geoconvention
Calgary • Canada • May 11-13 2026

Evaluation of Heat Transfer across Matrix and Micro-Fractures in Enhanced Geothermal Systems

Mahsa Parhizgar Keradeh, Saeid Khasi, Apostolos Kantzas
Department of Chemical and Petroleum Engineering, University of Calgary

Summary

In enhanced geothermal systems (EGS), total energy extraction is controlled by heat exchange across interface of heat source rock and induced fractures. Such heat exchange can be predicted by different modeling approaches for heat transfer on the fracture matrix wall. In fully resolved 3D models of fractured systems, outlet temperatures of an isolated fracture can be accurately reproduced without relying on predefined heat transfer coefficients between the fracture and matrix. However, this approach is not feasible for field-scale simulations due to the extreme mesh requirements and computational cost. To enable field-scale modeling, the fracture is often simplified as a 2D internal surface embedded within a 3D porous rock matrix. This dimensional reduction simplification introduces the need for a heat transfer coefficient to model energy exchange between the fracture and the surrounding rock. In this study, we developed a representative 3D cylindrical core model with a 2D fracture and demonstrated that matching the experimental outlet temperature requires introducing a heat transfer coefficient. Using an overall heat transfer coefficient value derived from experimental inlet and outlet temperatures allows accurate matching, but it makes the model dependent on measured data. To build a predictive model, heat transfer coefficient must instead be calculated independently using dimensionless correlations such as Nusselt, Reynolds, and Prandtl numbers. Therefore, several dimensionless correlations were tested to compute the heat transfer coefficient independently. It was found that conventional Nusselt-based correlations typically developed for millimeter-scale hydraulic diameters significantly overestimated the heat transfer in micro-aperture fracture geometry. To resolve this limitation, a new specific Nusselt number correlation was proposed and validated, yielding significantly improved thermal predictions across a range of flow rates.

Method

Numerical simulations were conducted using developed models of fluid flow and heat transfer in a fractured granite core with a micro-scale aperture. The objective was to evaluate the accuracy of conventional Nusselt-based correlations in predicting fracture–matrix heat exchange at the micro-scale.

The model geometry replicates a 10 cm × 5 cm cylindrical granite core containing a single, horizontally oriented planar fracture with an aperture of 6.8 µm. To reduce computational demands while preserving physical realism, the fracture was simplified as a 2D internal surface embedded within a 3D porous rock matrix. This dimensional reduction is essential for developing scalable field-scale geothermal models, where resolving full 3D fracture domains would otherwise require prohibitively fine meshes and excessive computational cost.

Water was used as the working fluid, injected at 25 °C into the fracture. The surrounding granite matrix was maintained at a uniform temperature of 70 °C, establishing a thermal gradient for heat

transfer. Simulations were performed at flow rates up to 20 mL/min to match experimental conditions. The primary geometric and thermal parameters are summarized in Table 1.

Table 1. Summary of simulation input parameters.

Parameter	Value	Unit
Fracture aperture	6.8	μm
Fracture width	50	mm
Fracture length	100	mm
Matrix temperature	70	°C
Fluid inlet temperature	25	°C
Flow rate	20	mL/min
Fluid density	983	kg/m³
Rock density	2650	kg/m³
Fluid Heat capacity	4180	J/kg·K
Rock Heat capacity	790	J/kg·K
Fluid dynamic viscosity	4.6×10^{-4}	Pa·s
Fluid Thermal conductivity	0.65	W/m·K

The simulation incorporated four coupled physics interfaces: heat transfer in fracture, heat transfer in porous media, fluid flow in fracture, and Darcy's Law. These physics were coupled to enable simultaneous solution of the thermal and hydraulic fields and allow interaction between the fracture and surrounding rock. The model was solved in COMSOL Multiphysics.

In the simplified model, where the fracture is represented as a 2D internal surface, heat exchange across the fracture–matrix interface is not inherently resolved. As a result, initial simulations without an interfacial heat transfer coefficient produced unrealistic outlet temperature predictions, indicating insufficient representation of energy exchange across the fracture–matrix interface. To address this limitation, a heat transfer coefficient was applied as a boundary condition along the fracture–matrix interface. Two approaches were investigated to define this coefficient:

1. Overall Heat Transfer Coefficient

In the first approach, an overall heat transfer coefficient was calculated directly from the experimental data using the measured inlet and outlet temperatures, as expressed in Eq. (1).

$$h = \frac{\rho c_p q (T_{\text{out}} - T_{\text{in}})}{D_0 L \left(T_c - \frac{T_{\text{out}} + T_{\text{in}}}{2}\right)} \quad (1)$$

Where h is heat transfer coefficient, ρ is density of water, c_p specific heat capacity of water, q is volumetric flow rate, T_{in} and T_{out} are inlet and outlet fluid temperatures, T_c is constant rock temperature, D_0 is fracture width and L is the fracture length. This calibrated value was applied as a boundary condition and served as a reference for comparison with predictive models.

2. Predictive Heat Transfer Coefficients from Nusselt-Based correlations

In the second approach, predictive heat transfer coefficients were obtained independently from published Nusselt number correlations commonly used for laminar flow in narrow channels and fracture-like geometries. The heat transfer coefficient was evaluated using the following correlation.

$$h = \frac{Nu\, k_f}{D_h} \tag{2}$$

Where Nu is the Nusselt number, k_f is the thermal conductivity of the fluid, and D_h is the hydraulic diameter of the fracture. All fluid properties and flow parameters required for these calculations were taken directly from the numerical model and experimental conditions. Table 2 summarizes the Nusselt number correlations evaluated in this study. Although these correlations are widely used in geothermal and fracture-flow modeling, they were originally developed for fractures or channels with millimeter-scale hydraulic diameters. As shown in the table, the fracture aperture ranges for these correlations vary from 0.1 to 1.5 mm, which is orders of magnitude larger than the 6.8 μm aperture used in this study. Therefore, their direct application to micro-scale fracture systems is questionable and requires validation. For each correlation, the corresponding heat transfer coefficient was calculated and applied to the model under consistent conditions, and the resulting outlet temperatures were compared.

Table 2. Calculated heat transfer coefficients based on selected Nusselt number correlations.

No.	Nu Expression	Range of Fracture Aperture	Reference
1	$Nu = 0.94 \times Re^{1.23} Pr^{\frac{1}{3}}$	0.3-0.9 mm	(Zhang et al. 2020)
2	$Nu = 0.0046 \times Re^{1.15} Pr^{\frac{1}{3}}$	0.1-0.5 mm	(Li et al. 2024a)
3	$Nu = 1.67 \times Re^{0.3} Pr^{\frac{1}{3}} (\frac{\lambda_w}{\lambda_b})^{-7.35} (\frac{\rho_w}{\rho_b})^{-1.33}$	0.2 mm	(Li et al. 2024b)
4	$Nu = 0.664 \times Re^{\frac{1}{2}} Pr^{\frac{1}{3}}$	mm-scale fracture	(Ma et al. 2018)

Results

The effect of different definitions of the fracture–matrix heat transfer coefficient on predicted outlet temperatures is illustrated in Figure 1, which compares the following four cases:

1) The experimentally measured outlet temperature,
2) The simulation result without any applied heat transfer coefficient,
3) The simulation result using the calibrated overall heat transfer coefficient,
4) Multiple simulations using heat transfer coefficient values derived from five different Nusselt-based empirical correlations.

These comparisons highlight the sensitivity of thermal predictions to the choice of heat transfer coefficient and reveal the limitations of commonly used empirical models when applied to micro-scale systems.

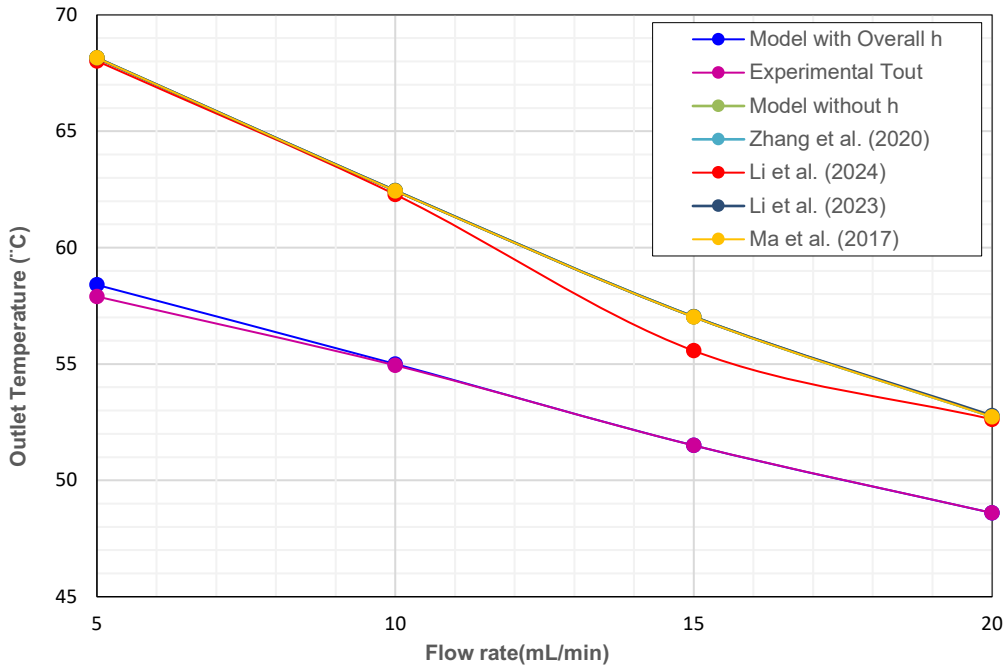


Fig.1. Comparison of outlet fluid temperatures predicted by different modeling approaches

1. Overall Heat Transfer Coefficient

As shown in Fig. 1, the simulation that used a calibrated overall heat transfer coefficient produces an outlet temperature that closely matches the experimental measurement. This result demonstrates that the simplified 2D fracture–3D matrix configuration can accurately reproduce the observed thermal response. The agreement also validates the selected geometry, boundary conditions, and multiphysics coupling strategy. However, because this approach relies on prior experimental data, it lacks predictive capability and is not suitable for forward modeling or field-scale simulations, where such measurements are typically unavailable.

2. Correlation-Based Heat Transfer Coefficients

Using the dimensionless-based correlations introduced in the Method section, a range of heat transfer coefficients was calculated for Reynolds and Prandtl numbers representative of the simulated flow regime (Re ≈ 7-30). The resulting coefficients, ranging from approximately 3.4×10^3 to 5×10^6 W/m^2·K, were applied at the fracture–matrix interface to assess their predictive performance. Although all correlations were applied within their nominal validity ranges under idealized assumptions (laminar flow through a smooth, planar fracture), the predicted outlet temperatures varied substantially. This discrepancy is attributed to the fact that these correlations were originally developed for fractures or channels with millimeter-scale apertures and do not

accurately capture heat transfer behavior in micro-scale fractures such as the one modeled in this study.

This variability underscores the strong sensitivity of thermal predictions to the definition of the interfacial heat transfer coefficient and suggests that conventional Nusselt-based correlations may not be sufficiently accurate for modeling fracture–matrix heat exchange at the micro-scale. This limitation is particularly significant in fractured geological media, where localized conduction, narrow flow paths, and coupled thermal interactions dominate heat transfer processes. In EGS, stimulation commonly generates networks of micro-scale fractures that exert primary control on fluid circulation and heat extraction. Consequently, accurately representing heat transfer within these micro-scale fractures is essential for reliable reservoir-scale thermal modeling and long-term performance assessment.

Proposed Correlation

To improve the accuracy of thermal modeling in fractured granite cores with micro-scale apertures, a new Nusselt number correlation was derived through inverse modeling:

$$Nu = 1.50 \times 10^{-4}\, Re^{1.15}\, Pr^{1/3} \tag{3}$$

This formulation is tailored to laminar flow in micro-scale planar fractures embedded in high-conductivity granite and is valid within the investigated Reynolds ranges.

Compared to traditional correlations developed for millimeter-scale fractures, the proposed expression has a significantly lower scaling factor, reflecting the reduced role of convective enhancement and the dominance of conduction in narrow fractures. Although the functional form in terms of Reynolds and Prandtl numbers remains similar, using mm-scale correlations for microscale systems leads to a systematic overestimation of interfacial heat transfer. The proposed correlation provides a better match with experimental outlet temperatures and is more suitable for modeling fracture–matrix heat exchange in EGS.

Novel/Additive Information

This study demonstrates that conventional Nusselt number correlations, while commonly used in geothermal heat-transfer models, need to be scaled appropriately to accurately capture fracture–matrix heat exchange at the micro-scale. To overcome this limitation, specific Nusselt number correlations can be developed, tailored to narrow-aperture fractures in granite. The presented scaled formulation improves predictive accuracy and offers a more physically consistent approach for modeling micro-fracture behavior in EGS.

Acknowledgements

Financial support from the Energi Simulation Centre for Geothermal Systems Research, The Energy Harvesting Processes Program (NSERC, Mitacs, ConocoPhillips, Kalina Distributed Power, Telsec, Remedy Services, The Alberta Geological Survey and The Geological Survey of Canada) and the Fundamentals of Unconventional Resources program (NSERC, Alberta Innovates, Chevron, CNRL, ConocoPhillips and Enerplus) is gratefully acknowledged.

AI-assisted Editing Statement

An AI-based tool was used solely for grammar checking and language refinement. The scientific content, analysis, and conclusions were developed and verified entirely by the authors.

References

Zhang X, Wang Z, Sun Y, Zhu C, Xiong F, Tang Q. Numerical Simulation on Heat Transfer Characteristics of Water Flowing through the Fracture of High-Temperature Rock. Geofluids. Hindawi Limited; 2020.

Li D, Liu G, Liao S. Study on Flow and Heat Transfer in Single Rock Fractures for Geothermal Heat Extraction. Processes. Multidisciplinary Digital Publishing Institute (MDPI); 2024a Feb 1;12(2).

Li J, Ma W, Jiang P, Xu R. Heat transfer characterizations of water flow through a single fracture with integrating water dissolution effects for the Enhanced Geothermal Systems. Appl. Therm. Eng. Elsevier Ltd; 2024b Feb 15;239.

Ma Y, Zhang Y, Yu Z, Huang Y, Zhang C. Heat transfer by water flowing through rough fractures and distribution of local heat transfer coefficient along the flow direction. Int. J. Heat Mass Transf. Elsevier Ltd; 2018 Apr 1;119:139–47.