Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Artificial Intelligence-Coupled CFD Optimization of a Helical Borehole Heat Exchanger: Effects of Key Parameters and Thermal Design Constraints on Thermal Performance

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Keywords: Ground heat exchanger (GHE); Helical borehole heat exchanger (HBHE); Conjugate heat transfer; Computational fluid dynamics (CFD); Deep learning; Optimization; Thermal efficiency; Parametric analysis; Sustainable heating and cooling

ABSTRACT

Ground heat exchangers (GHEs), particularly compact and efficient helical borehole type heat exchangers (HBHEs), enable year-round renewable heating and cooling by utilizing stable subsurface temperatures, offering higher thermal performance and lower spatial impact than conventional systems—crucial for sustainable, space-limited urban energy solutions. Despite progress in GHE research, HBHE studies lack design optimization using comprehensive datasets. Existing works often ignore combined effects of helical aspect ratio (D/L), where D is the diameter and L is the vertical length of the BHE, soil conductivity (k_soil), number of helical turns (N), and inlet fluid temperature (T_in). The present study therefore fills the gap by coupling computational fluid dynamics (CFD) simulation dataset with a Deep Learning based optimization algorithm to maximize the thermal efficiency of the HBHE. With this coupled approach, a comprehensive analysis of combined effects of such parameters on thermal efficiency is successfully made while identifying key constraints, enabling efficient, predictive heat extraction modelling. Conjugate heat transfer phenomenon in the HBHE is simulated in transient manner using a multi-physics finite element fluid flow solver under varying conditions. Feature importance analysis identifies critical design constraints for optimization. The results show that D/L, k_soil, N, and T_in significantly affect the HBHE thermal performance. Tighter helicals increase surface area and heat extraction rate. Soil conductivity dominates in low-flow conduction regimes. The initial inlet temperature captures inlet-ground interaction, indicating responsiveness. The deep learning model exceeds 95% accuracy, identifying D/L and T_in as most sensitive. Findings reveal complex parameter interdependencies shaping thermal behavior of HBHE structure.

1 INTRODUCTION

The rapid increase in global energy demand and the growing awareness of the environmental impacts of energy consumption necessitate the design of energy systems with higher efficiency, sustainability, and innovative approaches. In this context, the importance of ground heat exchangers that enhance the performance of energy systems has been increasingly recognized. Ground-coupled systems can be used for both heating and cooling due to stable subsurface temperatures, reducing environmental impacts and providing long-term energy savings. However, traditional vertical and horizontal BHE systems may be limited in certain applications because of their large space requirements and cost disadvantages. In contrast, HBHEs have become a significant alternative in recent years due to their compact configuration and cost-effective performance (Cui and Zhu, 2018; Huang et al., 2020).

A review of the existing literature on HBHEs reveals that various parameters affecting the performance of helical configurations have mostly been studied individually. For instance, Congedo et al. (2012) examined the effects of geometric parameters such as helical pitch, height, and diameter on energy efficiency, reporting that increasing the helical diameter enhances heat transfer efficiency by enlarging the soil contact area. Dasare and Saha (2015) conducted an experimental study using a 20 m long pipe with a fixed helical diameter (1.0 m) and pitch (0.2 m), forming a helical with approximately six turns. Their results indicated that increasing the number of turns enhances heat exchange with the ground but simultaneously increases the pressure losses in the working fluid. However, since the parameters were not nondimensionalized, systematic comparisons could not be made. Kim et al. (2016) modeled the temperature gradient distribution in a laboratory-scale HBHE setup in detail and showed that such systems provide more stable heat distribution compared to conventional straight-

pipe systems in low-temperature applications. Jeon et al. (2018) performed a time-dependent finite element analysis of HBHEs using COMSOL Multiphysics under 108 different scenarios that considered climatic and soil factors, but their work was restricted to a limited range of geometries and lacked a broad parametric exploration. Serageldin et al. (2021) carried out a multi-objective optimization for a double-helical BHE by considering parameters such as helical geometry, pipe length, flow rate, and burial depth. However, since their analysis did not employ dimensionless parameters, the generalizability of the results remained limited. Roy et al. (2024) analyzed 17 different helical configurations both experimentally and numerically by considering geometric variables such as helical diameter, pitch, and number of turns. In their analyses, performed with helical diameters ranging from 1.0 m to 1.5 m and between 20 and 40 turns, up to 20 % improvement in heat transfer performance was observed. However, the study did not include time-dependent solutions; the thermal behavior of the soil was assumed to be static, and analyses were carried out under fixed boundary conditions.

Recent studies have focused on three main strategies to improve the thermal performance of GHEs i) geometric design optimization; ii) enhancement of thermo-physical properties through phase change materials, and iii) hybrid system integration (Faizal et al., 2016; Wang et al., 2024). Despite these advances, a significant research gap remains in the comprehensive parametric optimization of HBHEs using extensive datasets.

In the literature, the inlet temperature parameter has generally been assumed constant, and its influence on system performance has often been neglected. Only a very limited number of studies have examined the effect of inlet temperature on soil heating; however, this parameter has not been systematically evaluated in terms of time-dependent system efficiency or total heat transfer performance. The lack of detailed analysis of the transient heat transfer behavior of these systems restricts the generalizability of design decisions. This indicates that multidimensional and interactive analyses of dynamic parameters affecting the performance of HBHEs have not been adequately addressed in the literature. Focusing on these identified research gaps, the present project aims—at the first stage—to investigate for a single vertical HBHE the simultaneous and combined effects of the helical aspect ratio, number of helical turns, soil thermal conductivity, and initial inlet temperature difference on the overall energy performance for the first time.

2 METHODOLOGY

In this study, three different heat and mass transfer phenomena are coupled and modeled using the computational fluid dynamics (CFD) methodology: three-dimensional heat and mass transfer through soil (porous medium), one-dimensional conductive heat transfer along the heat exchanger tube wall, and one-dimensional convective heat transfer of the fluid flowing inside the tube. Within this context, using different values within the determined ranges of design parameters, a time-dependent solution is obtained through a multi-physics finite element fluid flow solver (COMSOL Multiphysics). A multi-dimensional computational dataset is generated for optimal design and/or design improvement conditions. This dataset is then used to validate a Temporal Fusion Transformer (TFT)-based deep learning surrogate model, which is developed and trained to replace computationally expensive CFD simulations for future HBHE performance prediction with larger dataset.

2.1 Governing Equations

The fluid convection inside the helical pipe is resolved using the following governing flow equations for incompressible fluid:

$$\nabla . \boldsymbol{u} = 0 \tag{1}$$

$$\rho \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} . \nabla \boldsymbol{u} \right) = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} \tag{2}$$

where ρ is the fluid density, $\boldsymbol{u}$ is the fluid velocity vector, μ is the absolute viscosity, p is the pressure, t is the time, and $\boldsymbol{g}$ is the gravitational vector. The transient heat equation on the hand is solved using the following equation for incompressible fluid:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \boldsymbol{u} . \nabla T \right) = \nabla . (k . \nabla T) + Q \tag{3}$$

where c_p is the specific heat capacity at constant pressure, T is the temperature, k is the thermal conductivity and Q is the heat source other than viscous heating.

2.2 Computational Principals

2.2.1 Model Geometry and Computational Domain

Figure 1a illustrates the model geometry of a multi-physics volume of the HBHE system consisting of a three-dimensional pipe representing the helical heat exchanger, the heat transfer fluid, and the ground (soil). The basic model geometry is created with a ground diameter of 40 m and length of 20 m with a helical pipe structure placed in the ground between 2 m and 6 m from the ground surface in accordance with the system geometry utilized in the study of Dehghan (2017). Figure 1b illustrates the three-dimensional computational domain and the corresponding mesh configuration generated with non-uniform tetrahedral mesh cells. A higher local mesh resolution is used in the vicinity of the helical pipe surface to accurately determine the temperature gradients between the ground and pipe surface while less dense mesh elements are used for the rest of the computational domain. The minimum and maximum mesh cell sizes are 0.06 m and 1.75 m, respectively for the optimal mesh configuration.

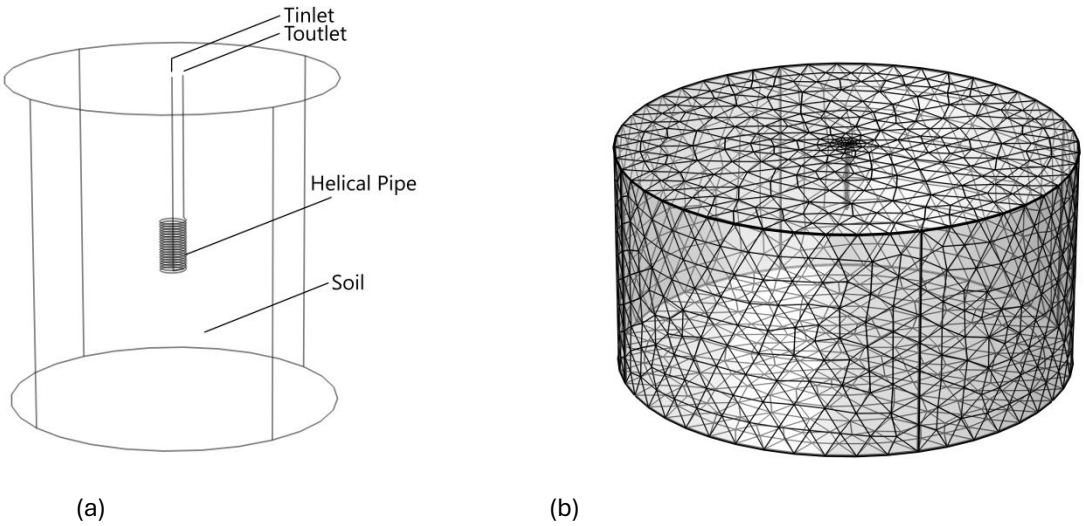


Figure 1. Three-dimensional model set up, a) Model geometry; b) Computational domain

2.2.2 Working and Boundary Conditions

Table 1 summarizes the working and boundary conditions of the baseline design model which are imposed in accordance with the experimental data.

Table 1. A summary of working and boundary conditions of the baseline design model of HBHE.

Conditional parameters	Value
Volumetric flow rate	15 L/min
Average inlet fluid temperature	50.7 °C
Average outlet fluid temperature	49.3 °C
Average fluid temperature	50 °C
Initial temperature of the system	18 °C
Average undisturbed uniform ground temperature	18 °C
Simulation period	150 h

2.2.3 Modelling Setup and Assumptions

Since the settings of the fluid flow/heat transfer solver developed within the computational modeling approach directly affect the stability, accuracy, and convergence of the planned multi-parametric simulations, preliminary simulation tests are conducted under different solver configurations and related computational parameter values, also considering the sensitivity of mesh resolution. In these simulations, the non-linear fundamental conservation equations are transformed into equivalent algebraic equations for each computational element within the discretized computational domain and solved under the assumptions using a discretized approach within the solver environment that i) the soil and heat exchanger pipe materials are assumed to be isotropic; ii)the interface surface between the heat exchanger pipe and the soil satisfy the continuity conditions of

temperature and heat flux; iii) the heat transfer mechanism is modeled by coupling the convective heat transfer between the heat transfer fluid and the inner surface of the pipe with the conductive heat transfer between the soil and the outer surface of the pipe (conjugate heat transfer analysis); iv) laminar flow conditions are assumed; v) adiabatic boundary conditions are applied to all external surfaces (heat losses from the soil to the external environment are neglected); vi) energy transport within the pipe flow is modeled using the "Heat Transfer in Pipes" module available in the fluid flow/heat transfer solver environment, considering only the axially directed energy transport (1D axial approach). This allows the computation to be performed with reduced solution time and memory consumption without the need for fully 3D flow domain modeling. The circumferential effects of the pipe is integrated into the model through the "Wall Heat Transfer" component; vii) the solid domains (soil and pipe body) are modeled using the "Heat Transfer in Solids" physics interface within the fluid flow/heat transfer solver, where only conductive heat transfer is considered. The variation of thermophysical properties with temperature in these regions are neglected; viii) boundary conditions are defined as adiabatic on the outer surfaces, and constant temperature conditions are imposed at the pipe inlet and outlet. With this approach, heat exchange between the system and the external environment is ignored.

2.3 Optimization Algorithm

A Temporal Fusion Transformer (TFT)-based deep learning surrogate model is developed to replace computationally expensive CFD simulations for helical type ground heat exchanger performance prediction. The model is trained on 800 parametric CFD simulations to predict time-dependent outlet temperature and heat transfer rate across complete operational time series. This TFT architecture with 3.5 million parameters achieves high accuracy while delivering predictions approximately 10^5 times faster than traditional CFD approaches, making it suitable for future multi-objective design optimization studies.

The overall methodology is illustrated in Figure 2, which includes the complete workflow from CFD data collection through pre-processing and model training to a final evaluation. The model architecture utilizes bidirectional Long short-term memory (LSTM) layers with 160 hidden units and a 4-head attention mechanism to capture temporal heat transfer dynamics from transient to steady-state regimes. Five static parameters (helical radius, number of turns, soil thermal conductivity, soil temperature, and inlet temperature) combined with time as dynamic input are processed through variable selection networks. The model generates three quantile outputs at P10, P50, and P90 levels, providing uncertainty intervals for risk assessment. Training employs AdamW optimizer with mixed precision training, learning rate scheduling, and gradient clipping to prevent over-fitting.

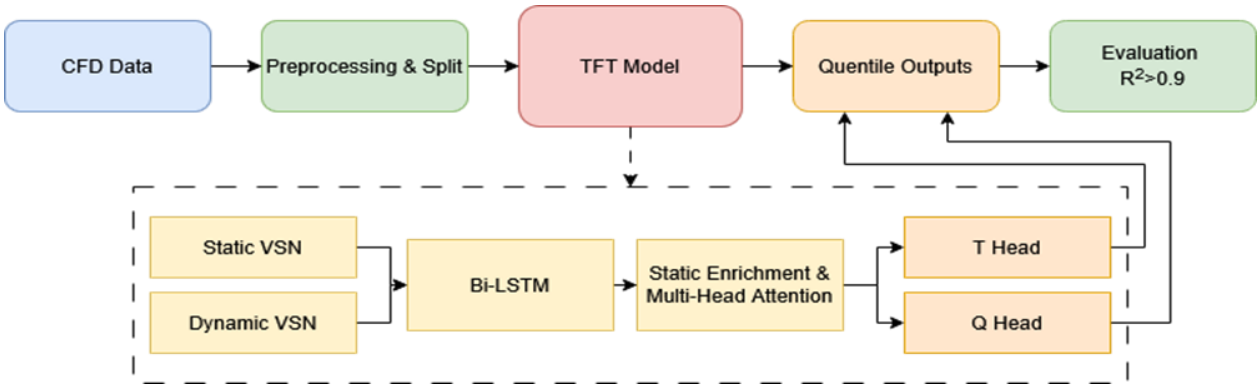


Figure 2. TFT surrogate model workflow from CFD data to quantile outputs with $R^2 > 0.9$ evaluation

3 RESULTS AND DISCUSSION

The present computational modeling approach is first validated against the experimental data reported in the literature (Dehghan, 2017) for the baseline design model of the HBHE. As shown in Figure 3, the simulated heat transfer rate (HTR) curves for seven different mesh resolutions with different time increments chosen are compared with the experimental data. The results demonstrate that all mesh configurations consisting of different mesh resolutions from 70000 to 1.0 x 10^6 tetrahedral cells with different time increments chosen in the range of 0.01 s to 0.02 s reproduce the characteristic transient decay behavior of the experimental data, with rapid heat dissipation during the first hours followed by a gradual stabilization. The numerical results converge after Mesh 4, and no significant differences are observed beyond Mesh 5, confirming the adequacy of the selected computational mesh resolution for further analyses. The slight overprediction of HTR in the initial period can be attributed to the idealized boundary conditions and perfectly uniform soil temperature assumptions,

which are inherent in steady thermal initialization. Good agreement with experimental evolution validates the robustness of the developed CFD model for subsequent parametric investigations.

Once the computational modeling approach is validated against the experimental data (Dehghan, 2017) for the baseline design model, parametric simulations are sequentially conducted with thermal conductivity of the soil, k_soil in the range of 0.5 to 5 W/mK, aspect ratio of the helical pipe, D/L in the range of 0.04 to 0.42, the turning number, N in the range of 5 to 15, and inlet temperature of the fluid, T_in in the range of 20 to 30 °C. Average undisturbed ground temperature, T_soil and volumetric flow rate remain constant at 18 °C and 0.00025 m^3/s, respectively.

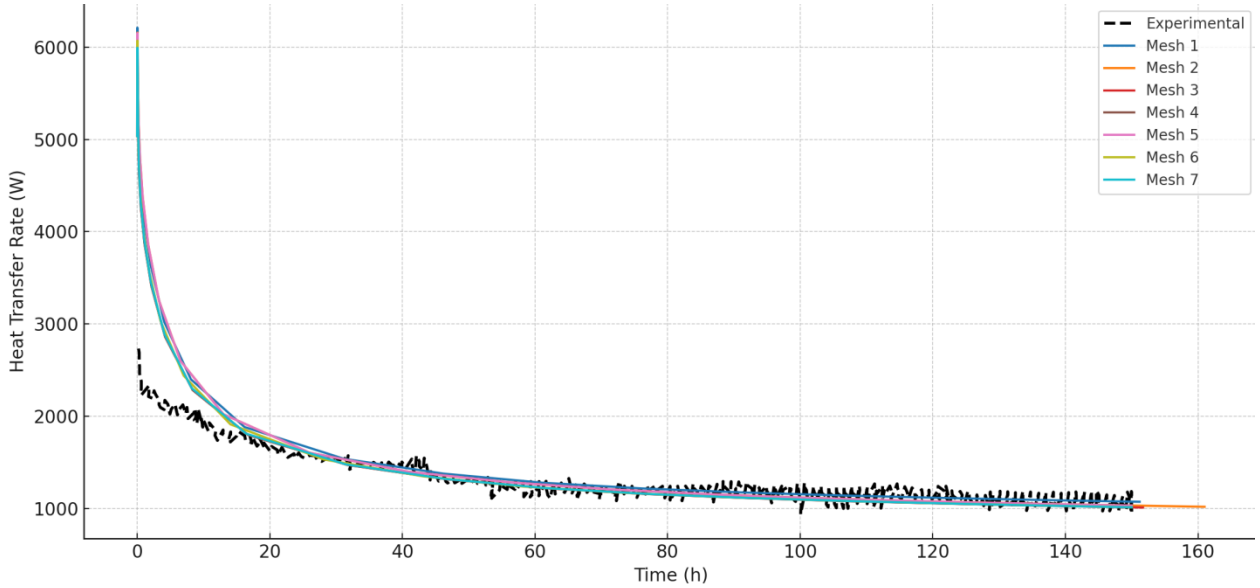


Figure 3. Validation of the computational modeling approach with the experimental data for different mesh resolutions and time increments, Δt (Mesh 1: 20,000 tetrahedral cells with Δt = 0.1 h; Mesh 2: 100,000 tetrahedral cells with Δt = 0.015 h; Mesh 3: 1.000,000 tetrahedral cells with Δt = 0.015 h; Mesh 4: 225,000 tetrahedral cells with Δt = 0.01 h; Mesh 5: 70,000 tetrahedral cells with Δt = 0.02 h; Mesh 6: 100,000 tetrahedral cells with Δt = 0.02 h; Mesh 7: 220,000 tetrahedral cells with Δt = 0.02 h)

The effect of the inlet temperature on the heat transfer rate is examined under fixed geometric and soil conditions (N = 10, D/L = 0.075, k_soil = 3 W/m·K), as illustrated in Figure 4a. A clear dependency between the inlet temperature and the heat transfer rate is observed. For all inlet temperature values, heat is transferred from the working fluid to the surrounding soil as an indication of heat rejection to the ground (cooling mode). The higher the inlet temperature the higher the heat transfer rate is observed. The transient behavior reveals that the magnitude of HTR is highest in the initial phase (0–10 h), during which the temperature gradient between the pipe and the soil is maximal. After this period, the system gradually approaches quasi-steady-state conditions as the soil region near the helical pipe thermally saturates. These findings confirm that the inlet temperature critically determines the heat transfer magnitude, especially during the early transient stage. The influence of soil thermal conductivity (k_soil) on the HTR is evaluated for the same geometry at the inlet fluid temperature of 25 °C (Figure 4b). As the k_soil value is increased, the HTR significantly increases. The effect of D/L ratio on the overall heat transfer rate can be also observed as depicted in Figure 4c. In the initial phase, the effect of D/L on the HTR is more discernable. However, at later times (>100 h), the effect of D/L ratios diminishes as the soil reaches a thermal equilibrium state. These findings suggest that although increasing D/L improves short-term heat transfer, excessively large helices may offer diminishing returns over extended operation due to higher material cost and reduced vertical compactness. The variation of HTR with the number of helical turns (N) is depicted in Figure 4d. The results indicate that increasing N enhances the effective heat exchange surface area, leading to higher HTR values. For N = 7, the peak HTR exceeds 400 W during the initial transient, while it is found to be 700 W for higher N value of 14. It should be noted here that the reduction in individual-loop performance with increasing N arises from stronger thermal interference between adjacent loops and greater pressure losses within the fluid circuit. Consequently, an optimal N exists that balances the heat transfer improvement with pumping power and design compactness.

The time-dependent energy efficiency (η) of the HBHE is evaluated for various inlet temperatures, soil conductivities, D/L ratios, and N values (Figure 5). The energy efficiency here is calculated as the ratio of the

predicted heat transfer rate to the maximum heat transfer rate. For all simulation cases, η exhibits a steep initial drop within the first 10 hours, followed by gradual stabilization. This behavior reflects the rapid initial heat exchange between the pipe and the thermally undisturbed soil, which progressively decreases as the local temperature field becomes uniform. Increasing N and k_soil results in higher η values, indicating enhanced heat transfer potential. However, the change in inlet fluid temperature does not have significant effect on efficiency evolution in time. These results confirm that geometric and thermophysical optimization can significantly improve the system's transient and steady-state performance.

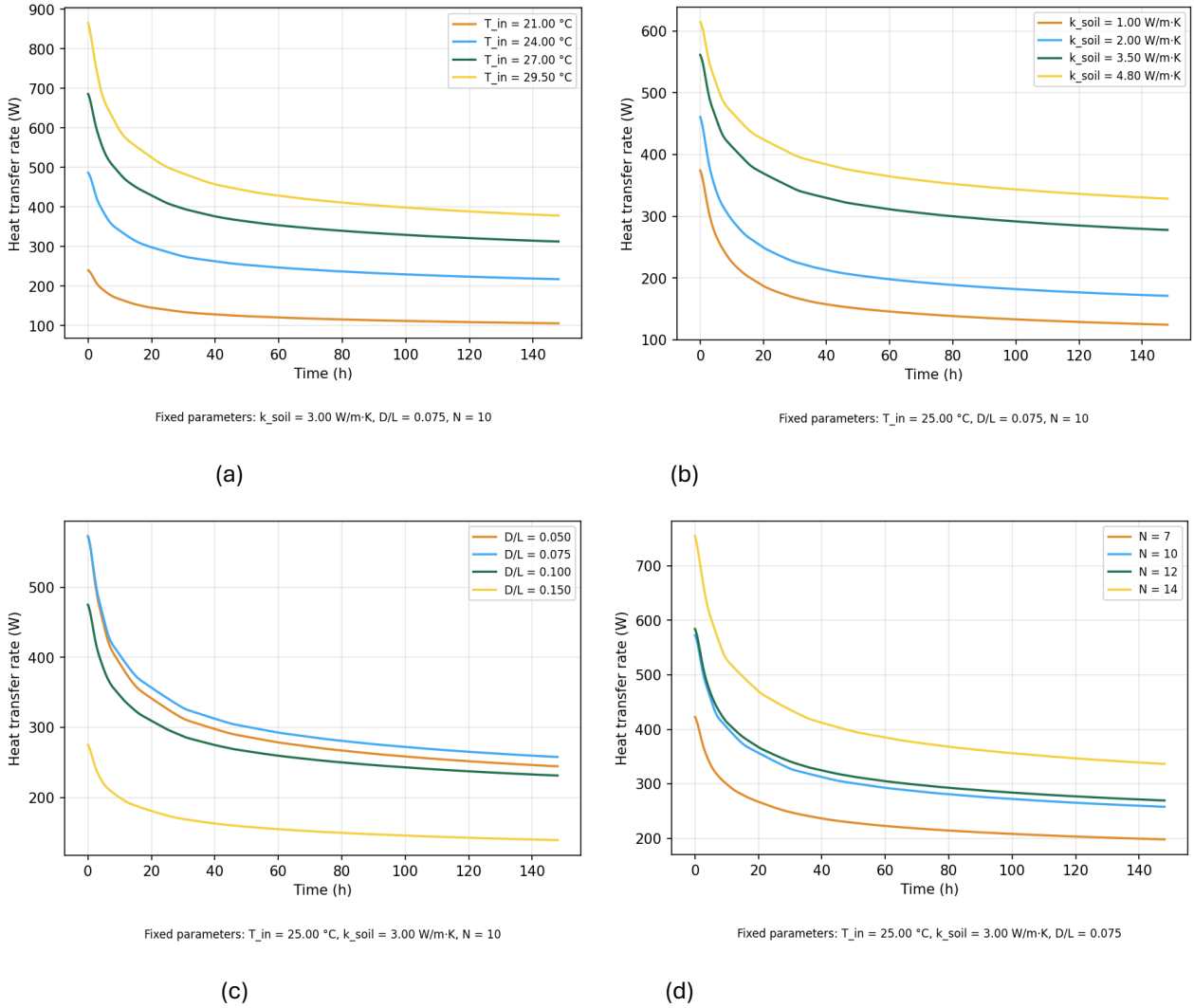
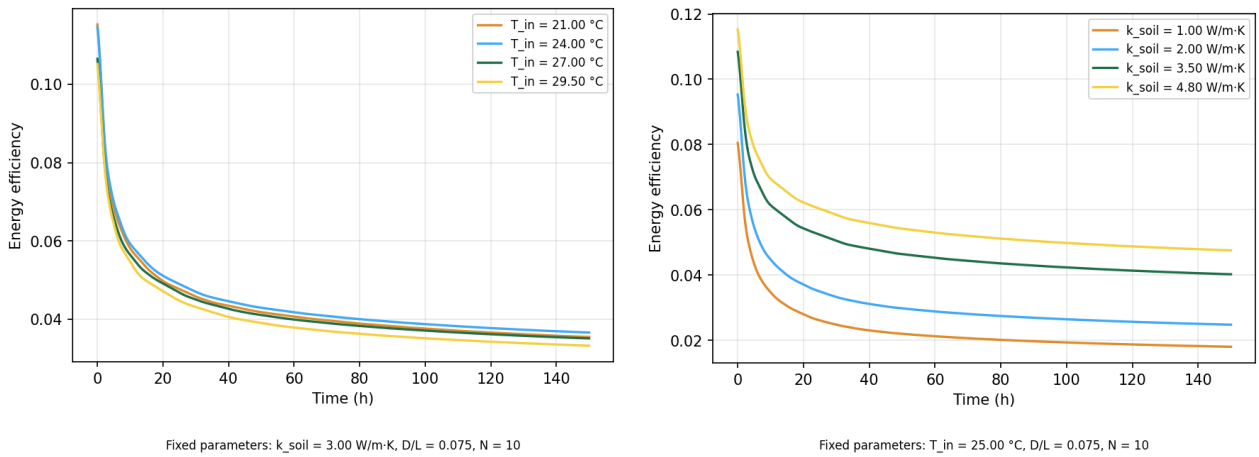


Figure 4. Comparative analysis of CFD results at different N, D/L, T_in, k_soil in terms of heat transfer rate vs time evolution.



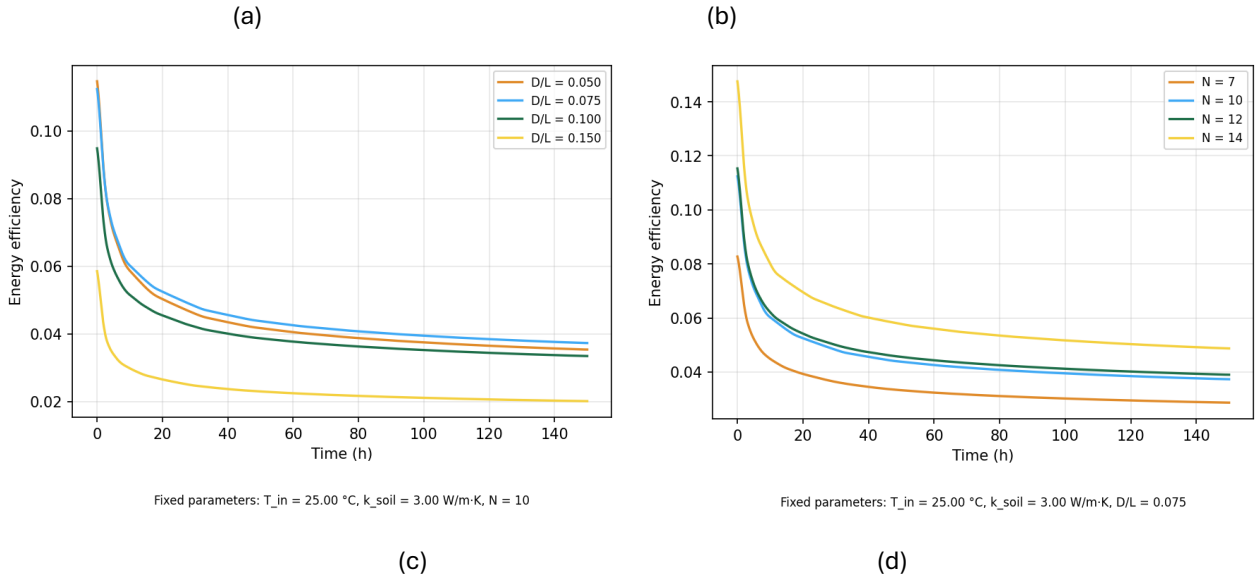
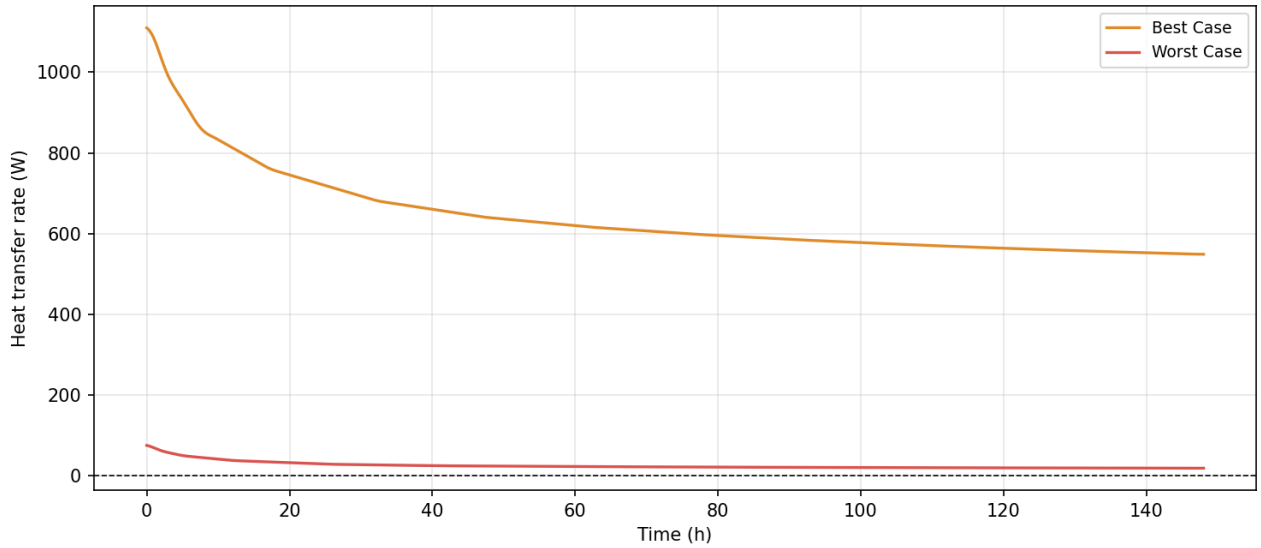


Figure 5. Comparative analysis of CFD results at different N, D/L, T_in, k_soil in terms of energy efficiency vs time evolution.

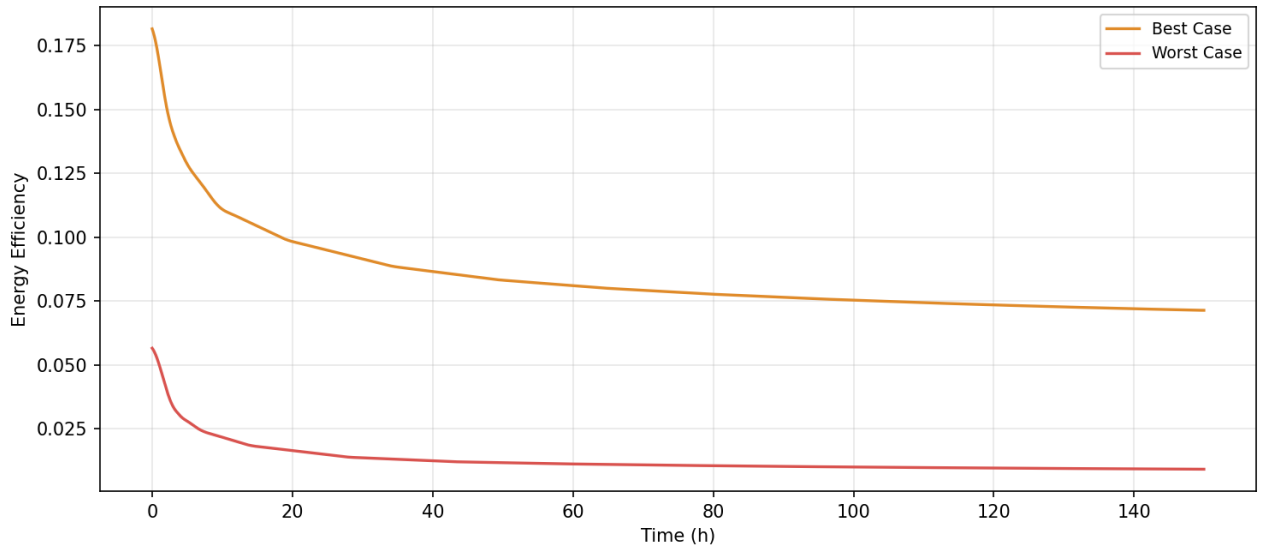
The results in Figure 5 show that increasing k_soil from 1.0 to 5 W/m·K substantially improves the system's thermal performance. For lower k_soil, the soil acts as a significant thermal resistance, limiting heat propagation and leading to a steeper decay in HTR over time. As k_soil increases, the effective heat dispersion capacity of the surrounding medium improves, resulting in higher and more stable HTR values even after long operation durations. This outcome highlights the importance of soil composition and moisture content, which directly affects k_soil, in determining the efficiency of ground heat exchangers. Practically, selecting installation sites with higher thermal conductivity soils can reduce borehole length and enhance long-term stability. To identify the performance extremes, best and worst case configurations are determined by combining the most and least favorable parameter sets, respectively.

Figure 6a compares the corresponding HTR evolutions. The best-case configuration yields a peak HTR of approximately 1000 W, while the worst case remains below 200 W after 150 hours. The difference underscores the synergistic effect of combined parameter optimization rather than individual effects alone. Similarly, Figure 6b presents the energy efficiency comparison between the best and worst configurations. The best case reaches a maximum efficiency of about 0.175 during the initial phase and stabilizes around 0.075, whereas the worst case maintains negligible efficiency (<0.02) throughout the entire operation. These findings clearly highlight that simultaneous optimization of inlet temperature, soil conductivity, and helical geometry is essential for achieving high thermal performance. The results reveal that the transient thermal behavior of HBHEs is governed by the interplay among geometric, thermal, and operational parameters. The first few hours of operation are dominated by steep gradients and strong heat exchange, whereas the long-term regime is characterized by asymptotic stabilization. Among the studied parameters, the soil thermal conductivity, number of turns and inlet fluid temperature exert the most pronounced influence, followed by the geometric parameters. The findings emphasize the importance of comprehensive, dimensionless, and time-dependent analyses for the design and optimization of HBHE systems, providing valuable insights for their practical application in geothermal and energy-efficient building system.

Figure 7 demonstrates the temporal evolution of model predictions for a representative test case with helical radius of 0.11 m, 13 turns, soil thermal conductivity of 4.32 W/m·K, soil temperature of 18 °C, and inlet temperature of 25.22 °C over 150 hours. The model accurately captures both rapid transient response in the first 20 hours and gradual approach to steady-state conditions. The narrow uncertainty bands demonstrate high model confidence, with prediction intervals successfully encompassing CFD results throughout the entire time series.



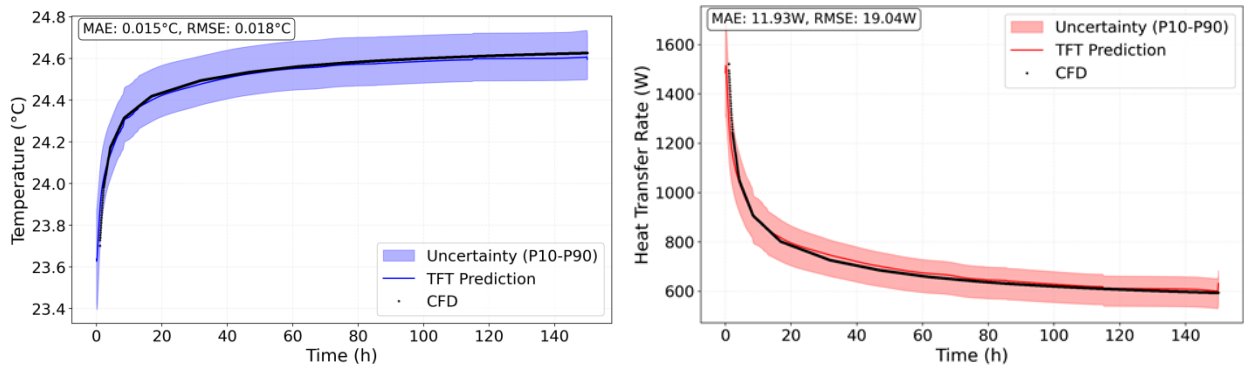
(a)



(b)

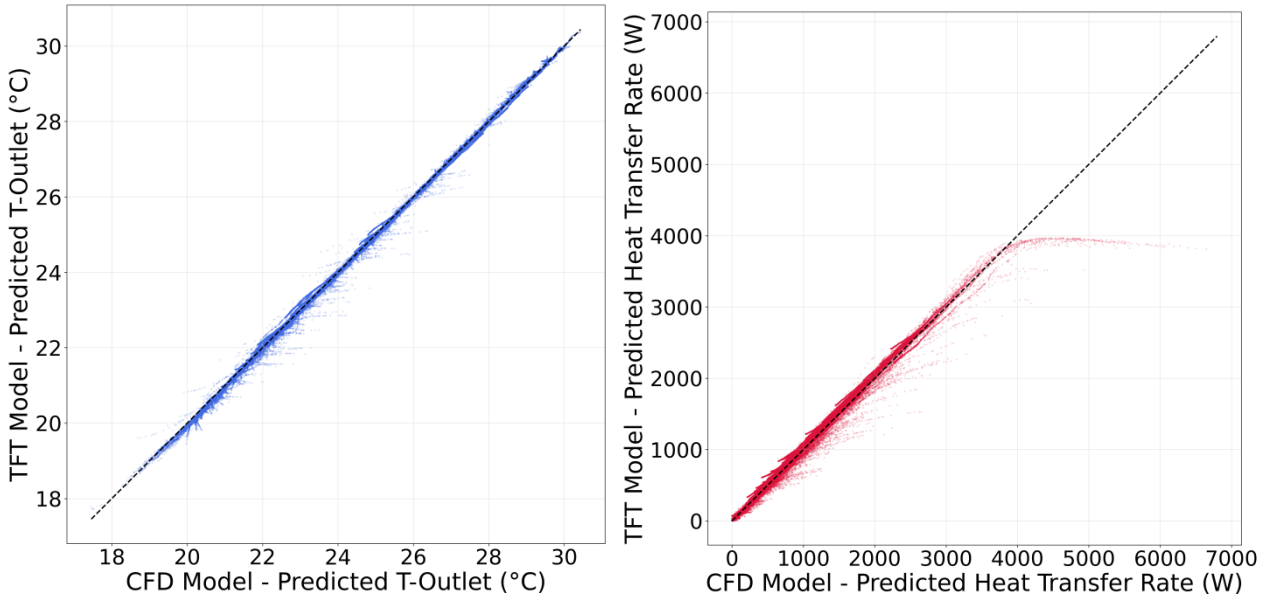
Figure 6. Comparative analysis of best possible optimal case and worst case in terms heat transfer rate and energy efficiency vs time a) Best Case: D/L=0.083, N=12, k_soil=4.87 W/mK, T_in=25.79 °C; and Worst Case: D/L=0.368, N=7, k_soil=0.82 W/mK, T_in=20.09 °C; b) Best Case: D/L=0.083, N=12, k_soil=4.87 W/mK, T_in=25.79 °C and Worst Case: D/L=0.125, N=6, k_soil=0.69 W/mK, T_in=25.13 °C.

The scatter plots in Figure 8 validate model accuracy across the full operating range, showing strong linear correlation between TFT predictions and CFD data for both temperature and heat transfer rate outputs. The trained surrogate model provides approximately 10 millisecond inference time per case on GPU hardware, enabling rapid exploration of vast design spaces. The model's interpretability through attention weights and quantile-based uncertainty quantification establishes a robust foundation for future NSGA-II multi-objective optimization studies, where it will enable efficient identification of Pareto-optimal configurations for helical ground heat exchangers while accounting for prediction uncertainty. The model performance metrics are also summarized in Table 2.



(a) (b)

Figure 7. Temporal predictions showing (a) outlet temperature and (b) heat transfer rate. Lines indicate P50 predictions, shaded regions show P10-P90 intervals, dots represent CFD data.



(a) (b)

Figure 8. Scatter plots validating TFT predictions against CFD data for (a) outlet temperature and (b) heat transfer rate across full operating range.

Table 2: Model Performance Metrics

Target Variable	R^2	Root Mean Square Error	Mean Absolute Error
Outlet Temperature	0.9996	0.054°C	0.038°C
Heat Transfer Rate	0.9927	41.89 W	19.20 W

4 CONCLUSION

Following below a few conclusions can be drawn from the present study:

• The results show that aspect ratio of the HBHE, thermal conductivity of the soil, number of helical turns and initial fluid inlet temperature significantly affect HBHE thermal performance.

• The simulation results demonstrate that simultaneous optimization of inlet temperature, soil conductivity, and helical geometry is essential for achieving high thermal performance.

• The present study therefore fills the gap by coupling CFD simulation dataset with a Deep Learning based optimization algorithm to maximize the thermal efficiency of the HBHE.

• A good correspondence with the CFD results clearly demonstrate that the developed deep learning model can be used with confidence for future multi-objective optimization studies in cost effective manner.

Acknowledgements

The funding received from The Scientific Research Projects Coordination Unit of Yasar University under the Project No. 153 (BAP) is acknowledged.

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