Arizona State University
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Thermal Performance Analysis of Novel Low-Cost Geothermal Heat Exchangers for Heat Pump Systems

MAE 589: Heat Transfer (2025 Spring C)
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Team: The Groundbreakers

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Project Objective

This project aims to evaluate and compare the thermal performance of innovative, low-cost geothermal heat exchangers (GHEs) against conventional systems used in geothermal heat pump applications. By developing a detailed numerical model and mesh analysis that simulates the counter-flow dynamics of U-tube configurations and investigates the effect of variable tube spacing, we intend to optimize heat transfer efficiency while reducing installation and material costs. The outcome will provide design guidelines that enable enhanced energy performance and pave the way for broader market adoption of cost-effective geothermal solutions.

Summary of Prior Related Work from the Published Literature

Several researchers have contributed to the understanding of geothermal heat exchangers. Esen *et al.* [1] compared ground-coupled and air-coupled heat pump systems, emphasizing the critical role of efficient heat transfer for space cooling. Esena and Yuksel [2] performed experimental evaluations of renewable energy sources for heating applications, underscoring the viability of geothermal energy in controlled environments. Retkowski *et al.* [3] investigated various heat extraction strategies for shallow vertical ground-source systems, providing insights into the influence of design parameters on thermal performance. Esa and Fung [4] utilized simulation-based approaches to compare the performance of single versus double U-tube borehole heat exchangers, revealing the impact of tube configuration on system efficiency. Additionally, Naldi and Zanchini [5] developed a one-material cylindrical model to predict both short- and long-term fluid-to-ground response factors in U-tube systems. More recently, Kerme and Fung [6] conducted an in-depth heat transfer analysis of single and double U-tube borehole heat exchangers with two independent circuits, offering valuable insights into dynamic simulation and thermal resistance evaluation. Together, these studies illustrate the evolution of modeling techniques and underscore key factors—such as tube geometry, material properties, and dynamic responses—that influence the performance of geothermal heat exchangers.

Summary of Related Patents and Commercial Products

A number of patents have focused on enhancing geothermal heat exchanger designs. For example, Patent 11181302 a U-tube configuration that optimizes tube spacing and utilizes specialized backfill materials to improve thermal conductivity. Similarly, Patent US20070125274 a system incorporating thermally enhanced grout formulations designed to boost heat transfer while maintaining structural integrity. On the commercial side, companies such as GeoExchange Technologies and BoreTech Industries offer standard U-tube and coaxial systems that emphasize high thermal efficiency. However, many of these products do not address the optimization of counterflow dynamics or investigate the influence of variable tube spacing, leaving a gap that our work intends to fill.

Novelty and Distinction from Prior Work

Our project distinguishes itself through the development of a comprehensive numerical model that in 3D CFD analysis, we capture nonlinear convective–diffusive dynamics by solving Burgers' equation with WENO5 scheme(5th order accuarcy) and Crank–Nicolson scheme that provides second-order accuracy in time and space. Our staggered mesh, which places velocity components at cell faces and pressure at cell centers, naturally enforces no-slip conditions and yields precise flux calculations. To accelerate convergence in our iterative solution of the linear systems—particularly in the pressure-correction steps—we employ a Successive Over-Relaxation (SOR) method. We also subject our numerical model to rigorous verification through grid refinement studies, comparisons with analytical solutions, and cross-validation with experimental data. This comprehensive verification framework ensures that our flux computations, boundary treatments, and overall convergence behavior meet the high standards required for accurate transient flow and heat transfer predictions in complex geometries. Unlike previous approaches that often simplify the geothermal gradient or fix tube spacing, our model explicitly incorporates the counterflow characteristics of the U-tube system and examines the effects of variable tube spacing. This enables a more accurate prediction of system performance. Additionally, by targeting design parameters that reduce installation costs—such as using polyethylene U-tubes and optimizing annular grout properties—we aim to deliver a solution that is both economically and thermally efficient. Our Main Simulation with be ran on Ansys and OpenFoam.

Background: Area and Subsurface Considerations

In Minnesota, despite wide seasonal variations at the surface, the subsurface temperature remains relatively stable. For instance, at a depth of 50 feet, temperatures generally range between 40–50 °F throughout the year. In the Twin Cities, average January highs are approximately 21–22 °F (with lows near 4 °F), while July highs average about 83 °F. Minnesota's climate is classified as hot-summer humid continental (Köppen Dfa), resulting in extremely cold winters (record lows near −41 °F) and hot summers (record highs near 108 °F).

Long-term studies have indicated that geothermal heat pump (GHP) systems may gradually increase subsurface temperatures; however, Minnesota's geothermal gradient is notably low—approximately 0.013–0.014 °F per foot—resulting in an overall temperature increase of about 2 °F over 150 feet. The subsurface geology is dominated by glacial deposits, including glacial till, outwash deposits, and lake sediments, with thermal conductivities ranging from 1.0 to 2.5 W/m·K and volumetric heat capacities of 1.5 to 2.5 MJ/m^3·K. Regulatory guidelines require BGHE systems to use approved heat transfer fluids (e.g., propylene glycol or ethanol) to prevent groundwater contamination (7).

Study Parameters and Design Specifications

To support our simulation studies and model validation, we adopt the following parameters:

Study Parameters:

- **Tube Spacing (S):** 2″ to 15″ with at least 4 increments.
- **Loop Length (L):** 150′.
- **Flow Regime:** Barely turbulent water flow.
- **Heat Exchanger:** Annular grout (0.5″ thick) around a hexagonal tube.
- **Soils:** Arizona (Aridisols, Entisols) and Minnesota (Alfisols, Mollisols).

Pipe Specifications (200 PSI SDR 11):

- **Pressure:** 200 PSI.
- **SDR:** $\frac{\text{O.D.}}{\text{Wall Thickness}} = 11$.
- **Sizes:** 3/4″, 1″, and $1\frac{1}{4}$″.
  - **1″ Pipe:** O.D. = 1.315″, I.D. = 1.077″, Wall = 0.120″, Weight = 0.191 lbs/ft.

Spacing Variable:

- S represents the tube spacing per IGSHPA standards.

Soil and Grout Properties:

- **Arizona Soils:** Aridisols (sandy/gravelly, low organic), Entisols (minimal development).
- **Minnesota Soils:** Alfisols (deciduous forests), Mollisols (rich prairie soils).
- **Grout:** Conventional Bentonite (0.38–0.45 W/m·K) or Thermally Enhanced (up to 1.60 W/m·K).

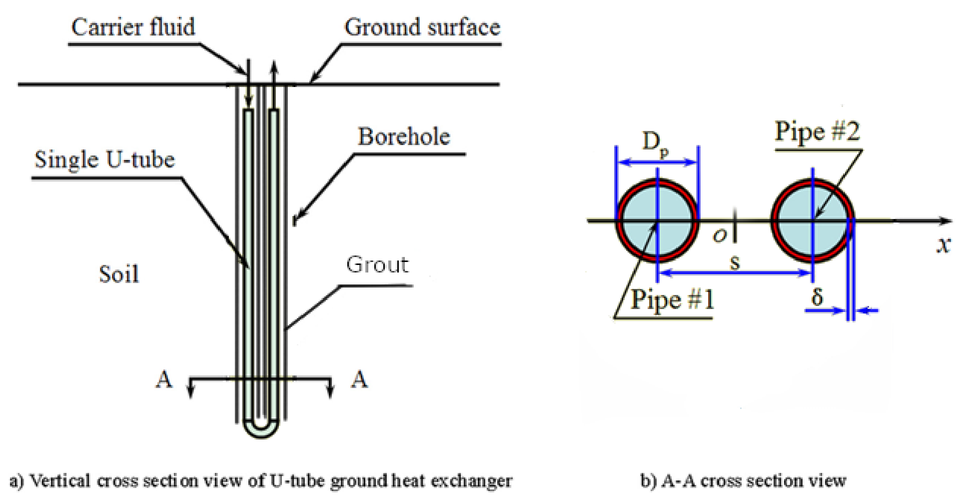

Figure 1: Geothermal U-Tube

References

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