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Closed-Loop Geothermal Systems: Modeling and Predictions

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Abstract. Geothermal energy is a sustainable baseload source recognized for its ability to provide clean energy on a large scale. Advanced Geothermal Systems (AGS)—offer promising prototypes—employ a closed-loop vascular layout that runs deep beneath the Earth's surface. A working fluid (e.g., water or supercritical carbon dioxide (sCO2)) circulates through the vasculature, entering the subsurface at the inlet and exiting at the outlet with an elevated temperature. For designing and performing cost-benefit analysis before deploying large-scale projects and maintaining efficiency while enabling real-time monitoring during the operational phase, modeling offers cost-effective solutions; often, it is the only available option for performance assessment. A knowledge gap exists due to the lack of a fast predictive modeling framework that considers the vascular intricacies, particularly the jumps in the solution fields across the channel. Noting that the channel diameter is considerably smaller in scale compared to the surrounding geological domain, we develop a reduced-order modeling (ROM) framework for closed-loop geothermal systems. This ROM incorporates the jump conditions and provides a quick and accurate prediction of the temperature field, including the outlet temperature, which directly correlates with the power production capacity and thermal draw-down. We demonstrate the predictive capabilities of the framework by establishing the uniqueness of the solutions and reporting representative numerical solutions. The modeling framework and the predictions reported in this paper benefit the closed-loop geothermal community, enabling them to determine the system's performance and optimal capacity.

AMS subject classifications: 86-08, 65M60, 80A20

Key words: Reduced-order modeling, geothermal energy, closed-loop systems, transient response, thermal efficiency, boundary conditions.

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1 Introduction and motivation

Conventional energy sources—originating from fossil fuels such as coal, oil, and natural gas—come with various drawbacks. First, the dwindling availability of these natural resources poses a threat to our long-term energy sustainability. Second, scientists recognize that energy production reliant on fossil fuels significantly contributes to the emission of greenhouse gases, widely acknowledged as a critical factor in driving climate change [18, 19]. Third, extracting, processing, and using these fossil-based energy sources pollute the environment [16]. Therefore, delving into alternative energy technologies and progressively transitioning towards a sustainable, low-carbon energy future is imperative.

Clean energy enables this transition. Often called renewable or green energy, it encompasses energy sources and technologies with minimal adverse environmental effects compared to traditional fossil fuels. The principal aim of clean energy is to decrease carbon emissions into the atmosphere. Some popular clean energy forms include solar, wind, hydrogen, and geothermal energy [21]. Among these clean energy alternatives, geothermal energy has emerged as a reliable renewable resource, capable of providing base load power during both peak (day) and off-peak (night) times [17].

Several factors make geothermal energy truly reliable and sustainable:

1. The Earth possesses extensive reserves of thermal energy: its core produces a power of approximately 40 TW [22, 35]. According to the World Energy Council (WEC), the Earth's crust alone holds a total energy of 5.4×10^{27} J [24]. A mere 0.1% of this energy could meet the planet's energy demands for 2000 years, considering the current global energy demand of 2.7×10^{21} J [4].

2. Geothermal energy excels in environmental friendliness, leading with a score of 7.23/10 for minimal air pollution among clean energy options [12].

3. Advancements in drilling technology, primarily from the hydraulic fracturing boom, enable the boring of vertical and horizontal channels spanning miles [6]. This flexibility in drilling makes geothermal energy competitive, as the amount of available thermal energy increases with depth.

4. With the technical know-how gained from various case studies [27], the ability to predict drilling fluids' rheology [31], and the availability of anti-sagging agents combined with novel drilling techniques [14], achieving intricate channel layouts is possible and economical.

Because of these favorable characteristics and technological developments, as of 2016, twenty-six countries across the globe use geothermal energy to generate electricity [5].

Currently, there are two prominent geothermal prototypes that are scalable: Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS). A typical EGS comprises two parallel channels, an injection well and a production well, extending deep