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Closed Loop Geothermal Analysis Modeling and Simulation Using Idaho National Laboratory' RELAP5-3D-FALCON Coupled Codes

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ABSTRACT

In the framework of the U.S. Department of Energy (DOE) "Geothermal Closed Loop" project, Idaho National Laboratory (INL) has developed a new software suite for the analysis of geothermal systems. The software suite is based on two INL codes, RELAP5-3D and FALCON, coupled via a dedicated Python-based software interface. RELAP5-3D is a well-established two-phase system thermal-hydraulic code with nuclear pedigree, based on a nonhomogeneous and nonequilibrium model for the two-phase system, and it allows a detailed analysis of two-phase networks. FALCON is a MOOSE-based application (a finite element framework designed in object-oriented C++) for simulating fully coupled thermal-hydraulic-mechanical-chemical (THMC) based on finite element methods processes in subsurface systems. During Fiscal Year 2022, we have optimized the coupling interface, and analyzed two closed-loop configurations, based on a central well and multiple descending/ascending legs. INL INEL-1 well and Utah-FORGE sites, hot-dry rock domains, have been used for defining the boundary conditions for the analysis. Reference solutions with systems performance are obtained as function of coolant mass flow, and number of legs.

1. INTRODUCTION

Idaho National Laboratory (INL) is part of the U.S. Department of Energy's (DOE) complex of national laboratories and part of INL vision is to discover, demonstrate and secure innovative nuclear energy solutions and other clean energy options. Research and Development (R&D) activities devoted to the improvement and optimization of geothermal energy systems are currently being conducted in the framework of the U.S. DOE "Geothermal Closed Loop" project, led by Pacific Northwest National Laboratories (PNNL). INL, as a national leader in developing advanced simulation tools, e.g., RELAP5-3D Code Development Team (2018), Williamson et al. (2012), is contributing to the project by developing and testing a new advanced software suite for the detailed analysis of geothermal systems. The software suite is composed by an ad-hoc developed software coupling interface and by two thermal-hydraulic codes widely used in nuclear and non-nuclear applications.

In this paper we will describe the progresses obtained during Fiscal Year 2022. We focused on the optimization of the coupling interface, the analysis of multi-later coaxial closed-loop configurations applied to the INL and Utah-FORGE sites. Both sites are hot-dry rock domains or similar to hot-dry rock domains. System performance have been obtained as function of coolant mass flow and number of loop lateral legs.

2. MODELING TOOLS AND BOUNDARY CONDITIONS

The INL geothermal software suite, a detailed description of the tool features and capabilities and the boundary conditions utilized for this study are reported in the following sections.

2.1 INL Geothermal Software Suite

The INL geothermal software suite is composed by three parts: a Python language-based codes-coupling interface, the RELAP5-3D system thermal-hydraulic code, RELAP5-3D Code Development Team (2018), and the MOOSE platform-based, Gaston et al. (2015), FALCON a finite-elements thermal-hydraulic-mechanical-chemical code, Podgorney et al. (2021). All these software tools are developed and maintained by the INL staff. The data flow scheme is shown in Figure 1. Proof of the validation of the INL geothermal suite can be found in Parisi et al. (2021).

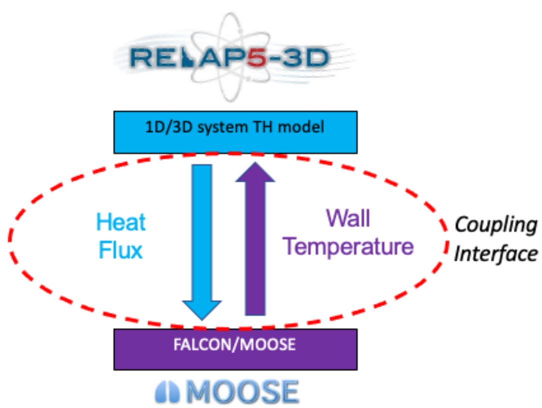

Figure 1: INL Geothermal Software Suite.

<u>2.1.1 Codes-coupling interface</u>

The codes-coupling interface is a Python language-based software, whose development has been supported by the "Geothermal Closed Loop" project. The interface has been developed having in mind the following functional requirements:

- be able to perform two-codes coupling using:
  - a sequential two-ways explicit coupling.
  - an implicit coupling using Picard Iterations.
- manage codes execution on INL' High Performing Computers (HPC) clusters.
- perform process monitoring.
- perform data post-processing.

The codes-coupling interface uses an implicit external coupling, performing several Picard iterations for every time step, up to a maximum number of iterations chosen by the user. The actual number of iterations per time step, up to the maximum, it is decided by an algorithm which checks the convergence of the two coupled-codes solutions at the interface (the borehole walls). The coupling software interface, once it detects that the number of Picard iterations per time step decreases, it tries to extend the coupling time steps (adaptive time step), speeding up the total calculation time.

The coupling scheme interface exchange the following data between the two coupled codes:

- Borehole fluid temperature and heat exchange coefficients, calculated by the system thermal-hydraulic code (RELAP5-3D), are sent to the rock-domain analysis code.
- Wall temperature, calculated by the rock-domain analysis code (FALCON), are sent back to the system thermal-hydraulic code.

The data exchange is performed by the coupling interface through the reading of each code output files. Such information is then used for the automatic compilation of each code input deck and code execution. This process is then repeated for every iteration of a time step.

2.1.2 RELAP5-3D

The fluid in the borehole well and the borehole well are simulated using INL RELAP5-3D code. RELAP5-3D is a nuclear system thermal-hydraulic code that is part of the RELAP5 codes family developed for light-water reactor transient analysis. RELAP5-3D is based on nonhomogeneous and nonequilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme (semi-implicit and nearly implicit) to permit economical calculations of system transients. Solving a 6-equation model (mass, momentum and energy conservation equations for both liquid and vapor phases) allows RELAP5-3D to calculate in every node/junction of the discretized system water and steam velocities and temperatures. The pressure of both phases is assumed to be identical. RELAP5-3D code improvements, compared to the previous RELAP5 versions, include multi-dimensional neutron kinetics and thermal-hydraulic modeling capabilities. Three-dimensional flows can be simulated using specific hydraulic components, while heat transfer mechanisms (radiation, convection, and conduction) can be simulated with one-dimensional or two-dimensional approaches. A generic modeling approach is used that permits using RELAP5-3D in simulating a variety of nuclear and non-nuclear thermal hydraulic systems. The code has been successfully applied to non-nuclear systems like conventional steam plants and cardiovascular blood flow. The application of RELAP5-3D to geothermal problems presented in this paper represents a very first attempt.

2.1.3 FALCON-MOOSE

FALCON code is a finite-element (FE) geothermal reservoir simulation and analysis code for coupled and fully implicit Thermo-Hydro-Mechanical-Chemical (THMC) geosystems. FALCON can simulate three-dimensional multi-phase flows, heat convection, heat conduction, mechanical and chemical phenomena. The code is part of the INL' MOOSE computational framework and it has been used for simulating highly nonlinear coupled subsurface dynamics for problems such as carbon sequestration, reactive transport, geothermal energy, etc. Due to the flexibility in the virtual abstract physics and transport interfaces, FALCON is highly extensible and can accommodate both multi-species and multi-phase formulations. Finite elements give to the code the possibility of simulating also complex three-dimensional geometries. Since FALCON is built on the MOOSE framework, it can use the libMesh finite element method (FEM) library with the nonlinear solution and preconditioning capability of the Portable, Extensible Toolkit for Scientific Computation (PETSc). The use of a FE spatial discretization permits the use of unstructured meshes based on a variety of element types (1-D up to 3-D problems).

2.2 Boundary conditions: INL and Utah-FORGE sites

Two different geothermal sites have been selected for the analysis. The first one is the well-known U.S. DOE Utah-FORGE (Frontier Observatory for Research in Geothermal Energy) site. Located near the town of Milford in Beaver County, Utah, on the western flank of the Mineral Mountains, it is characterized by a thermal gradient of 78.8 °C/km (4.32 °F/100 ft) and a rock thermal diffusivity of 1.40E-06 m^2/s, Podgorney et al. (2020).

The INL site boundary conditions are instead based on the geothermal characteristics of the INEL-1 well, Doherty et al. (1979), Mann (1986), Blackwell (1990). INEL-1 well is located on the U.S. DOE INL site, a 980 square mile area very close to the Yellowstone caldera and part of the Snake River Plain (see Figure 2).

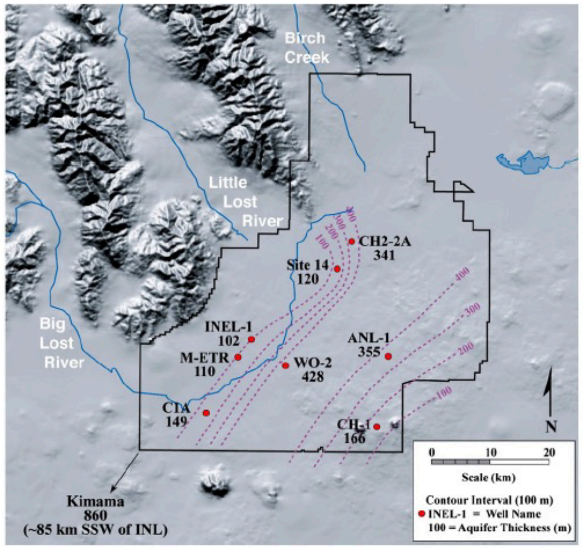

Figure 2: INL INEL-1 well location, McLing et al. (2016).

Information on the geological characteristics has been obtained drilling the INEL-1 well, a 3,159 m deep (10,365 ft) well, characterized by a gradient of ~44.0 °C/km (2.41 °F/100 ft). The INEL-1 well geological stratigraphy is composed of layers of volcanic rock, with basaltic lava flow and interbedded sediments up to a depth of 762 m (2,5000 feet). Rhyolitic welded ash-flow of tuffs/air-fall ash deposits and non-welded ash-flow tuffs are instead composing the geological layers below 762 m. The low hydraulic conductivity found at the bottom of the well (2E-6 cm/s, or 2E-3 ft/day) suggests that the hot dry-rock is a good approximation for our simulation.

3. MODELING

The closed-loop system that was selected for the numerical analysis is composed by a single long vertical coaxial well that reaches a proper depth and several smaller lateral horizontal legs (i.e., multi-legs configuration, see Wang et al. (2021)). Activities in the oil & gas industry in last decade have shown considerable advancements in the technology of multi-lateral well drilling, e.g., see Husain et al. (2011), Ghadami et al. (2022), Almedallah et al. (2021), so we assumed this configuration as technological ready.

In this closed-loop configuration, the water is flowing on the outer annular space of the vertical well and after it reaches the end of the borehole is equally distributed in the annular space of one of the n-horizontal legs. Flowing in the horizontal leg(s), the water is heated up by the hot rocks and it returns to the central vertical borehole via a coaxial insulated casing. The horizontal casings are all connected to a vertical coaxial pipe installed in the borehole. This pipe conveys the hot water back to the surface where it is then sent to a heat exchanger to release part of its enthalpy for industrial uses (see Figure 2).

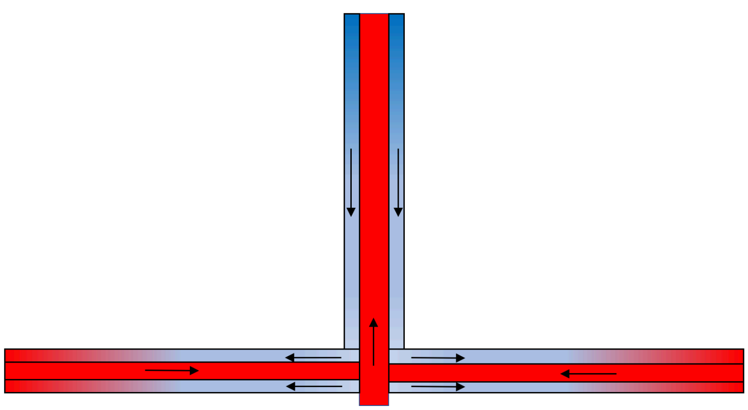

Figure 3: Multi-later coaxial well configuration.

Compared to a U-shaped closed system, this multi-leg system has the advantage of minimizing the number of drilling locations and containing the external infrastructure costs. On the other hand, it is more complex to realize because of the installation of the internal casings that keep hot/cold water flows separated.

The computational domain for the rock formations is identified in Figure 4. The rock domain has a lateral dimension of ~200 m. Previous analyses, see Parisi et al. (2021), demonstrated that this rock domain thickness is sufficient for modeling energy transfer in the rock domain using closed-loop technology. Considering the limited radial dimensions of the borehole (< 1m) compared to the lateral dimensions of the system (200 m), the rock domain has been modeled as a continuous domain (no hole). This approximation has proved to be efficient in saving computational time (mesh simplification) without compromising the results accuracy. The wetted perimeter of the borehole is used to define the zone of heat transfer between the rock domain and the borehole/water.

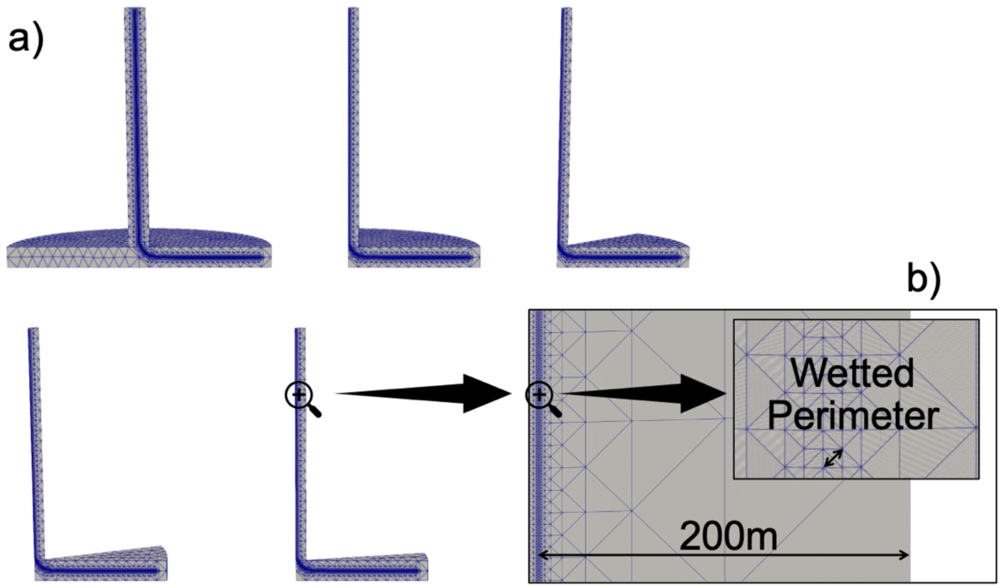

Figure 4: a) Multi-later leg mesh for 1 to 16 legs configuration, b) detail of the mesh refinement.

Simulation up to 16 independent lateral legs have been performed, taking into account a rock domain per leg that is inversely proportional to the number of legs (see Figure 5). Vertical dimensions of the central borehole well are 2640 m for the Utah FORGE site and 4728 m for the INL INEL-1 site.

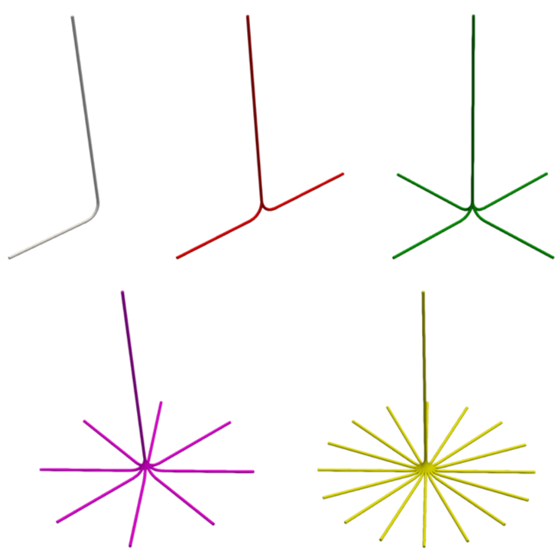

Figure 5: Multi-later well configuration, 1 to 16 legs (hole diameter not in scale).

4. RESULTS

Calculations of the different multi-leg configurations (1, 2, 4, 8, 16 legs) have been performed considering different injection mass flows (5, 10, 20, 40 kg/s) for a simulation time of 20 years. Inlet water pressure was adjusted to avoid boiling on the returning part of the vertical borehole. INL INEL-1 site has been used as reference site for all the analyses, while Utah-FORGE site has been compared for the 20 kg/s mass flow cases (average mass flow for all cases). It should be noted that lateral legs total flow area has been kept constant in all cases such that the liquid velocity is constant (i.e., the mass flow is equally split between the legs). The Figure of Merits (FOMs) considered for this analysis are the fluid (water) outlet temperature, the system pressure drops (relevant for the calculation of pumping power), and the thermal power output. These FOMs can be used later for calculating the system efficiency and economics, White et al., (2022).

Results for the INL INEL-1 FOMs are reported in Figures 6 to 8. In Figure 6 it can be seen that the higher the number of lateral legs, the lesser the outlet water temperature is sensible to the inlet mass flow rate. Results also shows that the 8 legs configuration is the one that allow to minimize the variation of the water outlet temperature versus the inlet mass flow, while at the same time it is minimizing the complexity of the drilling. Increasing the water inlet to 40 kg/s has detrimental effects on the fluid outlet specific enthalpy (outlet temperature drops to ~150 C for the 8 legs configuration).

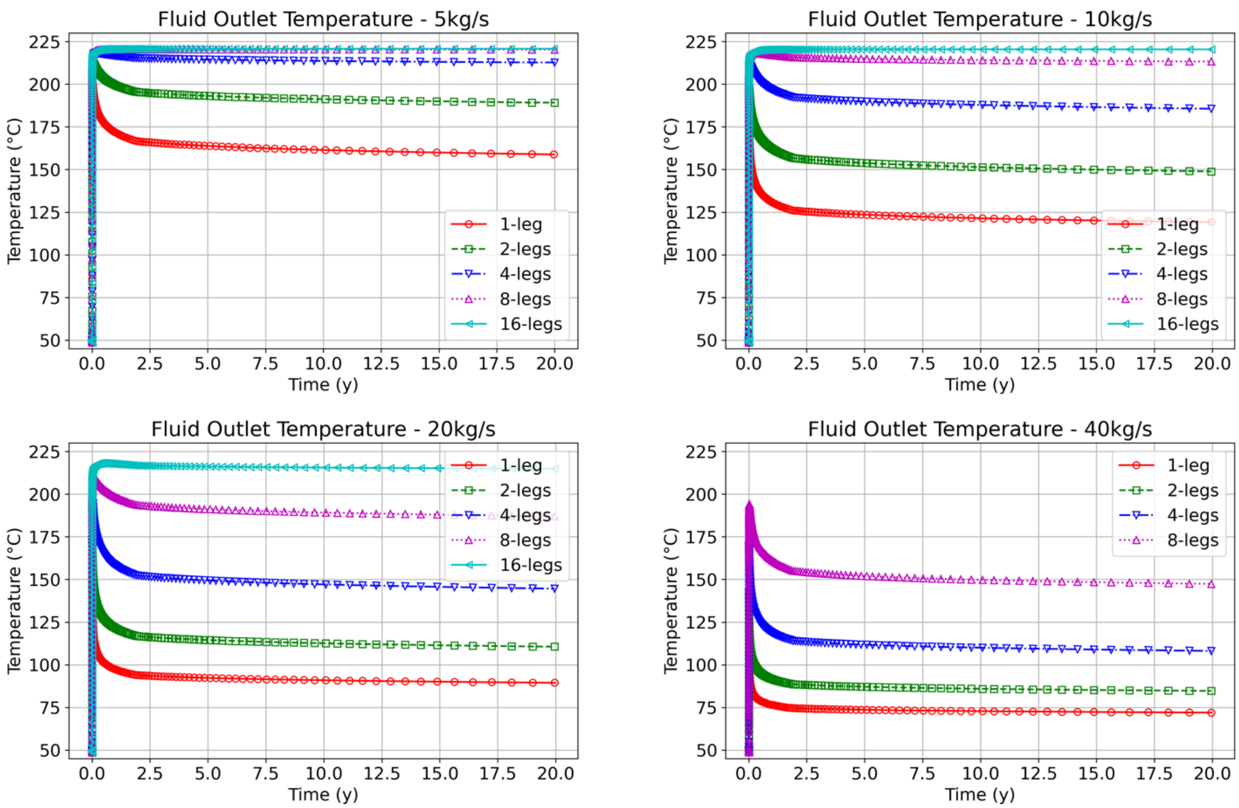

Figure 6: Fluid outlet temperature for 1, 2, 4, 8, 16 legs configurations and 5, 10, 20, 40 kg/s total mass flow rate.

Figure 7 shows the effect of mass flow and number of lateral legs on the system pressure drops. The lower mass flow rates (5 to 10 kg/s) allow a thermosiphon effect, resulting in system negative pressure drops. At 20 kg/s mass flow rate, the 16 and 8 legs configurations still result in negative pressure drops, while the other legs have positive pressure drops. The 40 kg/s case require active pumping power for all the configurations.

Figure 8 shows the thermal power obtained as function of the mass flow and number of legs. As expected, the higher the mass flow, the higher the output thermal power. The 8 legs configuration seems again to maximize the thermal output while minimizing the system complexity and inefficiencies. Results for the 16 legs configuration, 40 kg/s where not obtained since this configuration resulted to be unstable because of boiling.

Results for the Utah FORGE looked like the INL INEL-1, however, because of the superior thermal gradient of Utah FORGE (78.8 °C/km vs. 44 °C/km), this configuration needed a shallower central borehole. The heat exchange area of the lateral legs where kept constants for both cases, to facilitate the comparison. Results in Figure 9 shows, as expected, that thermal power and fluid temperature are similar for both configurations provided the boundary conditions described above. However, system pressure drops for multi-leg configurations resulted to be sensibly smaller for Utah FORGE because of the shorter vertical well.

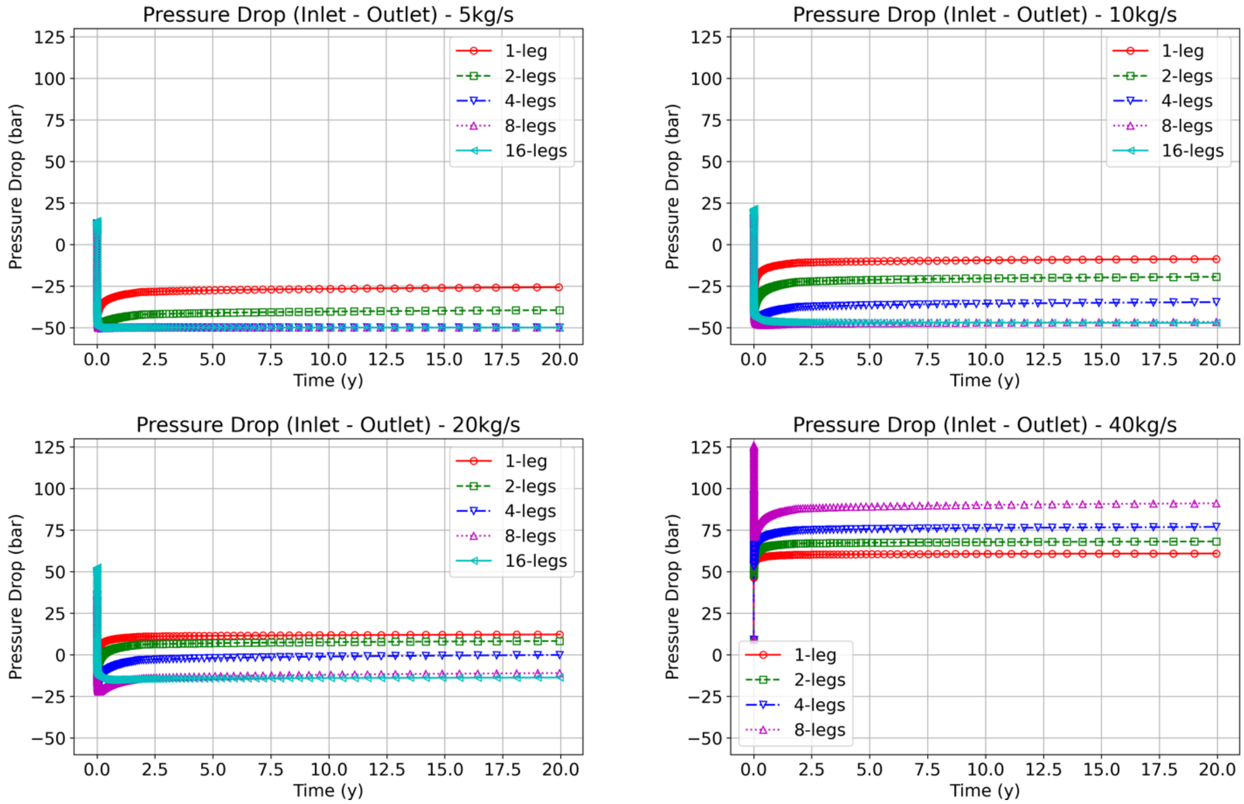

Figure 7: Pressure drop for 1, 2, 4, 8, 16 legs configurations and 5, 10, 20, 40 kg/s total mass flow rate.

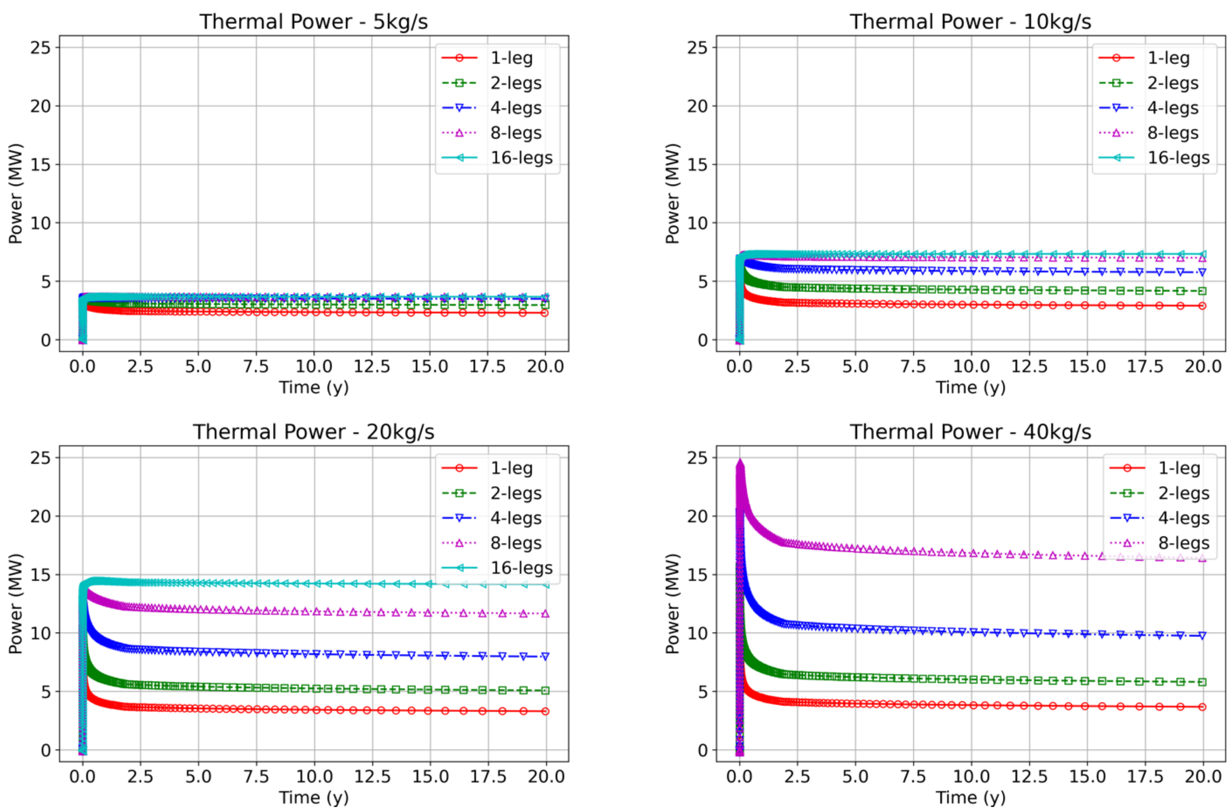

Figure 8: Thermal power output for 1, 2, 4, 8, 16 legs configurations and 5, 10, 20, 40 kg/s total mass flow rate.

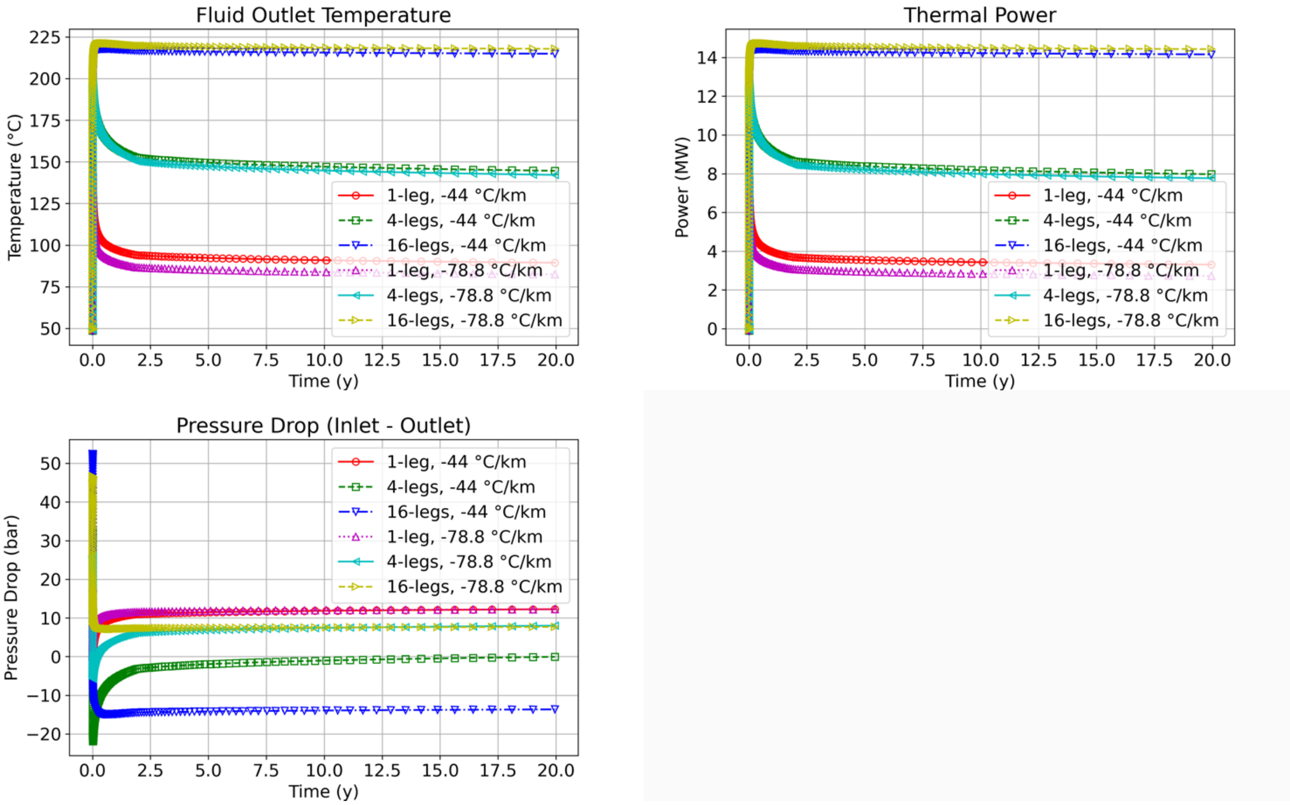

Figure 9: Comparison between INL INEL-1 site (44 °C/km) and Utah-FORGE site (78.8 °C/km), results for 1, 4, 16 legs configurations and 20 kg/s total mass flow rate.

4. CONCLUSIONS

This paper summarizes the activities performed during the Fiscal Year 2022 for the U.S. DOE “Geothermal Closed Loop” project. INL has improved the geothermal analysis software suite by coupling the RELAP5-3D system thermal hydraulic code with the MOOSE-based FALCON THCM code. The coupling interface has been optimized for running long transients (~decades) and for exploiting the meshing and post-processing capabilities of the MOOSE framework. The geothermal analysis software suite has been applied to the study of a novel multi-later coaxial well configuration, using Utah FORGE and INL INEL-1 sites as boundary conditions for the analysis. Results indicate that the 8 legs multi-lateral configuration is optimizing the FOMs (water outlet temperature, system pressure drops and thermal output) over a period of 20 years while minimizing the system complexity. The Utah FORGE site, because of his superior thermal gradient, provides better performance compared to the INL INEL-1 for an identical configuration. It should also be noted that other INL site wells could provide superior thermal performance than INEL-1 well. Finally, the results described in this paper will be used for assessing the economic performances of both sites and of the different multi-later well configurations.

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