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A NOVEL FULL-STACK SIMULATION TOOL FOR RAPID MODELING OF THERMAL PROCESSES IN BOREHOLE THERMAL ENERGY STORAGE SYSTEMS

Abstract. Ground thermal energy storage are effective systems for building climate control, however, their modeling is complicated by a sharp geometric disproportion, particularly the diameter of the heat exchanger is several orders of magnitude smaller than its depth. This makes full-scale 3D modeling practically unfeasible due to large computational costs. The situation is exacerbated by the multi-parametric nature of the problem. Hence, classical parametric studies and sensitivity analysis require high computational power, which hinders the process of rapid iterative design. To address this problem, this paper presents a novel integrated, full-stack software architecture that automates conjugate heat and mass transfer calculations, allowing for feasibility studies of various scenarios in an automated manner. The methodology relies on an accessible application and a localized database combined with an optimized explicit finite-difference backend, utilizing vectorized numerical solvers to calculate 1D hydrodynamics and thermal processes within the borehole heat exchanger and 3D heat conduction in heterogeneous soil. The calculations were validated by previously obtained results of field Thermal Response Tests. The proposed tool enabled the implementation of large-scale parametric studies and system sensitivity analysis to key physical factors. The model allows for a comprehensive assessment of the impact of the thermophysical characteristics of heterogeneous soil layers and the properties of the borehole grouting material on heat extraction efficiency. The future inclusion of the influence of groundwater flows into the computational scheme could potentially expand functionality, allowing for full-fledged dynamic modeling of the system under changing conditions. Consequently, the developed software represents a scalable and cost-effective desktop tool for rapid, dynamic modeling of geothermal systems. The program combines advanced theoretical thermodynamic principles with requiring practical design, by providing the capability for parametric optimization considering real soil properties, bentonite characteristics, and the impact of groundwater flows.

Keywords: Borehole heat exchanger, ground-source heat pump, full-stack software, transient thermal simulation, geometric optimization, thermal response test.

1. Introduction

Ground-source heat pump systems are increasingly recognized as highly efficient and sustainable solutions for building climate control [1]. Within these systems, vertical borehole heat exchangers (BHE) are commonly deployed due to their stable thermal performance and minimal land area requirements. Recently, advanced geometric configurations, such as spiral and helical pipe layouts, have been investigated to maximize heat transfer efficiency and reduce drilling depths, offering significant economic and performance advantages over traditional single U-tube designs [1], [2].

However, accurately simulating the thermal behavior of these advanced BHE geometries

introduces substantial challenges. Unlike traditional U-tubes with uniform cross-sections, spiral and helical configurations feature complex, asymmetrical flow paths [3] (Figure 1). Recent numerical and analytical developments further confirm that double-spiral ground heat exchanger configurations offer superior thermal performance compared to conventional layouts [4]. Detailed three-dimensional numerical models required to capture these transient heat transfer mechanisms demand exceptionally high mesh densities. Consequently, simulating the long-term thermal performance of these systems, especially over a lifespan of decades or within large-scale, multi-borehole arrangements, becomes computationally prohibitive and time-consuming, severely limiting iterative design and optimization [5].



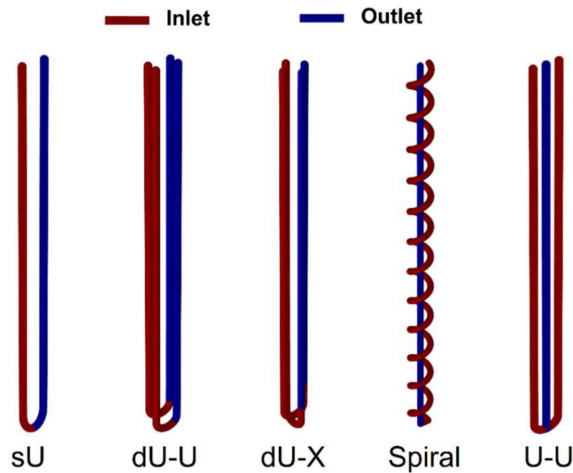


Figure 1. A schematic diagram comparing the simple geometry of a traditional U-tube BHE with the complex, three-dimensional fluid path of a spiral/helical BHE [5]

To overcome these barriers, an integrated simulation workflow is critically needed to bridge advanced theoretical modeling with practical engineering application. Providing users with a comprehensive, full-stack software architecture allows for the rapid testing, validation, and optimization of BHE designs without the overhead of manually configuring computationally heavy numerical solvers. Specifically, there is a high value in deploying a streamlined system where users can seamlessly input complex geological and geometrical data into an accessible desktop application. In authors' view the computational burden can be effectively managed by storing these parameters in a relational database and executing Python-based simulations via a REST API. Such an integrated environment accelerates the iterative design process and provides immediate, visualized feedback, ensuring that optimal, cost-effective geothermal solutions can be reliably engineered.

To accurately model the thermal performance of ground heat exchangers, foundational research has heavily relied on analytical solutions such as the infinite line source, infinite cylindrical source, and finite line source (FLS) models [4,7]. While the FLS model effectively captures long-term axial and radial heat conduction, it simplifies the dynamic thermal capacity of the internal borehole elements, limiting its accuracy for short-term transient analysis [7,8]. Beyond spiral and double U-tube designs, novel configurations—such as trilobular

heat exchangers utilizing high-conductivity satellite pipes have been introduced to enhance heat transfer efficiency while reducing drilling requirements [9]. Consequently, a shift toward three-dimensional numerical simulations can be observed, often employing Computational Fluid Dynamics (CFD), to capture the detailed transient heat and mass transfer within complex BHE geometries and heterogeneous soil layers [6].

Recent literature emphasizes the optimization of these geometric configurations to maximize heat exchange efficiency and reduce overall installation costs [10]. Traditional single U-tube layouts, while simple to install, are increasingly being outperformed by advanced geometries [6]. For instance, helical and spiral heat exchangers generate secondary flow vortices due to centrifugal forces, which significantly promote convective heat transfer between the working fluid and the surrounding ground [11]. Numerical comparisons demonstrate that spiral configurations can extract substantially more heat and save up to 34.6% in drilling depth compared to standard U-tubes [6]. Furthermore, novel concepts like the intertwined spiral-double ground heat exchanger exhibit an even higher thermal effectiveness and lower thermal resistance, making them highly suitable for deployment in densely populated urban areas [3].

Despite these performance benefits, simulating the precise thermal behavior of these advanced systems introduces a significant hurdle: the intricate, asymmetrical geometry of spiral and helical pipes requires an exceptionally high mesh density in numerical models, leading to prohibitive computational demands [12]. Performing full-scale, long-term simulations of multi-pile arrangements over decades of operation remains highly impractical using purely numerical methods, thereby limiting iterative design exploration and optimization [4].

To address the computational bottlenecks associated with detailed three-dimensional numerical models and to bridge the gap between advanced theoretical BHE research and practical engineering, this paper presents a novel, integrated full-stack simulation software architecture (Figure 2). The primary contribution of this work is the development of a streamlined desktop application, built utilizing the Electron JS framework, that orchestrates computationally efficient geothermal simulations.

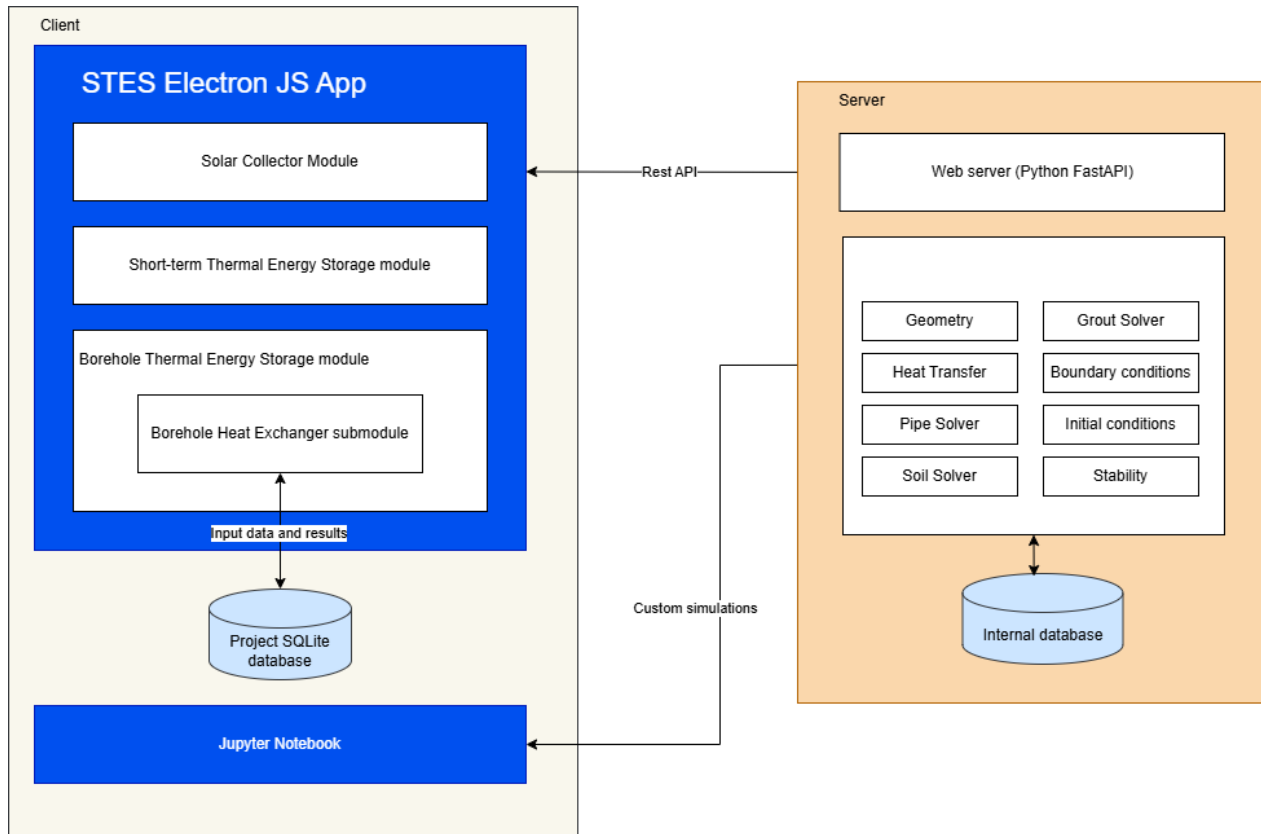


Figure 2. A high-level architecture diagram of integrated full-stack simulation software

Specifically, this work achieves the following.

1) Development of an integrated workflow by creating a complete software ecosystem was designed to connect a frontend developed with modern UX/UI techniques with a Python-based backend. Utilizing a local relational database to persistently store complex domain configurations, geological stratigraphy, and simulation results in the architecture automates the manual configuration of heavy numerical solvers.

2) Computationally efficient simulation engine to overcome the prohibitive processing time of traditional CFD meshing for complex spiral and helical geometries, the backend engine employs an optimized finite-difference approach. Coupling one-dimensional explicit solvers for the fluid and grout with a three-dimensional explicit solver for the heterogeneous soil allows the system to reduce the computational overhead required for long-term transient analysis.

3) Facilitation of iterative optimization by exposing the simulation engine through a REST API and managing the execution lifecycle asynchronously, the software allows for rapid,

iterative testing and validation of various BHE designs which provides engineers and researchers with immediate visualized feedback, making the optimization of highly efficient, complex BHE configurations practical and cost-effective.

Subsequently, the integrated package translates advanced theoretical heat transfer models into an accessible desktop environment, providing a scalable solution for designing and forecasting the efficiency of ground-source heat pump systems.

2. Materials and methods

2.1. The model

To accurately evaluate the transient thermal performance of BHEs, engineers typically rely on a conjugated heat and mass transfer model that couples the three-dimensional behavior of the surrounding soil with the one-dimensional fluid dynamics and heat transfer processes inside the pipes. Manually configuring this coupled numerical approach in standard CFD environments requires significant time and computational resources, particularly due to the extreme dimensional

disproportionality between the narrow BHE pipe diameter and the overall well depth. Combining physics-based simulation models with observational data and uncertainty quantification is vital for validating transient heat transfer solvers against field measurements [13]. The software architecture presented in this work is designed to automate the setup and execution of these governing physical equations, effectively removing the bottleneck of manual meshing and complex solver configuration.

The theoretical foundation of this automated simulation begins with modeling the surrounding ground, treating the underground soil layers as a complex 3D porous medium composed of solid, liquid, and gas phases. Heat flow through this heterogeneous environment is driven by the thermal interactions between the soil mass and the BHE. When a temperature gradient forms, heat is transferred through the ground via conduction, alongside convective transport if groundwater flow is present. This thermal process is defined by the energy balance equation for a porous medium (Equation 1) [6].

$$(\rho c)_{eff} \frac{\partial T_s}{\partial t} dV + (\rho c)_f \vec{v} \cdot \nabla T_s dV = \nabla \cdot (\lambda_{eff} \nabla T_s) dV + H \quad (1)$$

with T_s being soil temperature, H and c denoting heat source and specific heat capacity respectively.

In current case, the assumption is that there is no groundwater flow on any of subsurface layers, hence groundwater flow velocity ($\vec{v}$) is taken as 0. Although groundwater velocity is assumed to be zero in the baseline model, advective heat transport driven by natural seepage flow does affect subsurface thermal plumes and heat extraction rates [14]. The energy balance is resolved in the model by computing the effective thermal conductivity (λ_{eff}) and the effective volumetric heat capacity ($(\rho c)_{eff}$) of the soil, which are derived from the ground's porosity (ϕ) and the specific properties of both the solid matrix and the moisture of local domain, as detailed in Equation 2 and Equation 3.

$$\lambda_{eff} = (1 - \phi) \lambda_s + \phi \lambda_f \quad (2)$$

$$(\rho c)_{eff} = (1 - \phi) (\rho c)_s + \phi (\rho c)_f \quad (3)$$

Properly bounding this 3D domain is critical for the simulation's accuracy. The automated system

initializes the ground with an undisturbed temperature profile corresponding to the natural state of the soil layers prior to system operation (Equation 4).

$$T_s(t=0) = f(z) \quad (4)$$

To optimize processing time without requiring an impractically large computational domain, specific boundary conditions are established: the top boundary in contact with the atmosphere is governed by a convective heat transfer condition (Equation 5), while zero-heat-flux Neumann boundary conditions are enforced on the lateral and bottom faces of the domain (Equation 6).

$$\lambda_{eff} \nabla T \vec{n} = U_{as} (T_a - T_s) \quad (5)$$

$$\lambda_{eff} \nabla T \vec{n} = 0 \quad (6)$$

Moving from the external porous medium to the internal components of the BHE, the automated simulation models the circulation of the heat transfer fluid inside the pipes as a one-dimensional flow. To calculate fluid velocity (u) in pipes and pressure (p) variations along the pipe axis, the model assumes a fully developed flow regime, neglects shock phenomena, and assumes that velocity components transverse to the pipe axis are zero [6]. Under these assumptions, the fluid dynamics are governed by the one-dimensional momentum and continuity equations (Equation 7 and Equation 8).

$$\rho_f \frac{du}{dt} = -\nabla_t p \cdot \vec{e}_t - \frac{1}{2} f_r \frac{\rho_f}{d_p} u |u| + \vec{F} \cdot \vec{e}_t \quad (7)$$

$$\frac{\partial A \rho_f}{\partial t} + \nabla_t \cdot (A \rho_f u \vec{e}_t) = 0 \quad (8)$$

with f_r being a Darcy's friction factor, while $\vec{e}$ and $\vec{F}$ are unit tangent vector to the pipe axis and volume force respectively, ρ_f – fluid density.

The thermal interaction between the circulating fluid, the pipe walls, the grout, and the surrounding ground is subsequently resolved through a combined convective-conductive heat transfer approach. The energy balance of the fluid flowing through the pipes is defined by Equation 9, which fundamentally captures the convective transport of heat while also accounting for the thermal energy generated by viscous friction against the inner pipe walls depending on the diameter of the heat exchanger pipes (d_p) [6].

$$\begin{aligned} & \rho_f A c_f \frac{\partial T_f}{\partial t} + \rho_f A c_f u \vec{e} \cdot \nabla_t T_f = \\ & = \nabla_t \cdot A \lambda_f \nabla_t T_f + \frac{1}{2} f \frac{\rho_f A}{2 d_p} |u| u^2 + q_{wall} \end{aligned} \quad (9)$$

A critical aspect of the model is accurately quantifying the radial heat flux passing from the surrounding soil through the grout and pipe walls into the fluid. This is achieved using an effective overall heat transfer coefficient $((\hbar Z)_{eff})$ (Equation 10 and Equation 11) that incorporates the pipe's internal and external radii ($r_{p,\in}$ and $r_{p,out}$), the thermal conductivity of the pipe material (λ_p), and the convective heat transfer coefficient of the fluid ($\hbar_{f\Box}$). Notably, the model treats the backfill grout as the primary intermediate heat transfer medium; therefore, direct thermal exchange (short-circuiting) between the inlet and outlet pipes is not explicitly calculated as an independent parameter [6].

$$q_{wall} = (\hbar Z)_{eff} (T_{ext} - T) \quad (10)$$

$$(\hbar Z)_{eff} = \frac{2\pi}{\frac{1}{r_{p,\in} \hbar_{f\Box}} + \ln} \quad (11)$$

To ensure the model dynamically adapts to various flow regimes, it utilizes stable empirical correlations to define the internal convective heat transfer coefficient. Specifically, the Nusselt number is determined using the Gnielinski correlation, which relies on the Darcy friction factor. This friction factor is calculated via the Churchill equation, a versatile correlation that remains valid across laminar, transitional, and fully turbulent fluid flow conditions. Work [6] provides a detailed definition of the aforementioned parameters.

2.2. Software Architecture and Implementation

To provide an accessible and efficient interface for configuring and executing complex BHE simulations, the proposed software is deployed as a standalone desktop application built upon the Electron JS framework. The system architecture is structured around a standard three-context paradigm, comprising a Main Process, a Preload Bridge, and a Renderer Process, which ensures strict security boundaries, context isolation, and efficient resource management (Figure 3).

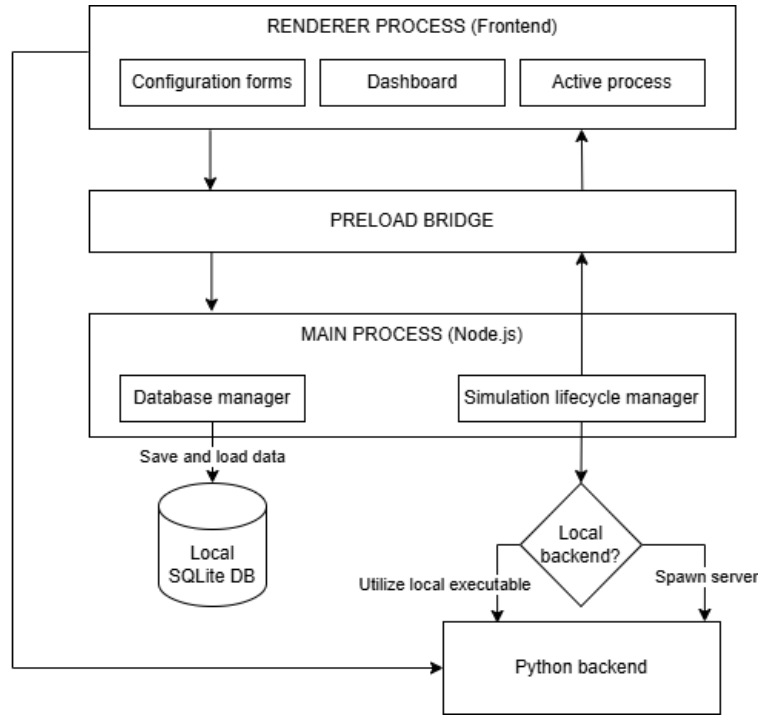


Figure 3. Frontend Electron application consists of 3 contexts

At the core of the application, the Main Process serves as the central controller. It manages system-level operations including application bootstrapping, project directory lifecycles, native operating system dialogs, and the initialization of the local database. Specifically, the Main Process also controls the lifecycle of the simulation server; and is responsible for spawning the background Python-based calculation engine upon startup and ensuring its stable termination when the application closes. To provide real-time feedback during a computational run, this process intercepts standard output and error streams from the simulation engine, buffers them, and broadcasts the logs to the frontend interface.

Secure operational environment is maintained with the fact, that the architecture strictly isolates the user-facing interface from the native system by disabling direct Node.js integration. Instead, a Preload Bridge operates as a secure intermediary. This bridging script exposes restricted set of categorized APIs to the frontend. These categorized methods manage database interactions, project configurations, and simulation controls, thereby safeguarding the underlying operating system while facilitating stable data exchange.

The user interface itself, while operating within the Renderer Process, is designed as a complex single page application. Rather than relying on heavy, computationally expensive web frameworks, the frontend employs Vanilla JavaScript paired with utility-first CSS styling to capture and visualize BHE configurations. A custom view router dynamically fetches and injects interface modules, allowing end-users to navigate through specialized configuration tabs that detail the physical domain, geological stratigraphy, and spatial grid parameters. User inputs are captured via native event listeners that asynchronously invoke the exposed APIs, ensuring responsive, offline-capable environment that prepares the theoretical models for subsequent numerical calculation in a timely manner.

Unlike traditional web-based simulation tools that rely on centralized cloud databases, the proposed software adopts a localized, project-based data persistence strategy utilizing SQLite to ensure that all sensitive geological data and complex simulation configurations remain strictly on the

local machine, enabling full offline capabilities, rapid data retrieval, and simplified project sharing.

The core of this persistence architecture is a Database Manager, implemented as a singleton class within the Electron Main Process. Whenever a user initiates a new session or opens an existing project, the Database Manager automatically establishes a connection to a specific database file located within the chosen project directory. If the database file does not already exist, the manager dynamically generates the necessary schema upon initialization.

To accurately capture the complex physical, geometrical, and geological parameters required for BHE modeling, the database schema (Figure 4) is structured into strongly typed relational tables. The primary configuration tables include: configuration storage with the fundamental physical and thermal properties of the BHE domain; BHE layers and layer groups to capture the depth-based stratigraphy, defining the heterogeneous geological layers surrounding the BHE; grid configurations defining the spatial resolution and meshing parameters required for the numerical solvers; simulation collection as an aggregate parent table that links specific domain, layer, and grid configurations into a cohesive, executable simulation run.

Long-term maintainability and system scalability is ensured by the modularization of database interactions. Rather than clustering queries within the main application script, all database operations are delegated to specific, purpose-built handlers (e.g., domain configuration handlers). Furthermore, the architecture enforces a strict separation of concerns regarding database write permissions: the frontend tables, which capture user configurations, are written exclusively by the Electron application, whereas the simulation result tables are written exclusively by the Python backend once a numerical calculation is successfully completed.

To manage the computationally intensive numerical procedures described in Section 2.1, the software architecture employs a Python-based backend server. This backend is developed using the FastAPI framework and is designed around a strict separation of concerns: it is implemented into a web-facing REST API layer and an isolated, pure-computation Physics Library.

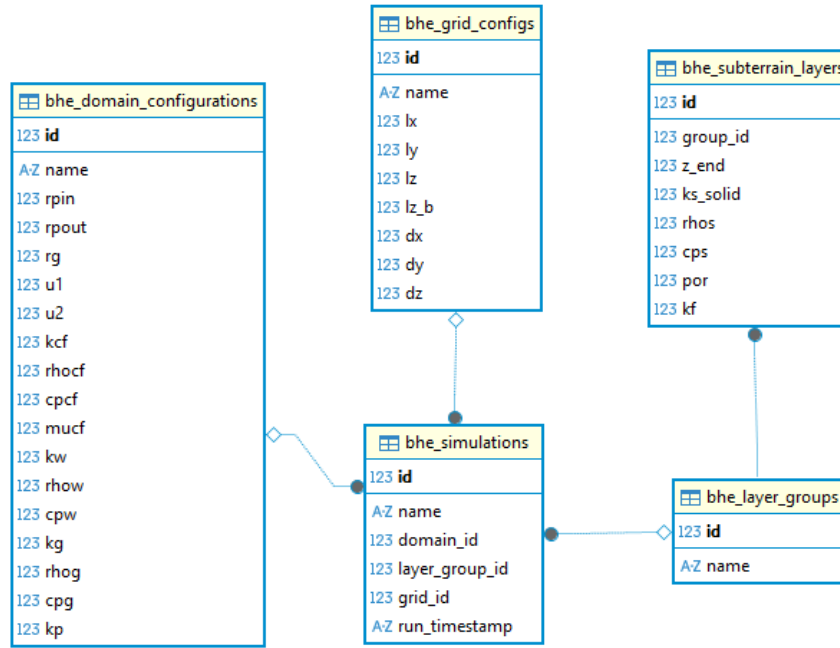


Figure 4. Entity-Relationship diagram illustrating BHE specific data model

The REST API layer is exclusively responsible for handling HTTP requests, managing shared server states, and controlling background tasks. Because simulating long-term BHE performance can take several minutes to hours depending on the grid resolution, the system cannot rely on synchronous HTTP requests. Instead, the backend utilizes an asynchronous execution strategy managed by a custom task manager that wraps a thread pool executor. When the frontend initiates a simulation via a POST request, the manager allocates a background thread for the calculation, generates a threading event to allow for graceful termination, and immediately returns a response to the user interface. The frontend then routinely polls a dedicated status endpoint to retrieve real-time, thread-safe snapshots of the simulation's progress, ETA, and calculation logs.

Underpinning the API is the Physics Library, which translates the governing theoretical models of conjugated heat and mass transfer into executable code. To ensure maximum computational efficiency, this library is implemented using pure functions that lack any database or HTTP side effects. All geometrical, physical, and geological parameters are initially validated and centralized into a single configuration object utilizing the data validation framework.

During execution, the library bypasses computationally expensive Python loops by leveraging vectorized array operations, while the solver pipeline executes sequentially at each time step: first resolving the one-dimensional explicit finite-difference equations for the downward and upward fluid flows inside the pipes, next calculating the one-dimensional intermediate heat transfer through the grout, and finally executing the three-dimensional explicit finite-difference solver for the heterogeneous soil domain. By isolating this numerical pipeline from the web server and database logic, the software achieves an optimized execution path capable of dynamically modeling transient thermal behaviors over extensive temporal scales.

To ensure the accuracy and reliability of the theoretical models before their deployment within the full-stack application, an isolated verification workflow is utilized. The core Physics Library of the backend is intentionally designed using pure, side-effect-free functions that operate completely independently of database writes or HTTP requests. This decoupled architecture allows researchers to import the simulation modules directly into Jupyter Notebooks. Within this interactive environment, engineers can isolate, test, and validate the explicit finite-difference solvers against empirical data and existing literature.

3. Results

The practical application of the proposed software architecture begins with the user interface, which is specifically designed to capture and manage the complex mathematical and physical parameters defined in Section 2.1. Upon launching the Electron-based desktop application, users are presented with a centralized dashboard that manages local simulation projects. To configure a new BHE model, the interface employs a modular tabbed system that logically categorizes inputs into three primary domains: physical properties, geological stratigraphy, and spatial grid parameters.

Within the domain configuration module, engineers can define the fundamental geometrical properties of the system, such as the total borehole depth, pipe inner and outer radii, and the specific

BHE configuration type. This module also captures the critical thermophysical properties required for the numerical solvers, including the thermal conductivity, density, and specific heat capacity of the heat transfer fluid, the pipe walls, and the backfill grout.

To accurately model real-world underground environments, the geological stratigraphy module allows users to define heterogeneous, depth-based soil profiles. Users can construct a stack of underground layers, assigning distinct effective thermal conductivities, porosities, and volumetric heat capacities to each specific depth interval. These user-defined inputs are asynchronously saved to the local SQLite database and subsequently transformed by the Python backend into the precise three-dimensional arrays required for the explicit finite-difference solvers (Figure 5).

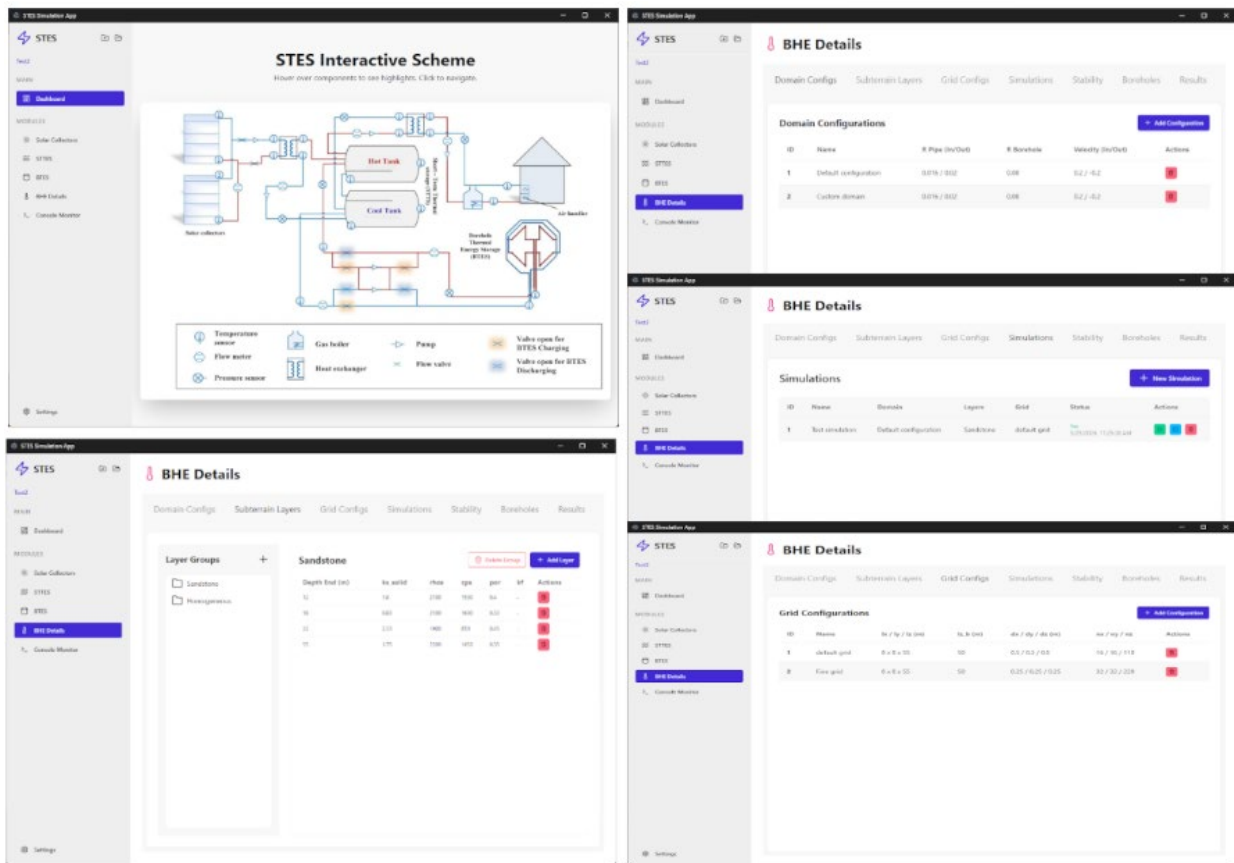


Figure 5. BHE module of full-stack STES simulation tool allows defining domain, grid, subterrain layer, borehole to run remote simulations

Once the physical and geological parameters are fully defined, the user initiates the mathematical modeling directly from the Electron interface. Upon initiation, the frontend transmits a POST request to the Python backend, which immediately delegates the computationally heavy solver pipeline to an isolated background thread managed by a custom TaskManager.

To ensure a responsive user experience without blocking the interface during calculation, the

frontend utilizes an asynchronous polling mechanism. It queries a dedicated status endpoint every 500 milliseconds to retrieve thread-safe snapshots of the simulation. These snapshots update a global state object within the frontend, which in turn dispatches custom Document Object Model events. These events dynamically drive active progress bars, display the ETA, and stream calculation logs directly to the user's dashboard in real time (Figure 6).

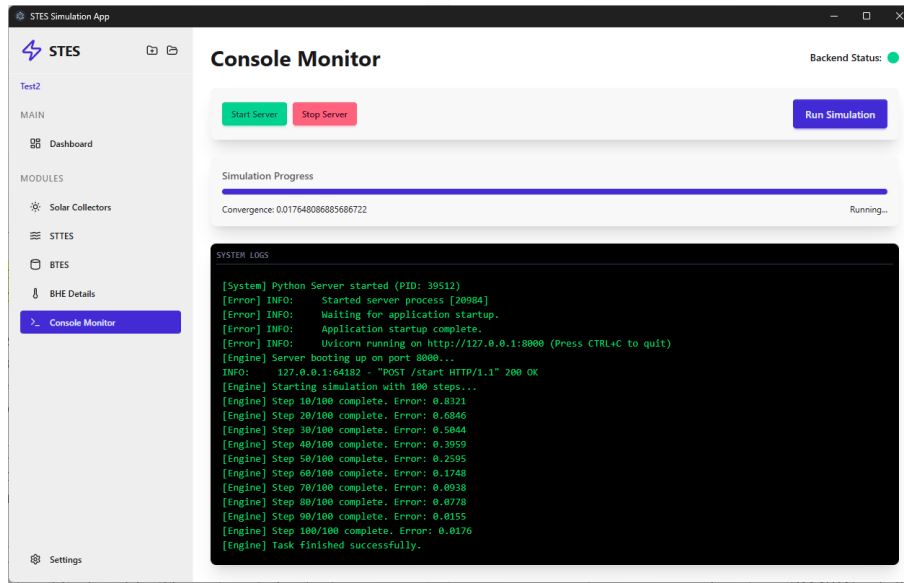


Figure 6. Upon establishing the connection with remote server, simulations are sent to execution with live results log

From a computational performance perspective, the backend engine is highly optimized for speed by structuring the explicit finite-difference equations as pure functions and processing the three-dimensional soil temperature arrays using vectorized NumPy operations, the physics library bypasses the inherent latency of standard Python loops. Consequently, long-term transient simulations that would traditionally require hours to mesh and solve in standard CFD environments can be executed in a fraction of the time, enabling practical, iterative optimization of BHE designs.

Accurately characterizing depth-dependent thermophysical properties across distinct geological strata during Thermal Response Testing is essential for effective multi-layer soil modeling [15]. To

verify the mathematical accuracy and reliability of the integrated software architecture, the system was utilized to replicate the results of a comprehensive Thermal Response Test documented in a recent Kazakhstan-based case study [6]. The geological stratigraphy (predominantly gravel and till/loam) and the specific dimensions of a 50-meter deep, single U-tube BHE were inputted into the software's Electron JS frontend. Upon execution, the Python backend's optimized explicit finite-difference solver generated a simulated fluid outlet temperature (T_{out}) profile (Figure 7). This automated output closely matched both the empirical In-Situ data and the original manual CFD simulations, successfully reproducing the highly accurate root-mean-square-deviation of 0.184 °C [6].

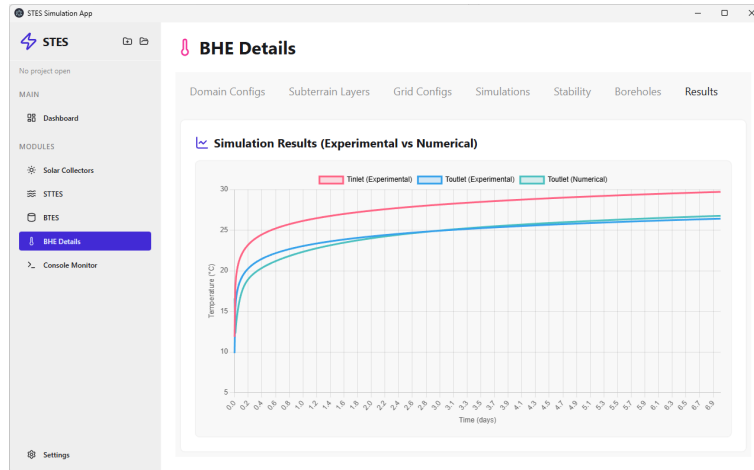


Figure 7. The comparison of the numerical and experimental data for the fluid outlet temperature

Following this baseline validation, the software was tested on its primary value proposition: the ability to rapidly simulate complex, asymmetric BHE geometries without the prohibitive overhead of manual CFD meshing. Utilizing the software's interface, engineers successfully configured and simulated multiple advanced pipe layouts, including double U-tube parallel, double U-tube cross, multi-tube, and spiral configurations, under identical geological

conditions. The automated simulations accurately reproduced the findings from the literature, confirming that the spiral configuration extracts the highest amount of heat (1.91 kW at a 50 m depth) and can achieve a 1/3 reduction in required drilling depth compared to standard U-tube setups [5]. This confirms that the proposed software architecture can reliably replace manual CFD workflows for complex geometric optimization (Figure 8).

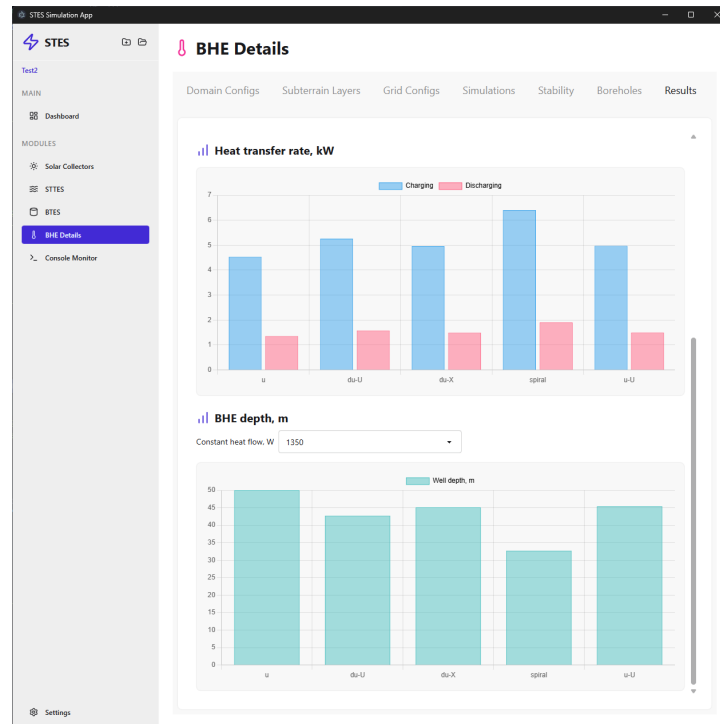


Figure 8. Heat transfer rates and well depths for various complex pipe configurations

4. Conclusions

This paper presented an integrated full-stack simulation software architecture designed to accurately and efficiently evaluate the transient thermal performance of ground-source heat pump systems. By coupling an accessible Electron JS frontend with optimized, Python-based explicit finite-difference backend, the developed system successfully automates the complex conjugated heat and mass transfer calculations that traditionally require manually configured, computationally heavy CFD environments. The deployment of a localized database ensures data privacy, offline capability, and rapid retrieval of geological stratigraphy, while the vectorized numerical solvers bypass the latency of standard programming loops to drastically reduce computation time.

The mathematical robustness of the software was strictly validated against empirical in-situ Thermal Response Test data from a recent case study in Kazakhstan. The automated simulation closely tracked the experimental fluid outlet temperatures, achieving a high degree of accuracy with a root-mean-square-deviation of 0.184 °C. Furthermore, the software proved effective at rapidly simulating complex, asymmetric pipe configurations without the prohibitive overhead of manual CFD meshing. The computational results confirmed that the spiral heat exchanger configuration extracts the highest amount of heat, outperforming multi-tube, double U-tube parallel, double U-tube cross, and conventional single U-tube setups. Crucially, the software verified that a spiral configuration can reduce the required drilling depth by a third compared to a standard single U-tube.

From a practical engineering perspective, this integrated software provides a highly scalable and cost-effective solution for designing the next generation of geothermal heating and cooling systems. By translating theoretical thermodynamics into an automated desktop tool, engineers can rapidly iterate design parameters to minimize drilling depths, typically the most expensive and labor-intensive component of system installation. This capability is particularly valuable for deploying advanced BHE geometries in space-constrained urban environments, where minimizing the footprint of the borefield is essential.

Despite these advancements, the current computational model possesses certain limitations that must be acknowledged. The theoretical

framework currently neglects convective heat transfer driven by natural groundwater flow within the porous soil medium, relying exclusively on conductive heat transfer through the heterogeneous layers. Additionally, the fluid dynamics inside the pipes are simplified to a fully developed one-dimensional flow, which assumes zero transverse velocity components and neglects shock phenomena. Finally, the solver currently utilizes static thermal properties for the ground and does not account for dynamic, temperature-dependent phase changes within the soil mass.

Consequently, future work will focus on expanding the software's physics library to address these constraints and broaden its applicability. Subsequent iterations will aim to model the freezing factor mechanisms around the borehole heat exchanger during operation in severe winter conditions, as well as investigate specific heat transfer features during alternating seasonal charging and discharging modes. Extending the computational framework to large-scale borefields requires accounting for spatial thermal interference between adjacent boreholes over multi-year operational lifespans [16]. Therefore, future development will include modules for predicting thermal interference across large-scale, multi-borehole arrangements and integrating multidimensional parametric optimization directly into the user interface to further streamline the practical BHE design process.

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Conflicts of Interest

Authors declare no conflicts of interests.

Author Contributions

Author Contributions: “Conceptualization, M.S.T. and D.Y.A.; Methodology, D.Y.A. and B.A.; Software, D.Y.A. and B.A.; Validation, T.E.A. and B.A.; Formal Analysis, D.Y.A. and B.A.; Investigation, T.E.A. and B.A.; Resources, M.S.T.; Data Curation, T.E.A. and D.Y.A.; Writing – Original Draft Preparation, T.E.A. and B.A.; Writing – Review & Editing, M.S.T. and D.Y.A.; Visualization, D.Y.A. and B.A.; Supervision, M.S.T.; Project Administration, D.Y.A.; Funding Acquisition, D.Y.A.”

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