a 5-spot well pattern [2,3]. His research further identified beneficial pressure/temperature conditions for CO_2 heat extraction, but the model considered only a highly simplified wellbore under isenthalpic and gravitationally stable conditions. While he conjectured that the natural thermosiphon would reduce parasitic loads, his model did not have the requisite wellbore physics to quantify what that reduction might be.

Atrens et al [4–6] considered a coupled wellbore reservoir model, making several simplifying assumptions that we have relaxed in our modeling effort. They considered a highly simplified reservoir model wherein Darcy flow is along a single streampath and temperature increase occurs as a fixed linear function of distance from injector well to producer. While they do consider frictional losses within the wellbore, fluid flow within them is still considered isentropic, ignoring heat transfer with the formation.

Our approach uses a generalized wellbore-reservoir model T2WELL[7], which relaxes many of the simplifying assumptions mentioned previously. It is based on the integral finite difference heat and mass transport simulator TOUGH2 which can incorporate complex flow geometries and heterogeneous porous media[8]. Using the appropriate thermodynamic equations of state, it incorporates the behavior of CO_2, CH_4, and brine systems permitting generalized heat and mass transport numerical simulations while ensuring complete adherence to mass and energy balance constraints.

We propose to use the SECARB Cranfield Site in Cranfield, Mississippi, USA, as the field demonstration location for initial testing of our heat engine because of the significant knowledge base gained during a Regional Carbon Sequestration Phase III demonstration program and the existing infrastructure [9-11]. At the site of the Cranfield Detailed Area Study (DAS) there are three existing deep wells completed in the Tuscaloosa Sandstone to a depth of 3.1 km. CO_2 injection commenced at the Cranifeld DAS Site in the CFU-31F1 well in December 2009 and the nearby CFU-31F2 and CFU-31F3 with offsets of ~70 m and ~100 m respectively were used to perform time-lapse geochemical and geophysical monitoring of the evolution of the CO_2 plume. The reservoir has been under a nearly continuous CO_2 flood, ensuring that water is at or near residual conditions and that the reservoir is for the purposes of our geothermal test dry. Given that the timescale for our project will only permit a few months of field testing, we plan to continue to use the CFU-31F1 well as an injector with the CFU-31F3 well as a producer. The modeling we have performed indicates that the ~100 m separation will allow pressure and temperature transients associated with the injection and withdrawal of CO_2 to settle down quickly, allowing us to obtain a practical dataset for performing model validation.

2. Methodology

2.1. Coupled reservoir-wellbore simulation

As the pathways from surface to reservoir, the injection and production wells play important and unique roles in a geothermal heat extracting system. The unique thermophysical properties of the compressible CO_2 make the interactions between the reservoir and the wellbores more complicated and tight. Using a decoupled model would not be able to capture those important interactions and could lead to misleading conclusions. We use a fully coupled wellbore-reservoir simulator, T2Well [7], with a TOUGH2 equation of state module, ECO7CMA. ECO7CMA incorporates a comprehensive description of the thermodynamic and thermophysical properties of the H2O-CO_2-CH_4 system that are in the appropriate pressure and temperature ranges for typical geothermal systems. In T2Well/ECO7CMA, we treat the wellbore-reservoir flow problem as an integrated system in which the wellbore and reservoir are two different sub-domains where flow is controlled by different physics, specifically viscous flow in the wellbore governed by the 1D momentum equation, and 3D flow through porous media in the reservoir is governed by a multiphase version of Darcy's Law. As a result, the governing equations for the flow processes in wellbore-reservoir system are an extended set of those used by the standard TOUGH2 (Table 1). As shown in Table 1, the major differences in governing equations between the wellbore and the reservoir are the definitions of energy flow terms and the phase velocities. Both the kinetic energy and the gravity potential energy are included in wellbore energy balance equations but they are neglected in reservoir energy balance equations. Meanwhile, the phase velocities in reservoir are simply determined by Darcy law whereas the phase velocities in wellbores are obtained by solving the momentum equations (1) using the Drift-flux model approach [12].

$$\frac{\partial}{\partial t}(\rho_m u_m) + \frac{1}{A}\frac{\partial}{\partial z}\left[A\left(\rho_m u_m^2 + \gamma\right)\right] = -\frac{\partial P}{\partial z} - \frac{\Gamma f \rho_m |u_m| u_m}{2A} - \rho_m g \cos\theta \tag{1}$$

where the term $\gamma = \frac{S_G}{1-S_G}\frac{\rho_G \rho_L \rho_m}{\rho_m^{*2}}\left[(C_0 - 1)u_m + u_d\right]^2$ is caused by slip between the two phases.

The terms ρ_m, u_m, and ρ_m^* are the mixture density, the mixture velocity (mass centered), and the profile-adjusted average density of the mixture.

The wellbores and the reservoir meet at the perforation interfaces where the flow is assumed to be dominated by the resistance in reservoir formation. For the unperforated sections of the wellbores, only heat exchanges between the wellbore and the caprock is calculated using an analytical solution developed by Ramey [13]. The heat flux between the reservoir formation and the basement rock is also calculated semi-analytically [8].

Like TOUGH2, the component mass- and energy-balance equations of Table 1 are discretized in space using the conventional integrated finite-difference scheme for both the wellbore and the reservoir. Apart from the special hybrid schemes of the momentum equation for wellbore, time discretization is carried out using a backward, first-order, fully implicit finite-difference scheme. The discretized mass and energy conservation equations are written in residual forms as functions of primary variables and are solved using Newton-Raphson iteration until the norm of the residual vector meets the prescribed criteria. During iteration all elements in the Jacobian matrix are evaluated by numerical differentiation. More details about the general conservation equations and solution methods can be found in Pruess et al. [8] while more details about the solution of the momentum equations in wellbores and coupling approach can be found in Pan and Oldenburg [7] and Pan et al. [12].

A heterogeneous six-layer model was developed to reflect major lithologic variations within the reservoir. The grid extends out to 10 km by 10 km and is refined locally near the wellbores. Figure 1a shows the numerical grid and figure 1b highlights the refinements near the boreholes. Table 2 shows key reservoir thermal and hydrological parameters assumed for the model. The background geothermal gradient is assumed to be 35.6 °C/km corresponding to a temperature of 127 °C at the top of the reservoir. The reservoir simulator assumes a one dimensional production tubing with smooth bore (roughness 1.5×10^{-6}) with an I.D. of 0.061 m installed in a casing with an I.D. of 0.1397 m. Vertical resolution is 10 m for most of the well, but has been refined to 3m near the ground surface and 4 m near the top of the reservoir. To obtain the initial reservoir conditions for operating the geothermal dipole, CO_2 was injected at a rate of 3.33 kg/s for 950 days. This roughly duplicates the average injection rate maintained during the SECARB DAS injection study prior to testing the geothermal heat engine. Because the Cranfield site is under CO_2 flood for EOR purposes, there is a regional increase in subsurface pressure of ~0.068 bar/day. To mimic this pressure increase water is injected in the simulation at a rate of 171 kg/s at the four distant corners of the grid. The outside of the reservoir is considered closed for fluid flow, and heat exchange between the wellbore and the reservoir as well as between the reservoir and confining beds is calculated analytically. The gridblocks surrounding the injection wellbore out to a radius of 0.168 m are assumed to be altered by well completion damage and have been assigned the reservoir properties listed in Table 2 under the name "skins" which reflects the observed reduced permeability determined by well testing. The production wellbore is assumed to be undamaged, and both injection and production wells are perforated through layers 2 – 6. Our initial simulations of the thermal evolution of the Cranfield reservoir were performed assuming a recirculation rate of 6 kg/s of a mixture of 92% CO_2 and 8% CH_4. Figure 2 shows the thermal evolution of the reservoir after (a) 100 days of CO_2/CH_4 injection, (b) 950 days, and (c) 10 days of geothermal production and (d) 50 days of geothermal production. Wellhead and surface pressures and temperatures are shown in Figure 3.

Table 1. Equations Solved by T2WELL

	Conservation of mass and energy	$\frac{d}{dt}\int_{V_n} M^{\kappa} dV_n = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet n\, d\Gamma_n + \int_{V_n} q^{\kappa} dV_n$
	Mass accumulation	$M^{\kappa} = \phi \sum_{\beta} S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}$ for each mass component
	Mass flux	$\mathbf{F}^{\kappa} = \sum_{\beta} X_{\beta}^{\kappa} \rho_{\beta} \mathbf{u}_{\beta}$ for each mass component
Porous media	Energy flux	$\mathbf{F}^{\kappa} = -\lambda \nabla T + \sum_{\beta} h_{\beta} \rho_{\beta} \mathbf{u}_{\beta}$
Porous media	Energy accumulation	$M^{\kappa} = (1-\varphi)\rho_R C_R T + \varphi \sum_{\beta} \rho_{\beta} S_{\beta} U_{\beta}$
Porous media	Phase velocity	$\mathbf{u}_{\beta} = -k \frac{k_{r\beta}}{\mu_{\beta}} (\nabla P_{\beta} - \rho_{\beta} \mathbf{g})$
Wellbore	Energy flux	$F^{\kappa} = -\lambda \frac{\partial T}{\partial z} - \frac{1}{A} \sum_{\beta} \frac{\partial}{\partial z}\left(A \rho_{\beta} S_{\beta} u_{\beta}\left(h_{\beta} + \frac{u_{\beta}^2}{2}\right)\right) - \sum_{\beta}(S_{\beta} \rho_{\beta} u_{\beta}\, g \cos\theta) - q^{\prime\prime}$
Wellbore	Energy accumulation	$M^{\kappa} = \sum_{\beta} \rho_{\beta} S_{\beta} \left(U_{\beta} + \frac{1}{2} u_{\beta}^2\right)$
Wellbore	Phase velocity	$u_G = C_0 \frac{\rho_m}{\rho_m^*} u_m + \frac{\rho_L}{\rho_m^*} u_d$ $u_L = \frac{(1-S_G C_0)\rho_m}{(1-S_G)\rho_m^*} u_m - \frac{S_G \rho_G}{(1-S_G)\rho_m^*} u_d$

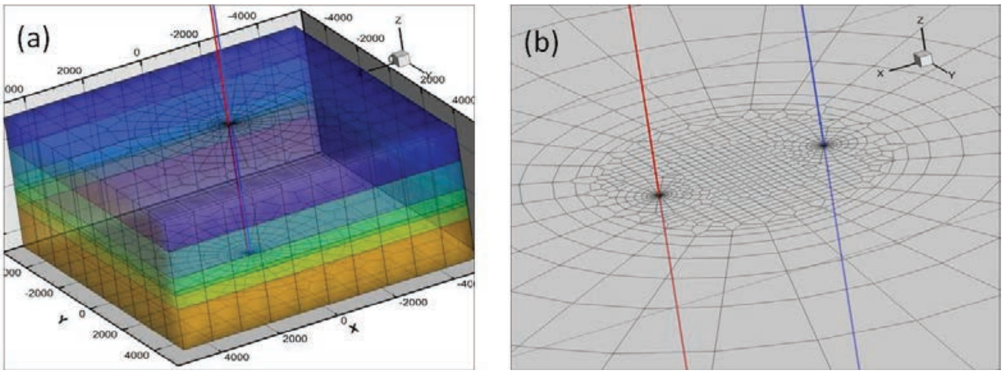

Fig. 1. (a) Multi-layer grid used for simulating combined carbon storage and geothermal energy production. (b) Grid refinements near the injection and production well.

Table 2 Reservoir Parameters for Cranfield Geothermal Simulation

Name	Thickness(m)	Porosity	Lateral permeability (X 10^{-15} m^2)	Vertical permeability (X 10^{-15} m^2)	Pore compressibility (Pa^{-1})	Heat conductivity (W/m ^{o}C)	Specific heat (J/kg ^{o}C)
Layer1	6.86	0.169	8.60	1.058			
Layer2	6.10	0.254	130.7	1.058			
Layer3	2.90	0.288	230.0	47.94			
Layer4	0.90	0.139	2.4	0.082	3.0E-9	2.51	920.0
Layer5	3.00	0.315	349.2	84.87			
Layer6	3.40	0.283	225.7	2.229			
skins	0.1679 (lateral)	0.139	1.35	0.1058			

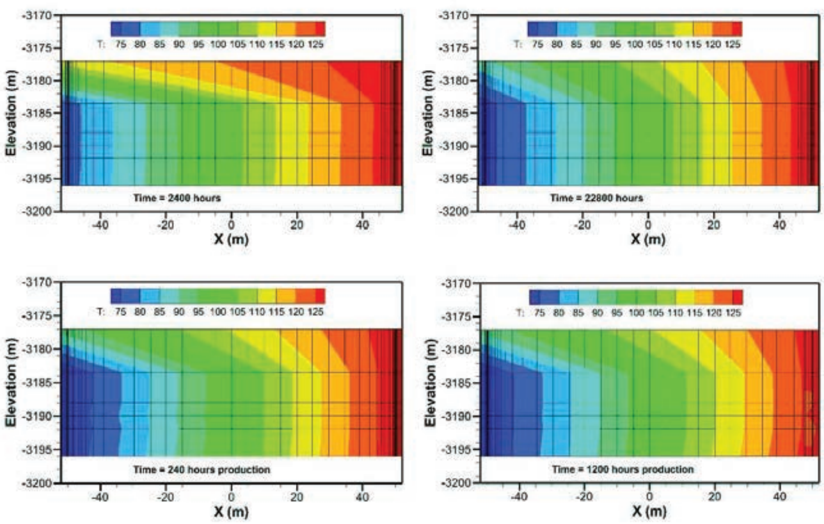

Fig. 2. Thermal evolution of the reservoir after (a) 100 days of CO_2 injection, (b) 950 days of CO_2 injection, (c) 10 days of geothermal production and (d) 50 days of geothermal production.

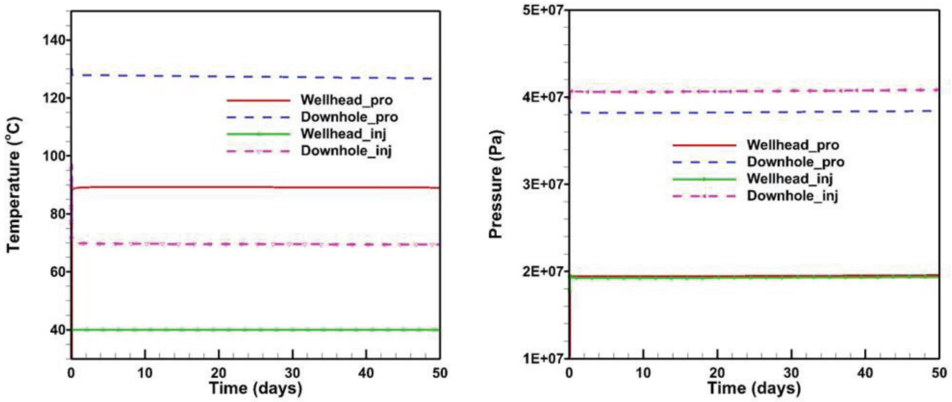

Fig. 3. Wellhead and bottomhole (a) Temperature and (b) pressure evolution of the cranfield reservoir during geothermal energy production.

2.2. Thermal engine

The surface power plant design is based on a modified Rankine Cycle engine originally developed to harness waste heat, relying upon $ScCO_2$ as the working fluid. In the basic system, heat energy is introduced through a waste heat exchanger installed in an exhaust stack, boiler or turbine exhaust duct, etc. For the geothermal application, the waste or exhaust heat exchanger is replaced by the geothermal reservoir. So, the power recovery system becomes a direct, semi-open system. The sequestered CO_2 becomes the working fluid for the system, avoiding the use of potable water in the main flow path. Water will be required if water is used for heat rejection at the surface or as make up water due to evaporation in the cooling tower. Where possible in full scale systems, an air-cooled approach is preferred to minimize the requisite infrastructure.

The proposed Cranfield Site energy recovery system is designed as a test bed for the investigation of the generation of electric power from the geothermal reservoir heat. The major system components include the power turbine, pump, motor/generator and condenser. The basic Echogen system utilizes a recuperator to recover and apply the temperature from the turbine discharge flow back to the system. Early analysis indicates that the turbine discharge temperature for this application is relatively low; thus using a recuperator would not be effective in recovering system heat. Figure 2 is a diagram of the Cranfield Site heat recovery system.

We have developed both system-level and component-level models for analysis to optimize the heat recovery system. These models are imported into IPSE PRO (SimTech Simulation Technology) with a flexible graphical user interface. This program allows for the analysis of the full system model with potential for modeling feedback control. Fluid properties are based on NIST REFPROP (National Institute of Standards and Technology) routines. The system-level model incorporates the results of the fully coupled wellbore- reservoir modeling to determine inlet CO_2 pressure and temperature conditions.

The geothermal heat engine will be built on a single skid and will consist of a single shaft, rotating assembly design which includes the turbine, motor/generator and pump. Other components of the energy recovery system include the condenser, gas/liquid separator, solid particle filter, micron filter, power electronics and control package and valves needed to control the flow and instrumentation required for both control and data acqusition. The skid will be connected to the production well discharge and the injection well input piping. The condenser will be connected to an off-skid cooling tower.

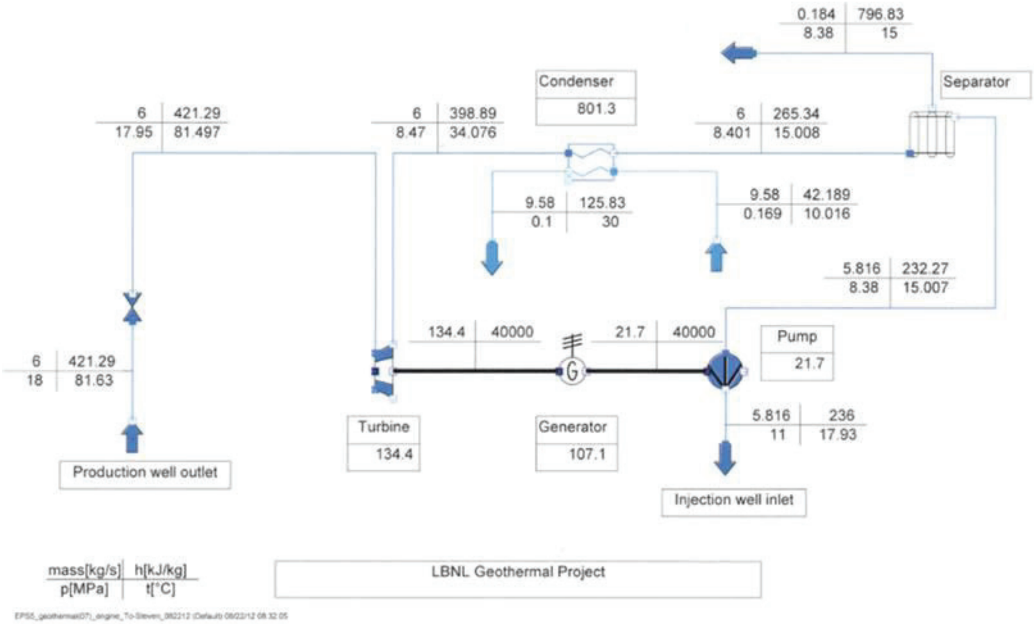

Fig. 4. Design analysis results for geothermal heat energy system showing mass and energy fluxes.

By positioning bypass valves and piping at appropriate positions, different options will be available for testing. One loop will bypass the turbomachinery module and test the thermoshipon effect on the CO_2 flow in the production well. Another "loop" utilizing the turbine and motor/generator, but bypassing the pump will be configured. This loop will be used to confirm that the thermoshipon effect will result in no need for a pump or a gas/liquid separator when the condenser output pressure is greater that the CO_2 vapor pressure. Initial testing will be performed at the Echogen facility using a conventional heat source; the skid will then be transported and installed at the Cranfield demonstration site. The demonstration skid is designed to operate at both locations.

The design speed of the rotating assembly is set by balancing the performance requirements of the turbomachinery including the efficiency of the pump and turbine, pump cavitation limits, bearing capability and the limiting speed of the motor/generator in the acceptable size range to meet stress and material limitations. The critical design parameter of the motor/generator is the tip speed of the rotor which is limited by the stress limits of the rotor assembly and rotor sleeve material. The design speed of the rotating module is set at 40,000 rpm resulting in a compact turbomachinery module. The design generator output will be 100 kw.

2.3. The SECARB Cranfield Site

A detailed description of the SECARB Cranfield reservoir can be found in [3–5]. The Cranfield reservoir is a four-way structural closure, ~20 km east of Natchez, in Southwest Mississippi, U.S.A. The targeted Upper Cretaceous Lower Tuscaloosa reservoir is at a depth of ~3000 m. The site is the location for a large-scale CO_2 injection study led by the Southeast Regional Carbon Sequestration Partnership program [3]. Subsurface conditions in the 15 m to 25 m thick sandstone are temperatures of 127 °C and pressures of 305 bar. The sandstone is composed of predominantly low reactivity minerals (average quartz 79.4%, chorite 11%, kaolinite 3.1% illite 1.3%, concretionary calcite and dolomite 1.5%, and feldspar 0.2%) [4], ideal for circulating CO_2 without some of the dissolution/precipitation issues that may occur in formations with a larger proportion of reactive clay minerals and carbonates.

Given the existing CO_2 pipeline infrastructure at the Cranfield Site is integrated into Denbury Onshore LLC's continuing EOR operations at the Cranfield Site, the CFU31-F1 is still undergoing CO_2 flood. With the addition of the geothermal heat recovery engine we will have the option of switching to a fully recirculating mode, where the mass of CO_2 injected is equal to the mass produced, or we can continue to provide "make-up" CO_2 and operate the well-pair as an unequal strength dipole. Our ongoing modeling effort will inform us as to which mode of operation best meets our program objective of providing a effective data set for model validation. With the relatively close spacing of the injector and withdrawal well, we are likely to operate under several different boundary conditions (changing flowarate and dipole strength) so that we can use inverse modeling techniques to reduce uncertainties in parameter estimation.

3. Conclusions

We have assembled all of the necessary enabling elements for the first ever test of geothermal electricity production using CO_2 as a working fluid. Our wellbore-reservoir models incorporate key thermo-hydrologic processes needed to predict system behavior. Furthermore our heat engine has been optimized for extraction of energy from the relatively cool (90 °C) wellhead temperatures predicted for our system. Upon fabrication of the heat engine we plan to test the system at the site of the SECARB Cranfield DAS test using the existing infrastructure and supply of CO_2. The potential to harness electricity in tandem with carbon sequestration holds a promise to reduce costs by offsetting some of the energy penalty that accompanies carbon capture. Using a natural CO_2 thermosiphon to mine heat can open up areas not previously considered for geothermal energy extraction because the use of a water-based system could not overcome the parasitic loads associated with operating the necessary pumps. It is not until we proceed with a field demonstration will we know if the models presented here are appropriate and sufficient for advancing to a full commercial scale demonstration of the technology.

Acknowledgements

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