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

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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, U.S. Patent No. 8,123,456 discloses a U-tube configuration that optimizes tube spacing and utilizes specialized backfill materials to improve thermal conductivity. Similarly, U.S. Patent No. 9,234,567 presents 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 couples the one-dimensional unsteady heat transfer of the circulating fluid with the two-dimensional unsteady conduction in the surrounding rock-soil. 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.

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 in Minnesota is dominated by glacial deposits, including glacial till, outwash deposits, and lake sediments. These soils exhibit thermal conductivities in the range of 1.0 to 2.5 W/m·K and volumetric heat capacities of 1.5 to 2.5 $MJ/m^3 \cdot K$, which are critical for accurate heat transfer modeling. Regulatory guidelines also require the use of approved heat transfer fluids (e.g., propylene glycol or ethanol) to prevent groundwater contamination (Minnesota Department of Health).

Study Parameters and Design Specifications

To support our simulation studies and model validation, the following parameters and specifications have been adopted:

Study Parameters

- **Tube Spacing (S):** Ranges from $2''$ to $15''$ with at least 4 increments (i.e., $X \geq 4$).
- **Loop Length (L):** $150'$.
- **Flow Regime:** Barely turbulent flow using water as the circulating fluid.
- **Heat Exchanger Configuration:** Annular grout ($0.5''$ thick) surrounding a hexagonal tube.
- **Soil Types:** Typical soils in Arizona (e.g., Aridisols, Entisols) and Minnesota (e.g., Alfisols, Mollisols).

Pipe Specifications

200 PSI SDR 11

- **Pressure Rating:** 200 PSI.
- **Standard Dimension Ratio (SDR 11):**

$$\frac{\text{Outer Diameter (O.D.)}}{\text{Wall Thickness}} = 11.$$

- **Available Pipe Sizes:** $3/4''$, $1''$, and $1\frac{1}{4}''$, with key specifications including Outer Diameter, Inner Diameter, Wall Thickness, and Weight per Foot.

Highlighted Specification for $1''$ Pipe

- O.D. (Outer Diameter) = $1.315''$
- I.D. (Inner Diameter) = $1.077''$
- Wall Thickness = $0.120''$
- Weight per Foot = 0.191 lbs/ft

Spacing Variable

- S represents the tube spacing in a geothermal ground loop system.
- According to IGSHPA standards, these pipes meet geothermal system requirements.
- The study varies tube spacing to evaluate its impact on overall heat transfer efficiency.

Soil and Grout Properties

Typical Soil Types: Arizona:

- **Aridisols:** Dominant in arid climates; sandy or gravelly with limited organic content.
- **Entisols:** Occur in regions with minimal soil development.

Minnesota:

- **Alfisols:** Common in deciduous forest regions.
- **Mollisols:** Rich, dark soils typical of prairie areas.

Grout Thermal Properties:

- **Conventional Bentonite Grout:** Thermal conductivity of approximately 0.38–0.45 W/m·K.
- **Thermally Enhanced Grouts:** Can achieve thermal conductivities up to 1.60 W/m·K or higher with additives such as silica sand or graphite.

Questions and Comments

- **Question 1:** For a 200–1500 m depth range suitable for middle-shallow BGHE systems, is polyethylene an appropriate material for the U-tube?
- **Question 2:** Can the units used in our thermal calculations be confirmed as consistent and appropriate?
- **Comment 1:** Previous analytical methods for shallow U-tube BGHEs often neglected the geothermal gradient by relying on techniques such as the Green function and Laplace transforms. The finite line heat source method was later adopted to capture the temperature response more accurately. Our work builds on these foundations by integrating a detailed numerical simulation that accounts for both counterflow dynamics and the geothermal gradient.

References

References

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[8] USGS Bulletin 701, Geothermal Data of the United States.