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Effect of Thermal-Shock Damage on Heat Extraction from Hot Dry Rock

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Abstract

Heat extraction from hot dry rock (HDR) reservoirs depends on the efficiency of heat transfer between the surrounding rock mass and the circulating working fluid. In geothermal operations, rapid cooling of hot rock can occur and induce thermal-shock damage, progressively modifying the thermophysical properties of the reservoir. Although such effects are well documented in laboratory studies, their direct influence on heat extraction behavior—particularly when damage is unevenly distributed around the wellbore—remains insufficiently understood.

In this study, a Thermo-Hydraulic (TH) numerical model is developed to investigate heat extraction from HDR while explicitly accounting for progressive thermal-shock damage. Five damage states are defined based on laboratory rapid-quenching experiments, and the corresponding thermophysical properties are measured after each treatment. To represent realistic near-wellbore conditions, the damaged rock is modeled as concentric layers surrounding the wellbore, allowing a layer-by-layer assessment of the thermal response. Outlet fluid temperature and heat extraction rate are used as the primary performance indicators, and all results are compared with an intact reference condition (T-25).

The results demonstrate that thermal-shock damage significantly affects the thermal performance of the HDR geothermal system. Compared with intact rock, thermally damaged formations exhibit lower production temperatures due to reduced thermal conductivity resulting from microcrack development. Severe damage (T-800 with a 5 m damaged zone) decreases the production temperature from 88.42 °C to 73.14 °C, corresponding to a 17.28 % reduction. This reduction also leads to noticeable decreases in energy output, where the thermal power drops by 19.53 % and the electric power by 23.37 % compared with the intact case. The results further indicate that larger damage zones produce greater performance losses. In contrast, radial damage surrounding the borehole causes slightly stronger reductions than depth-wise damage due to increased thermal resistance to heat flow. These findings demonstrate the importance of incorporating experimentally measured thermo-physical properties of thermally shocked rock into Thermo-Hydraulic (TH) models of HDR geothermal systems.

Keywords

Thermal-shock damage, Thermo-physical properties, Hot dry rock, Layered rock mass, Thermo-hydraulic response.

1 Introduction

Geothermal energy is increasingly recognised as a reliable and low-carbon resource capable of providing continuous heat and power. Conventional geothermal development through hydrothermal systems and Enhanced Geothermal Systems (EGS) relies on circulating fluids through naturally permeable or hydraulically stimulated reservoirs. Although technically established, these approaches may involve induced seismicity, scaling, water management issues and high drilling costs. As an alternative, closed-loop geothermal systems (CLGS) have received growing attention because the working fluid circulates within sealed pipes and heat is extracted from the surrounding formation primarily through conduction (Caulk and Tomac, 2017).

Early investigations of CLGS mainly focused on U-shaped well configurations. Song et al. (2018) demonstrated that parameters such as flow rate, inlet temperature and horizontal section length significantly influence production temperature behaviour, while Ma et al. (2023) highlighted the role of insulation length and well configuration in determining long-term performance. To enhance heat extraction, modified system geometries have also been explored. For example, Chappidi et al. (2024a) proposed a combined coaxial–U-shaped configuration and later a hybrid design that further improved thermal performance (Chappidi et al., 2024; Chappidi et al., 2023).

Coaxial borehole heat exchangers (CBHE) have also been widely investigated due to their relatively low hydraulic resistance and improved flow characteristics. Zanchini et al. (2010a, 2010b) showed that thermal short-circuiting between inner and outer pipes can influence system efficiency and that flow configuration plays an important role in reducing internal heat losses. Numerical studies by Holmberg et al. (2016) and optimisation analyses by Wang et al. (2025) further indicated that borehole depth and operating conditions strongly affect sustainable heat extraction.

Despite extensive work on closed-loop geothermal systems and deep borehole heat exchangers, most studies assume homogeneous rock properties around the borehole. In Hot Dry Rock (HDR) environments, rapid cooling during geothermal operation can induce thermal-shock damage, which alters the thermal conductivity and heat capacity of the surrounding rock. Although laboratory experiments have reported these changes, their spatial influence near the wellbore and their impact on geothermal heat extraction are rarely incorporated into Thermo-Hydraulic (TH) models.

To address this limitation, the present study develops a TH numerical model for a closed-loop HDR geothermal system in which experimentally measured thermo-physical properties of thermally shocked rock are incorporated. The damaged region surrounding the borehole is represented using radial multi-layer and depth-wise multi-layer configurations to capture the spatial distribution of thermal-shock damage. This modelling approach enables evaluation of the effects of progressive rock damage on outlet temperature behaviour and long-term geothermal energy extraction.

2 Methodology

The methodology adopted in this study integrates laboratory experimentation with Thermo-Hydraulic (TH) numerical modelling to evaluate heat extraction from a closed-loop HDR geothermal system.The overall workflow followed in this research is illustrated in Figure 1. Thermo-physical properties of granite subjected to rapid thermal-shock treatments were first experimentally determined to represent progressive damage states. Rock samples were heated to different temperatures and rapidly quenched, and the resulting thermal conductivity, density, and heat capacity were measured. These experimentally derived properties were subsequently incorporated into the numerical framework to represent spatially varying rock conditions around the borehole. This approach enables the model to realistically capture the influence of thermal-shock damage on geothermal heat transfer behaviour.

3 Thermo-Physical Characterization of Thermally Shocked Granite

Thermo-physical properties of granite subjected to thermal shock were obtained from the experimental investigation reported by Kalanji et al. (2025). In that study, rock specimens were heated to different target temperatures and rapidly quenched in water to simulate thermal shock conditions representative of geothermal operations. The rapid cooling induces micro-cracking and mineral expansion mismatch, resulting in progressive damage to the rock matrix. After each treatment, key thermo-physical parameters including thermal conductivity, density, and specific heat capacity were measured. These

experimentally determined properties represent different damage states and were subsequently incorporated into the numerical model to simulate spatial variations in rock behaviour around the borehole. The intact condition (T-25) was used as the reference case, while thermally shocked samples at higher temperatures represent progressively damaged rock states.

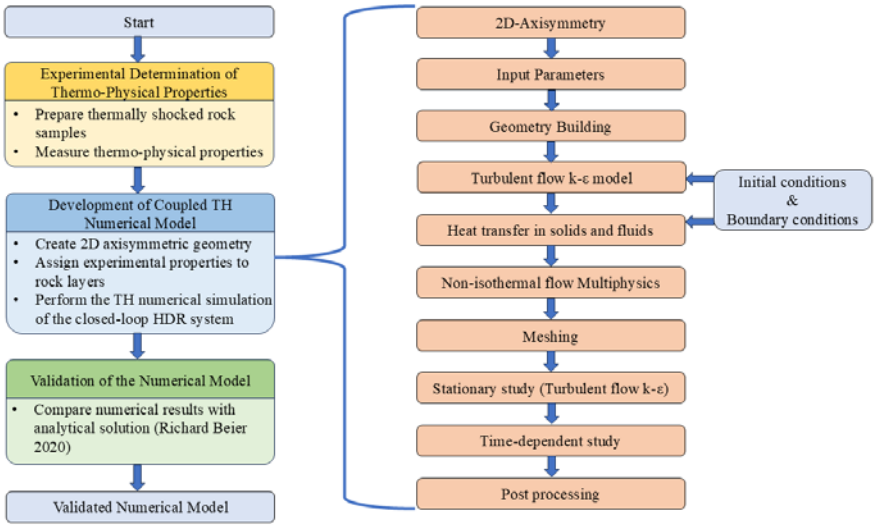


Fig. 1 Methodological framework for experimental characterization and Thermo-Hydraulic numerical modelling of the closed-loop HDR geothermal system.

Table 1. Thermo-physical properties of granite after thermal-shock treatment (Kalanji et al., 2025).

Rock Condition	Thermal Conductivity (k)[W/m·K]	Density (ρ)[kg/m³]	Specific Heat Capacity (Cp)[J/kg·K]
T-25(Intact Granite)	2.72	2653.8	652.11
T-200	2.55	2644.5	702.19
T-400	2.37	2620	760.57
T-600	1.74	2579.5	787.71
T-800	1.44	2549	810.80

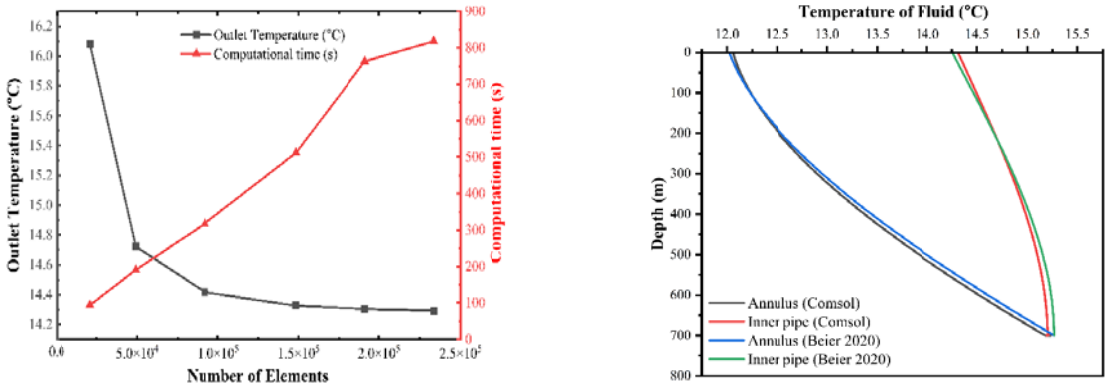
4 Validation of the Thermo-Hydraulic Numerical Model

The developed Thermo-Hydraulic (TH) numerical model was validated against the analytical solution proposed by Beier (2020) for a coaxial borehole heat exchanger with a depth of 700 m under identical operating conditions. Before validation, a grid independence study was conducted in which the outlet temperature at 100 h was used as the convergence parameter. The computational domain was discretized using a structured mapped mesh in the BHE domain to accurately resolve the axial and radial gradients of the fluid flow, while the surrounding rock domain was discretized using an unstructured triangular mesh to efficiently represent the larger geological region. The mesh convergence behaviour is presented in Figure 2(a), where the outlet temperature stabilizes with increasing element density while computational cost increases. Based on this analysis, Mesh-4 was selected as the optimal grid configuration. The temperature distribution along the borehole depth predicted by the TH model shows very good agreement with the analytical solution of Beier (2020), as illustrated in Figure 2(b). This close agreement confirms the accuracy of the numerical implementation and demonstrates that the adopted TH modelling procedure is capable of reliably predicting the thermal behaviour of the borehole heat exchanger system.

5 Numerical Simulation Scenarios

After validating the Thermo-Hydraulic (TH) numerical model, a series of simulations were conducted to investigate the influence of thermally induced rock damage on geothermal heat extraction performance. The experimentally determined thermo-physical properties corresponding to different thermal-shock treatments (T-25, T-200, T-400, T-600, and T-800) were assigned to the rock domain to represent progressive damage conditions around the borehole. In the numerical model, it was assumed that the damaged rock zones are uniformly distributed around the borehole, both in the radial and depth directions, allowing the effect of spatial damage distribution to be systematically evaluated. The

circulating working fluid was considered to be water, and its thermo-physical properties were taken from the built-in material database of COMSOL Multiphysics. The geometric parameters of the borehole system and the thermo-physical properties of the casing steel, insulation, and working fluid used in the model are summarized in Table 2.



(a) (b)

Fig.2(a) Grid independence study showing the variation of outlet temperature and computational time with the number of elements at 100 h. (b) Comparison of temperature distribution along borehole depth between the developed TH numerical model and the analytical solution of Beier (2020).

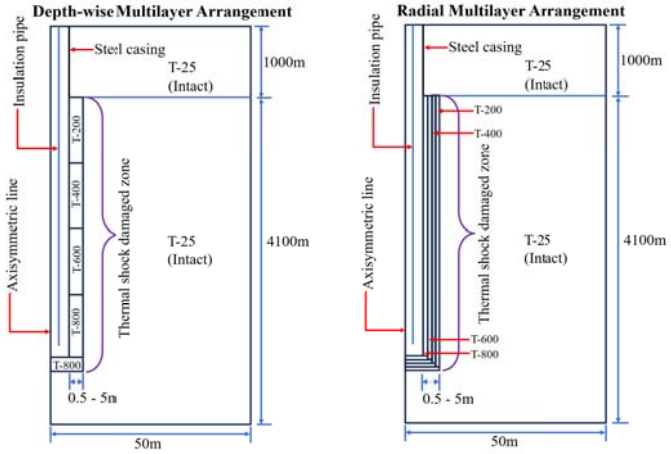


Fig. 3 Schematic representation of depth-wise and radial multilayer thermal-shock damage configurations surrounding the geothermal borehole used in the numerical simulations.

Two representative damage configurations were considered to examine the spatial influence of thermally altered rock properties surrounding the borehole as shown in Figure 3.

The thermal power extracted from the system is calculated as:

$$Q_{th} = \dot{m} * C_p * (T_{prod} - T_{inj}) \quad (1)$$

Where Q_{th} Thermal power (W)
$\dot{m}$ Mass flow rate (kg/s)
C_p Specific heat capacity of water (J/kg·K)
T_{prod} Production temperature (°C)
T_{inj} Injection temperature (°C)

The electric power is estimated from the available thermal power as:[Mohaman and Lee (2025)]

$$P_{el} = 0.45 * \left(\frac{T_{prod} - T_{inj}}{T_{prod} + T_{inj}}\right) * Q_{th} \quad (2)$$

Where P_{el} Electric power (W)
0.45 Maximum effective utilization coefficient of mechanical work into electricity

6 Results and Discussion

Figure 4 shows the variation of production temperature, thermal power and electric power for the different thermal-shock damage configurations analysed in this study. A broadly similar trend can be observed for all the simulated cases. As seen in Figure 4(a), the production temperature decreases rapidly during the early stage of operation. This behaviour is mainly associated with the extraction of heat from the rock located close to the borehole. At the beginning of circulation, the temperature difference between the injected fluid and the surrounding formation is large, which promotes strong heat transfer. With continued operation, the rock in the near-well region gradually cools. As a result, the heat stored in this region becomes limited. Heat must therefore be supplied from the surrounding formation through conduction. Since conductive heat transfer occurs over larger distances, the rate of temperature decline becomes slower. After long operating periods, the system tends to approach a relatively stable thermal condition.

Table 2. Geometry, material Properties and operating condition used in the TH Numerical Model.

Category	Parameter	Value	Unit
Geometry	Borehole depth	5000	m
	Radial rock domain	50	m
	Bottom rock extension	100	m
	Outer pipe radius	0.0689	m
	Outer pipe height	4999	m
	Inner pipe radius	0.0381	m
	Inner pipe height	4999	m
Casing Steel	Thickness	0.0092	m
	Density (ρ)	7850	kg/m³
	Specific heat capacity (Cp)	465	J/kg·K
	Thermal conductivity (k)	48.75	W/m·K
Insulation	Thickness	0.01	m
	Density (ρ)	55	kg/m³
	Specific heat capacity (Cp)	1210	J/kg·K
	Thermal conductivity (k)	0.03	W/m·K
Reservoir Condition	Geothermal gradient	30	°C/km
Operating Conditions	Mass flow rate	2	kg/s
	Injection temperature	10	°C
Working Fluid	Fluid type	Water	—
	Thermophysical properties	Built-in COMSOL material library	—

A clearer difference appears when the various damage configurations are compared. From Figure 4(a), it can be observed that the intact rock case (T-25) maintains a production temperature of approximately 88.42 °C after 25 years of operation. In contrast, the severe damage case (T-800 with a 5 m damaged zone) shows a temperature of 73.14 °C, corresponding to a 17.28 % reduction. For the smaller 0.5 m damage thickness, the reductions are 6.47 %, 8.92 % and 9.73 % for the depth-wise multilayer, radial multilayer and T-800 configurations, respectively. When the damaged region increases to 5 m, the reductions become 11.02 %, 14.50 % and 17.28 %. This observation indicates that a thicker damaged zone around the borehole introduces additional thermal resistance, thereby reducing heat transfer from the surrounding rock.

A comparable tendency can be observed in the thermal power results, as illustrated in Figure 4(b). The intact system produces around 655.04 kW of thermal power. When severe thermal damage is considered (T-800, 5 m), the output decreases to 527.12 kW, representing a 19.53 % reduction. The same pattern also appears in the electric power output, shown in Figure 4(c). In this case, the power decreases from 233.84 kW for the intact system to 179.19 kW for the severely damaged configuration, which corresponds to a 23.37 % reduction. These observations suggest that the extent of thermally damaged rock near the borehole plays an important role in determining the overall geothermal energy extraction performance.

Overall, the results indicate that both the size of the damaged region and its spatial distribution influence the system behaviour. Radial damage located around the borehole tends to produce slightly

larger reductions in performance. This is expected because heat flowing toward the well must pass through the damaged region, thereby increasing thermal resistance and limiting heat transfer from the surrounding formation.

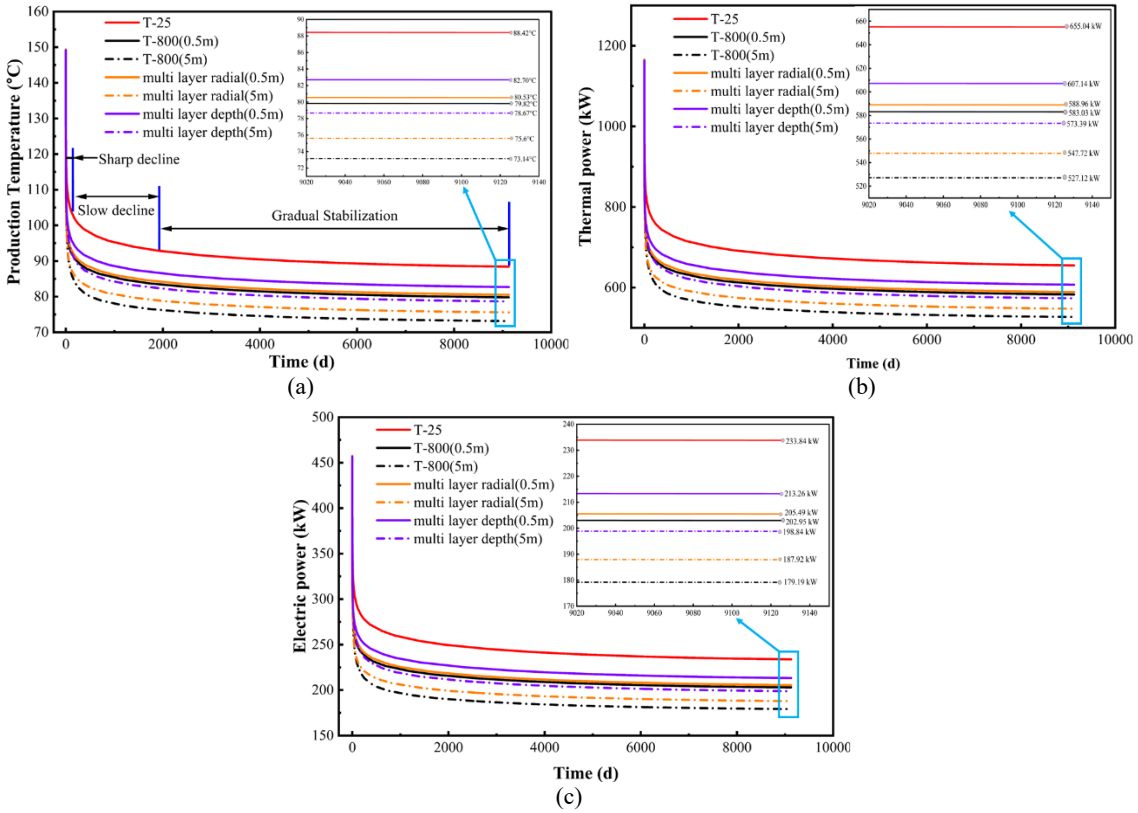


Fig. 4 Temporal evolution of (a) production temperature, (b) thermal power, and (c) electric power for different thermal-shock damage configurations in the geothermal system.

7 Conclusions

This study examined the effect of thermal-shock–induced rock damage on the performance of a closed-loop HDR geothermal system using a validated Thermo-Hydraulic (TH) numerical model. The simulation results show that the production temperature decreases rapidly during the early stage of operation due to the cooling of the rock close to the borehole. As operation continues, the temperature decline becomes slower and eventually approaches a stable condition as heat is supplied from the surrounding formation through conduction. The presence of thermal-shock damage reduces the long-term heat extraction efficiency because micro-cracking in the rock decreases its effective thermal conductivity.

Compared with the intact condition (T-25), the severe damage case (T-800 with a 5 m damaged zone) reduces the stabilized production temperature from 88.42 °C to 73.14 °C, corresponding to a 17.28 % decrease. A similar reduction is observed in the energy output. The thermal power decreases from 655.04 kW to 527.12 kW (19.53 %), while the electric power decreases from 233.84 kW to 179.19 kW (23.37 %). The results further indicate that increasing the size of the damaged region leads to greater performance loss. In addition, radial damage around the borehole produces slightly larger reductions than depth-wise damage because it increases the thermal resistance for heat transfer from the surrounding rock toward the well. Overall, these results highlight the need to incorporate experimentally measured thermo-physical properties of thermally shocked rock when predicting the long-term performance of HDR geothermal systems.

Acknowledgement

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