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Geothermal Analysis Modeling and Simulation Using Idaho National Laboratory' RELAP5-3D-PRONGHORN 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) is developing a new software suite for the analysis of geothermal systems. The software suite is based on two INL codes, RELAP5-3D and PRONGHORN, 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. PRONGHORN is a porous media-approach code, based on finite-volumes and finite-elements methods and it is being developed using the INL MOOSE computational framework. In this paper we summarize the key characteristics of the coupling interface, its validation and present the results of two benchmark exercises performed for the US DOE "Geothermal Closed Loop" project. For the first exercise, solutions of a U-shaped hot-dry rock (UHDR) configuration have been obtained, by analyzing the performances of the geothermal system as function of the borehole diameter, length, coolant mass flow, and insulation strategies. For the second exercise, solutions of hot-wet-rock scenarios have been obtained, investigating the thermal performances of a concentric borehole system. Finally, the computational performances of the RELAP5-3D/PRONGHORN coupled codes software suite and its accuracy in analyzing geothermal systems are summarized.

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 (2018a), 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 main characteristics of INL geothermal software suite and highlight its capabilities, showing the results obtained from its application to two different geothermal benchmark problems developed by the "Geothermal Closed Loop" project. This paper is organized as follows: section two describes the geothermal software suite components and structure, section three provides the benchmarks' results for the hot dry and wet rock scenarios while section four summarizes our work and discusses about the next future steps.

2. 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 (2018a), and the MOOSE platform-based, Gaston et al. (2015), PRONGHORN porous-media approach code, Novak et al. (2021). All these software tools are developed and maintained by the INL staff. The data flow scheme is shown in figure 1.

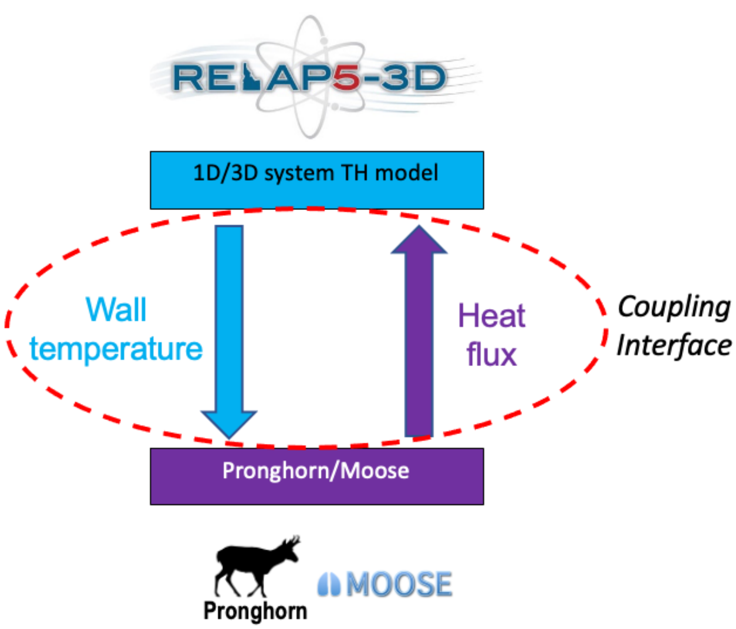

Figure 1: INL Geothermal Software Suite.

In the following subsection we provide a detailed description of their features and capabilities useful for the geothermal system analyses.

2.1 Codes-coupling Interface

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 main coupling scheme is reported in the figure 2 below. The sequential two-ways explicit coupling is represented by the "Picard 0" iteration, while the implicit coupling by the successive Picard iterations. The two-ways explicit coupling approach is fast and simple, but, as it will be shown in the following sections, it does not guarantee the due accuracy and the numerical stability. Therefore, the codes-coupling interface has also the capability of performing 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).

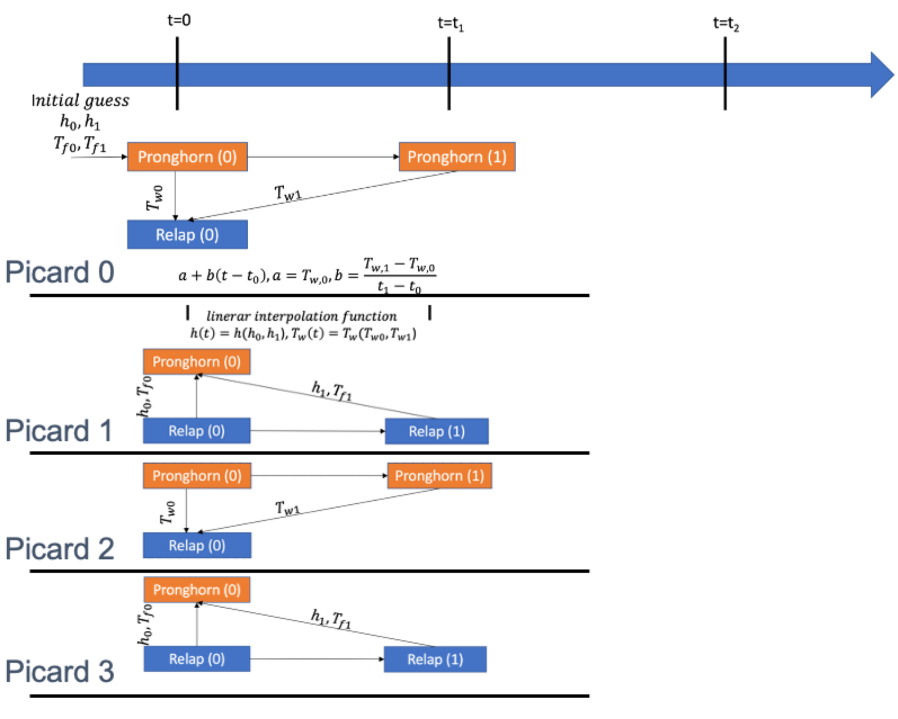

Figure 2: Coupling scheme of the codes-coupling interface.

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. These features will be shown in detail in the next sections.

As shown in figure 1, 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 (PRONGHORN), are sent back to the system 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.

2.2 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.

2.3 PRONGHORN-MOOSE

PRONGHORN code is a porous media approach code which can simulate three-dimensional one-phase flows, heat convection and heat conduction phenomena. The code is part of the INL' MOOSE computational framework and it has been used for simulating complex flow patterns and heat transfer for the high-temperature gas reactors. The code is solving the one-phase mass, momentum and energy conservation equations and the energy transfer using an implicit numerical scheme. Finite elements (FE) and finite volumes meshing scheme can be employed, giving to the code the possibility of simulating also complex three-dimensional geometries. Since PRONGHORN 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). Finally, PRONGHORN time integration can be implicit as well as explicit, since a wide variety of schemes are available in MOOSE. All the solutions documented in this paper have been obtained using an implicit time integration scheme.

3. Benchmarks Results

3.1 Simplified Case

To test the coupling interface technology, a simplified benchmark has been created at INL. The benchmark is based on a straight borehole well and a cylindrical rock domain, 500 meters deep, with an assigned rock thermal gradient. Because of the 1-D symmetry and the small domain, the simplified benchmarked allowed INL team to derive a reference solution using RELAP5-3D code stand-alone. The calculations were run for a 20-years transient, using RELAP5-3D fast nearly implicit numerical scheme.

Then, two RELAP5-3D/PRONGHORN solutions were calculated, using a sequential explicit (no Picard iterations) and an implicit coupling method. Simulations results shown that for this type of geothermal problems, an implicit coupling scheme is necessary to get an accurate solution, especially during the first strongly non-linear phases of the simulation (first years). Figure 3 shows that the codes explicit coupling reaches the reference solution only after half of the transient time (10 years). Therefore, it was decided that all the "Geothermal Closed Loop" project exercises would be calculated using an implicit coupling scheme with multiple Picard iterations per time step.

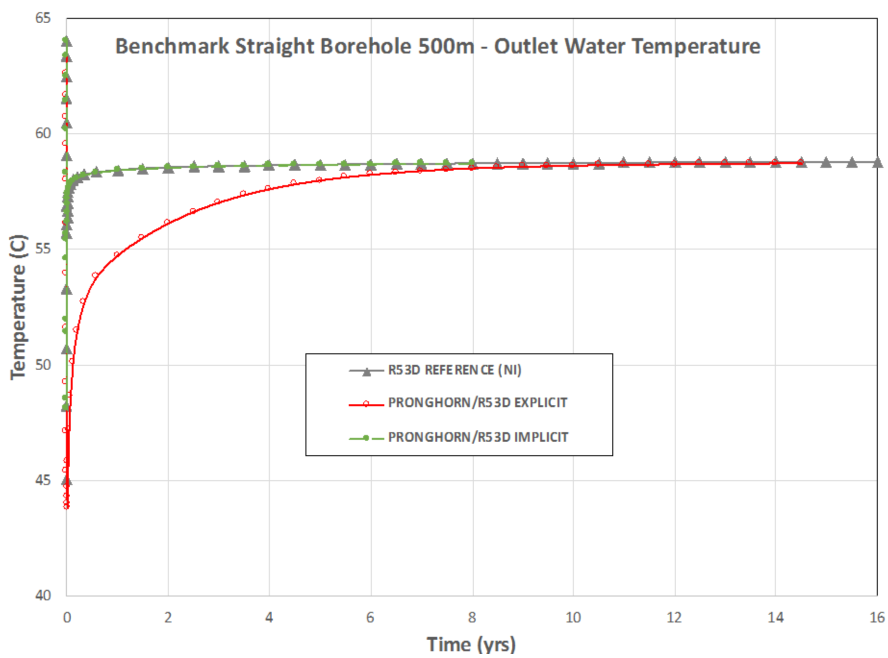

Figure 3: Simplified benchmark results.

3.2 U-shaped hot-dry-rock borehole calculations

The first benchmark of the project included the calculations of six different cases. In particular, the benchmark problem requested the calculation of the main thermal hydraulic parameters of the borehole well (water temperature/enthalpy, temperature of the rock domain) for a 5-km long U-shaped borehole well (see figure 4 below). The simulation time period was 20 years. The rock domain was assumed to have a surface temperature of 25 °C and a temperature distribution described by a linear thermal gradient of 0.0788 °C/meter. Consistent with benchmark specifications, Gnielinski correlation, Gnielinski V. (1975), for turbulent flow in tubes was selected in the RELAP5-3D input deck for calculating the wall to fluid heat transfer coefficient, RELAP5-3D Code Development Team, (2018b).

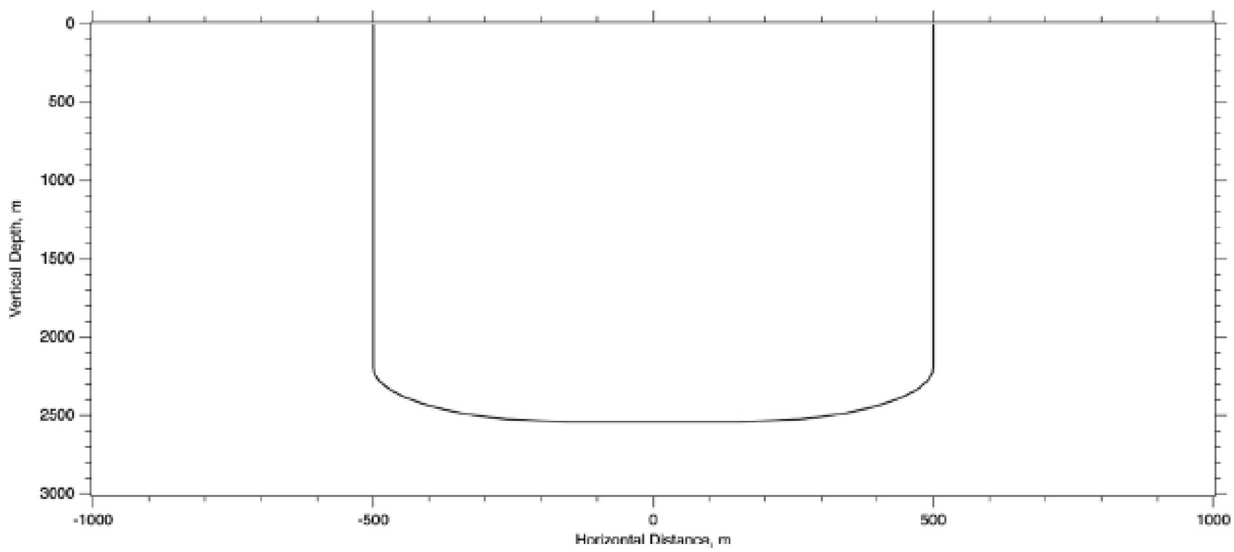

Figure 4: First Exercise – Domain calculation.

A cylindrical U-shaped rock domain was developed for the PRONGHORN calculations, in order to limit the computational loads. The final radius of the U-shaped rock domain (100 m) has been selected after performing several mesh convergence sensitivities. Figure 5 shows the whole PRONGHORN calculation domain and an axial section of it.

The 6 different cases that have been calculated include:

- Two different borehole diameters (8.5’’ and 9.5’’)
- For each of the two boreholes sizes, three different injected water mass flows (5, 20 and 40 kg/s).

Results of the outlet water temperature for the six different cases are reported in figure 6.

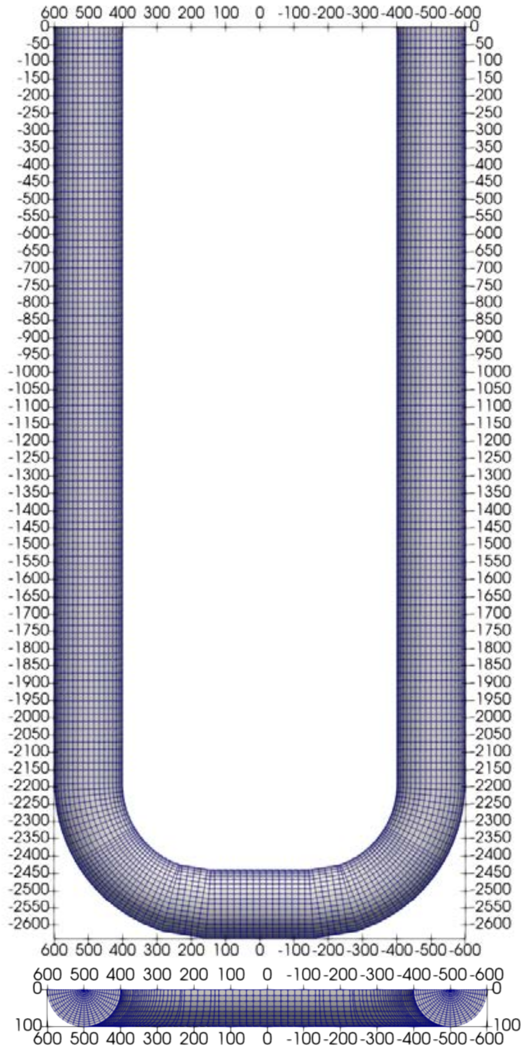

Figure 5: First Exercise – PRONGHORN calculation domain and axial section.

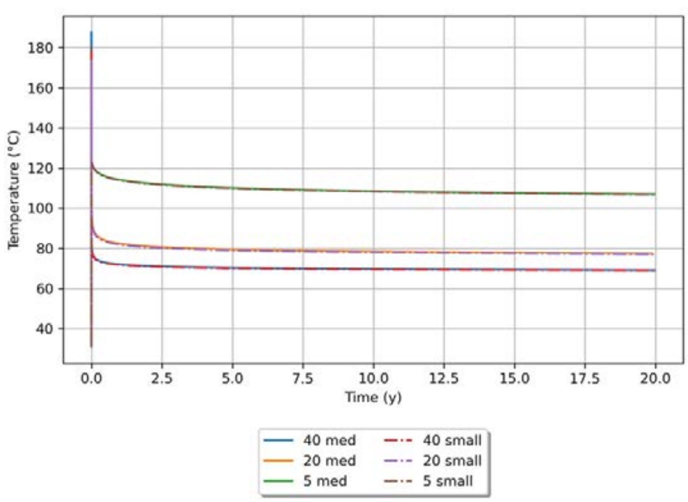

Figure 6: First Exercise – Results for the 20 years benchmark.

The calculations have been obtained using the RELAP5-3D nearly implicit scheme, and the implicit coupling with Picard iterations for the coupling interface. All the runs have been executed on FALCON HPC using 12 core processors for the 3D calculations of the rock domain temperature distribution. Each case required about 1 week of running time. An analysis of the numerical parameters' values (number of Picard iterations and time steps) versus time is shown in figure 7. The figures show how the coupling interface performs a quite high number of Picard iterations during the first 1-year time interval of the transient. This is particularly true for the 20 and 40 kg/s cases, which, because of the higher water velocities, results in lower Courant limit numbers and in faster rock temperature changes. After the 1-year time interval, the number of Picard iterations drops to 2 or 1 per time step.

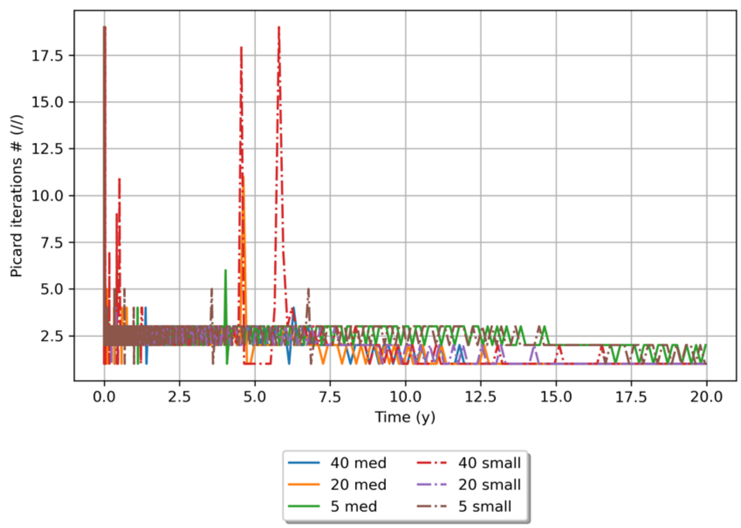

Figure 7: Number of Picard`s Iteration per time step.

Figure 8 below shows how the coupling interface is increasing the time step interval during the simulation, as the domain parameters (water and rock temperature) changes. The differences in the time step interval dimensions are caused by the water velocity (the slower the water the larger the time step), the satisfaction of the convergence criteria.

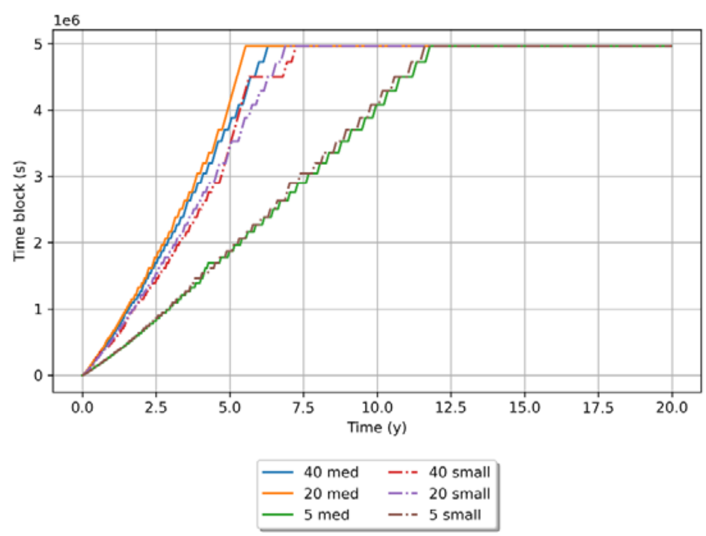

Figure 8: Time steps changes.

The total mechanical power for the 6 different cases is reported in figure 9 and an example of the rock domain temperature distribution at the beginning and at the end of the transient for the 5 kg/s, 8.5’’ diameter borehole case is shown in figure 10. The calculations, consistently with other benchmark participants results, show that:

- The size of the well is not causing significant differences in the simulation results (outlet temperatures and extracted power)
- The water mass flow rate is strongly correlated to the outlet temperature (the higher flow rates the lower the outlet temperatures)
- The water outlet temperature has a stronger change during the first one-year time interval. After this period, the water outlet temperature decreases very slowly, with an approximate linear behavior.

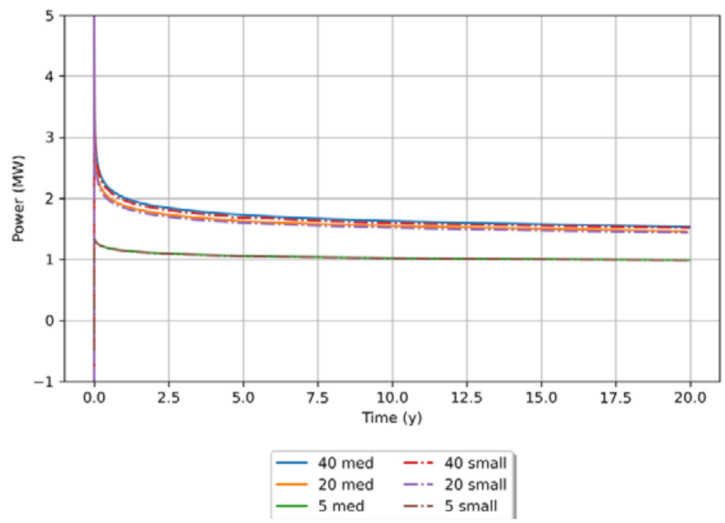

Figure 9: Mechanical power (MW).

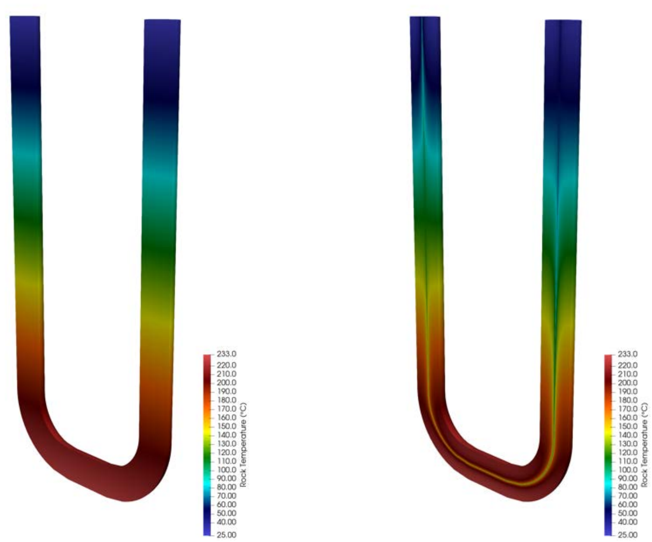

Figure 10: Rock domain temperature distribution at the beginning and the end of the transient for the 5 kg/s – 8.5 ‘’ borehole case.

3.3 Coaxial borehole hot-wet-rock problem solutions

Another scenario that has been simulated is a coaxial borehole in a hot wet-rock domain. The problem specifications are taken from the downhole coaxial heat exchanger (DCHE) experiment descried by Morita et al., 1992. Details of the analyzed scenario can be found in White et al., 2021. The DCHE has been modeled using RELAP5-3D pipes components, while the thermal coupling between the water flowing downward the outer pipe and water flowing upward the inner pipe has been modeled using the RELAP5-3D heat structure component (see figure 11). The hot-wet rock, the cement and pipe casings has been instead modeled using the PRONGHORN code. Rock thermal conductivity has been assumed to be k = 3 W/m K, with a rock porosity of 0.112 (see figure 12).

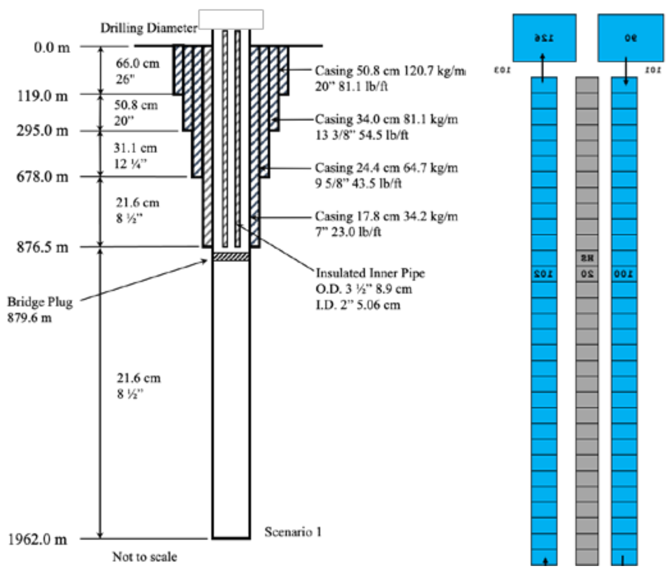

Figure 11: Pipe specifications and corresponding RELAP5-3D modeling.

The same coupling strategy used in the previous exercise has been used here (RELAP5-3D nearly implicit and Picard iterations). Because of the much smaller calculations domain and the transient simulation time, the running time for this exercise is in the order of 3 hours. The results show an underestimation of the water temperature compared to the experiment (35°C versus 46 °C after 7 days). This may be caused by selection of rock material characteristics (bulk density and bulk heat capacity) that are not consistent with the experiment boundary conditions. Sensitivities studies have been performed for addressing this issue, but the obtained solutions were not very sensitive to the perturbations (see figure 14).

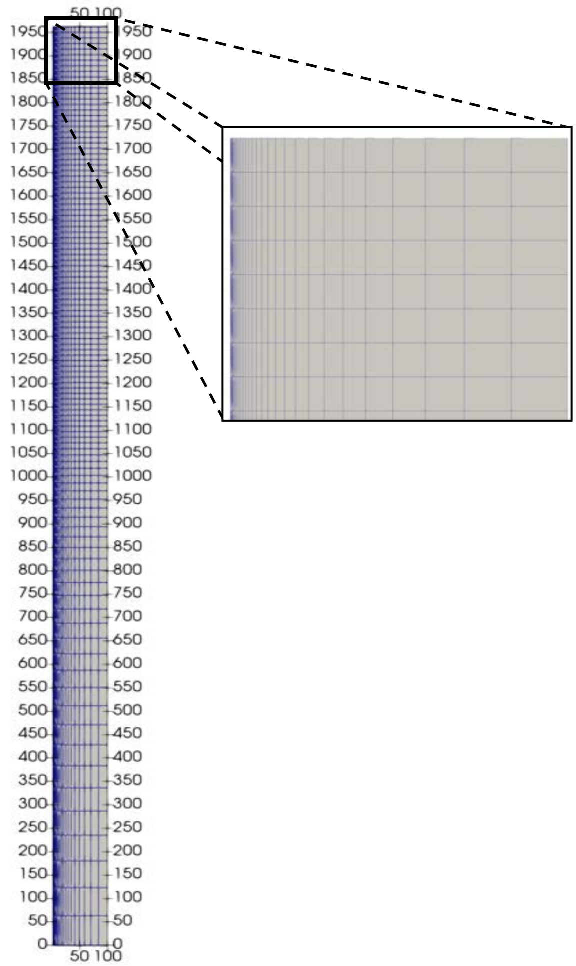

Figure 12: 2D Axisymmetric mesh for the DCHE experiment simulation.

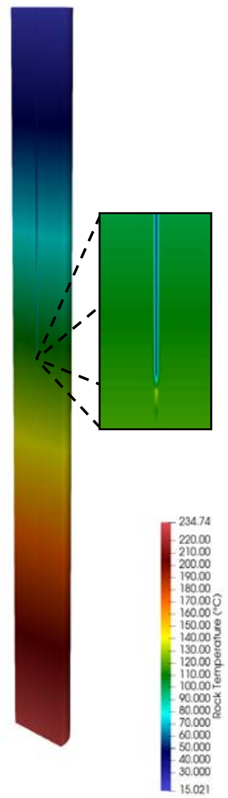

Figure 13: Rock domain temperature distribution at the end of DCHE experiment.

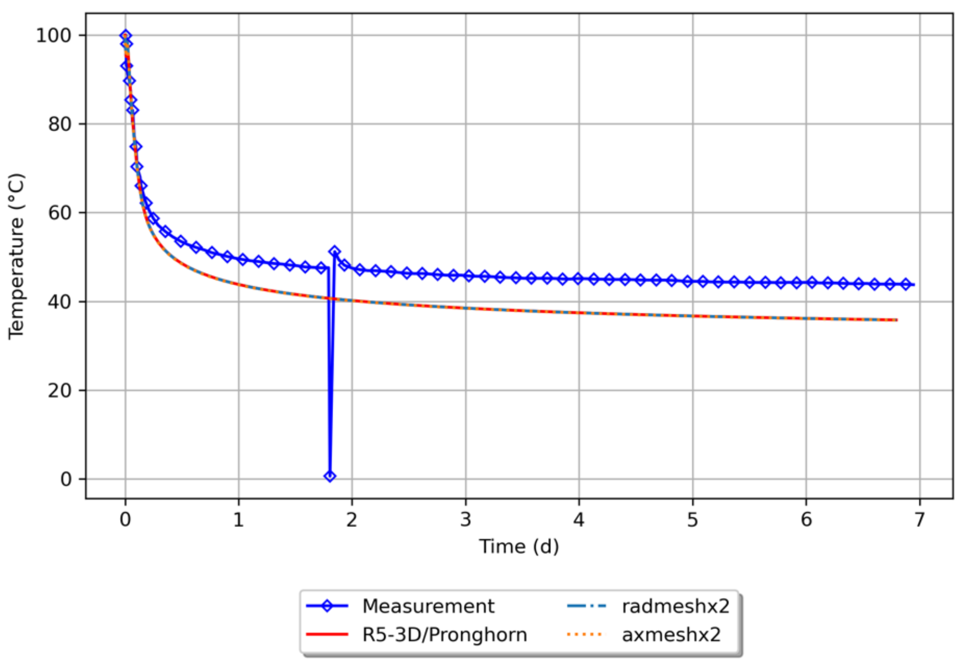

Figure 14: Water outlet temperature for the DCHE experiment.

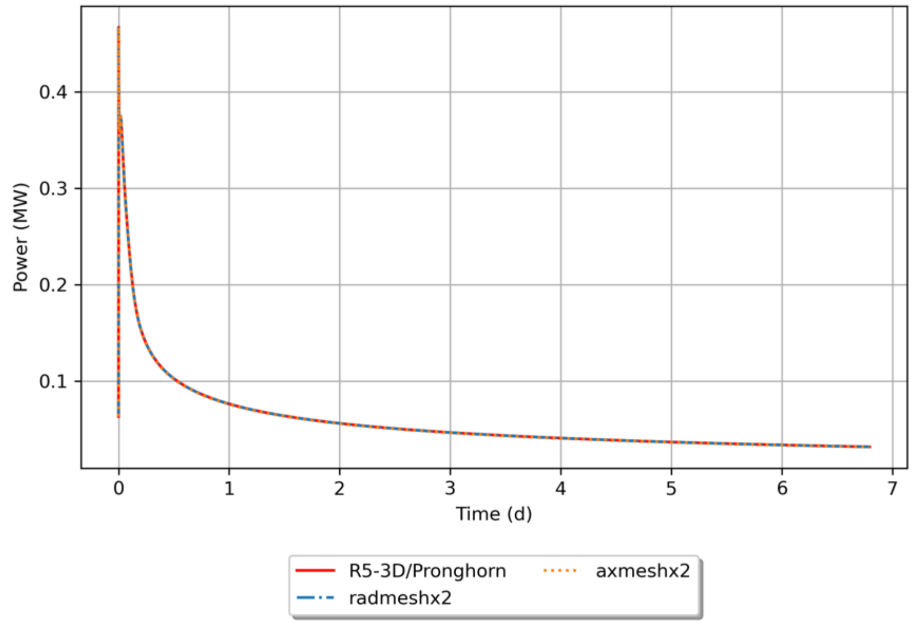

Figure 15: Gross thermal power for the DCHE experiment.

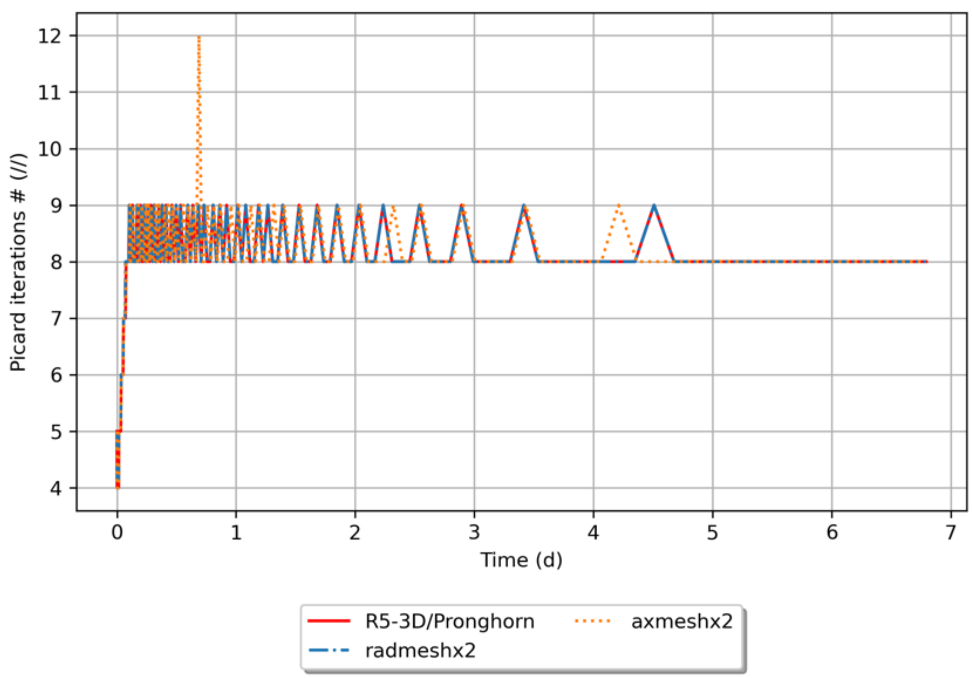

Figure 16: Picard iterations for the DCHE experiment.

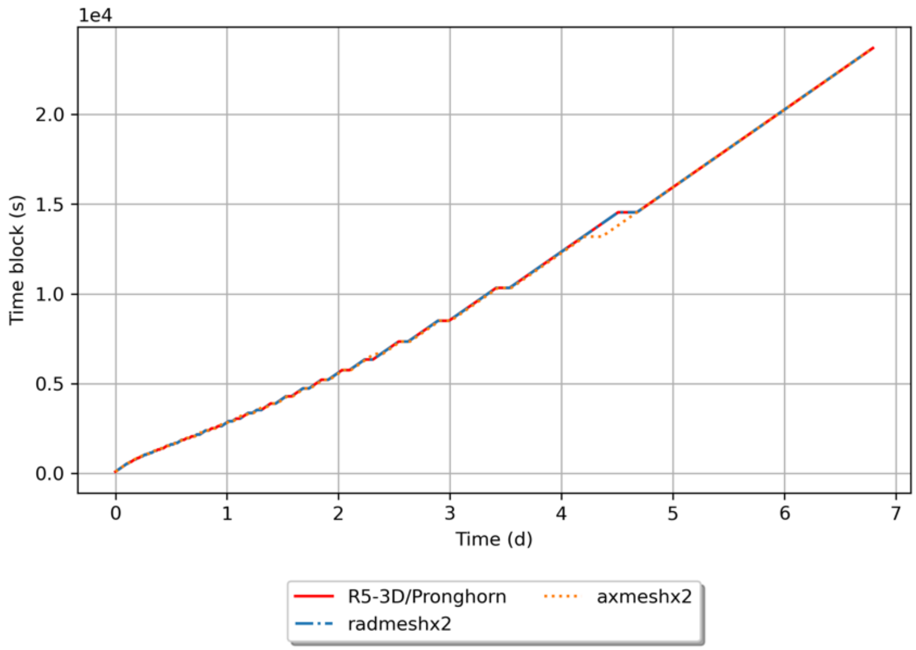

Figure 17: Time Blocks for the DCHE experiment.

3. Conclusions

The paper summarizes the activities performed at INL for the development of a geothermal software suite. The software suite is based on the coupling of RELAP5-3D and PRONGHORN code via an ad-hoc developed coupling interface. The combination of two different codes capabilities gives the software suite the possibility of:

- Performing detailed calculations of the borehole well fluid parameters, both in single phase and two-phase conditions. RELAP5-3D can calculate all the main thermal-hydraulic parameters considering the effects of concentrated and distributed pressure losses, heat transfers correlation, different flow regimes, etc.
- Performing detailed calculations of the 3D rock domain temperature distribution. PRONGHORN code solves the heat conduction equation in 3D without any significant geometry limitation, thanks to the use of unstructured FE meshes.

The coupling interface also allows the analyst to perform an efficient calculation monitoring and a fast data post-processing. Finally, the results obtained from the execution of two different case studies shows that:

- the software suite can obtain a converged solution in reasonable time (hours/days) using limited computational capabilities (12 core processors).
- the first exercise results (U-shaped borehole in hot dry rock domain) are consistent with the numerical results obtained by the other project participants.
- the second exercise results (DCHE in wet dry rock domain) are underestimating the final outlet temperature of about 10 °C. The reason for this underestimation is due to uncertainties in the rock domain boundary conditions.

Acknowledgement

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