

Ground Heat Exchangers - A Comprehensive Review on Thermal Performance

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Abstract - This literature review synthesizes recent experimental, numerical, and field studies on ground heat exchangers, including borehole and pile systems, to identify key performance-controlling factors and design trends. The findings indicate that soil and groundwater conditions are the primary determinants of thermal performance, with thermal conductivity, moisture content, saturation, and advective groundwater flow significantly influencing heat transfer behaviour. Geometric parameters such as pipe configuration, spacing, depth, and borehole diameter also play an important role, with most exhibiting optimal ranges beyond which performance may decrease. Double U-tube and pile-based systems generally outperform simpler configurations due to increased heat exchange area and improved thermal interaction. Material enhancements, particularly high-conductivity backfills and thermally modified HDPE composites, substantially reduce thermal resistance, although their effectiveness is strongly dependent on-site conditions and system design. Operational strategies, including intermittent operation, flow modulation, and load balancing, are shown to significantly improve long-term efficiency and reduce thermal drift, often compensating for design limitations.

Keywords: Fluid velocity, Ground heat exchangers, HDPE, Thermal operation modes, Thermal properties

INTRODUCTION

Geothermal energy is widely recognised as a sustainable and reliable renewable source for space heating and cooling in buildings. Future projections indicate a continued rise in energy demand, especially in summer-intensive regions (Bureau of Energy Efficiency, 2019), highlighting the need for efficient cooling solutions. Ground-source heat pump (GSHP) systems are among the most effective technologies for harnessing geothermal energy due to their reliability and continuous operation. A typical GSHP system includes ground heat exchangers (GHEs), heat pump units, and building distribution systems. Closed-loop GHEs commonly consist of single or double U-shaped high-density polyethylene (HDPE) pipes installed in boreholes or structural elements and surrounded by thermally enhanced grout. A circulating fluid transfers heat between the building and the ground, rejecting heat during summer and extracting heat during winter through convection within the pipe and conduction in the surrounding ground. The relatively stable subsurface temperature enables efficient heat exchange. GHEs are generally classified into horizontal, vertical borehole, and pile systems. The overall performance of GSHP systems depends largely on the thermal behaviour of these GHE configurations. In the subsequent sections, the vertical heat exchangers equipped in boreholes and piles are referred as BHE and PHE, respectively.

GROUND HEAT EXCHANGERS – THERMAL PERFORMANCE PERSPECTIVES

Based on a critical review of the available literature, the effect of geometric structure, thermal operating modes, pile material properties, borehole backfill thermal properties, backfill materials, circulating fluid type, fluid velocity, and soil thermal properties on the thermal efficiency of ground heat exchangers is discussed in the subsequent sections.

(i) Geometric structure

Table 2 presents a detailed review of the geometric layout of GHEs on the thermal effectiveness

Table 2. Summary of previous studies on the geometric layout of borehole and pile heat exchangers

Study	Methodology	Configuration / Focus	Key Findings	Key Implication
Luo et al. (2015) [1]	Field testing and simulation	Spiral BHEs in clay, sand, and gravel	Sandy soils show the highest heat transfer; thermal performance is strongly soil-dependent	Site-specific design is essential; soil properties govern thermal efficiency
Qi et al. (2019) [2]	Experimental study	Pipe connection configurations	Parallel systems provide better long-term thermal stability	Configuration affects long-term system behaviour
Lyu et al. (2020) [3]	Numerical investigation	U- and W-shaped in pile groups	Heat transfer varies with pipe layout; corner piles more efficient	Spatial effects significant in pile groups

Adebayo et al. (2023) [4]	Experimental study	Borehole vs. pile GHE (cold region)	Pile GHE shows higher heat exchange due to larger diameter and conductivity	Pile systems can outperform conventional boreholes
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The reviewed studies collectively demonstrate that the thermal performance of ground heat exchanger (GHE) systems is governed by a combination of geological conditions, exchanger configuration, and system design optimization. From a configuration perspective, the geometry and arrangement of heat exchangers significantly influence efficiency. Double U-tube systems generally outperform single U-tube configurations due to increased heat transfer surface area and reduced thermal resistance, with reported reductions in borehole thermal resistance. Similarly, parallel-connected pipe systems demonstrate better thermal stability and lower fluid temperature drops compared to series configurations, although they may increase design complexity. Pile-based GHE systems show notable advantages over conventional borehole systems in several studies, primarily due to larger diameter, improved spacing, and dual structural-thermal functionality. However, their performance is also influenced by pile group interactions, where spatial position leads to non-uniform heat transfer distribution. Despite their advantages, multi-U and complex configurations often introduce higher hydraulic resistance and system complexity, indicating a trade-off between performance and operational practicality. Overall, the literature indicates that GHE performance is not governed by a single parameter but rather by the interaction between soil properties, exchanger geometry, pipe configuration, and system layout. Effective design, therefore requires an integrated approach that balances thermal efficiency, hydraulic performance, and economic feasibility.

(ii) Thermal operation modes

Table 3 summarizes the literature review on operational modes of the GHEs

Table 3. Summary of Studies on Operational Strategies and Thermal Performance of GSHP Systems

Study	Methodology	Focus	Key Findings	Key Implication
Zheng et al. 2011[5]	Experimental	Steady vs. cyclic loads	Intermittent mode reduces peak temperature differences	Delays thermal saturation
Park et al. 2013[6]	Experimental (TRT)	Pile vs. borehole; continuous vs. intermittent operation	Piles show higher heat exchange; intermittent mode reduces thermal resistance	Larger diameter and intermittent operation are beneficial
Guo et al. 2016[7]	Experimental	Hybrid vs. continuous operation	Continuous cooling causes thermal imbalance; hybrid/intermittent prevents it	Load balancing is critical for sustainability
Ruiz-Calvo et al. 2016[8]	Long-term field data (11 years)	Continuous vs. intermittent loads	Intermittent operation allows ground thermal recovery	Reduces long-term temperature drift

The reviewed literature consistently highlights that the operational strategy of ground-source heat pump (GSHP) systems is as critical as their physical design in determining long-term thermal performance, efficiency, and sustainability. A central finding across studies is that intermittent or cyclic operation generally outperforms continuous operation. Intermittent modes promote periodic thermal recovery of the surrounding ground, reduce overheating, and limit long-term thermal drift. This leads to improved system stability, better control of outlet fluid temperatures, and reduced risk of thermal saturation in the subsurface. In contrast, continuous high-load operation tends to increase borehole thermal resistance over time, amplify axial thermal losses in deep systems, and contribute to ground temperature imbalance. In addition, hydro-thermal interactions and system configuration influence operational outcomes. In multi-borehole or pile groups, continuous operation can intensify thermal interference and lead to uneven heat distribution, while intermittent operation improves thermal uniformity and reduces interaction effects. Pile-based systems also demonstrate higher resilience under continuous operation due to greater thermal mass and improved heat dissipation capacity

compared to conventional boreholes. In cold-region applications, intermittent operation plays a particularly important role by reducing the risk of ground freezing and enhancing seasonal recovery, thereby improving long-term operational safety and efficiency. Furthermore, field and numerical studies indicate that neglecting realistic operational modes during design can lead to underestimation or oversizing errors, reinforcing the need for accurate representation of actual operating conditions. Overall, the literature demonstrates that optimal GSHP performance depends strongly on operational control strategies, where intermittent operation, flow modulation, and load management collectively enhance thermal stability, reduce energy consumption, and improve long-term system sustainability.

(iii) Pipe Material Properties

Table 5 presents the influence of thermally modified pipe materials on the thermal efficiency of GHEs. The reviewed literature consistently demonstrates that enhancing pipe material thermal conductivity is an effective strategy for improving ground heat exchanger (GHE) performance, primarily by reducing borehole thermal resistance and increasing heat transfer efficiency between the circulating fluid and surrounding ground. A key finding across studies is that thermally modified HDPE-based materials significantly outperform conventional HDPE pipes.

Table 5. Summary of studies on thermally enhanced pipe materials for ground heat exchangers

Study	Methodology	Material / Modification	Key Findings	Key Implication
Sobolciak et al. 2020 [9]	Experimental	Polyethylene and expanded graphite composite	Increased conductivity but reduced ductility	Optimal filler content required to maintain mechanical integrity
Yang et al. 2022[10]	Experimental	HDPE with boron nitride and bio-based carbon fillers	Moderate conductivity improvement with lower environmental impact	Potential for sustainable/green geothermal pipe materials
Travas et al. 2023[11]	Experimental	HDPE with graphite and boron nitride fillers	Enhanced conductivity with acceptable mechanical strength	Filler optimisation balances thermal and structural properties
Chen et al. 2023[12]	Experimental	Aligned nitride in HDPE matrix	Improved directional (axial) conductivity with retained strength	Filler alignment enhances anisotropic heat transfer

The incorporation of conductive additives such as aluminium wires, graphite, boron nitride (BN), and carbon nanotubes (CNTs) leads to substantial improvements in thermal conductivity, ranging from moderate increases (25-33%) to very high enhancements (up to 3 times or 250% in advanced nanocomposites). These improvements directly translate into higher heat exchange rates and reduced borehole thermal resistance. Another important conclusion is that composite and nanomaterial reinforcement enables multi-functional performance gains, not only improving thermal conductivity but also maintaining acceptable mechanical strength. For example, BN and graphite-based fillers improve conductivity while preserving structural integrity, whereas CNT-based systems enhance both thermal conduction and energy storage capability in phase change composites. However, some studies highlight that excessive filler content can reduce ductility, indicating the need for optimized filler concentration. The literature also emphasizes that geometry and microstructural design are as important as material composition. Modified pipe geometries and aligned filler structures significantly enhance directional (axial) heat transfer and reduce internal resistance. This demonstrates that performance improvement is not solely dependent on material conductivity, but also on engineered heat transfer pathways. From a system-level perspective, improved pipe materials contribute to reduced borehole length requirements and lower installation costs, with some studies reporting up to 12.8% reduction in borehole length due to enhanced conductivity. This highlights direct economic benefits in addition to thermal performance improvements. Overall, the findings confirm that advanced composite and nanostructured pipe materials significantly enhance GSHP efficiency, but optimal performance requires balancing thermal conductivity, mechanical strength, cost, and sustainability considerations.

(iv) Borehole backfill thermal properties

Table 6 summarize the studies on borehole backfill materials on the thermal performance of GHEs. The reviewed studies consistently show that backfill and grout materials are among the most influential factors governing borehole heat exchanger (BHE) thermal performance, primarily by controlling borehole thermal resistance and the efficiency of heat transfer between the pipe and surrounding ground. A key finding across the literature is that thermal conductivity of backfill material directly governs system performance. High-conductivity materials significantly reduce borehole thermal resistance and enhance heat exchange rates. Multiple studies report improvements ranging from moderate gains (10-48%) to substantial enhancements in heat transfer efficiency

when thermally improved grouts or backfills are used. In some cases, advanced formulations such as graphite-enhanced or metallic particle-modified grouts achieve conductivity values as high as 3.5-5 W/m.K, demonstrating strong potential for high-performance systems. Another major conclusion is that backfill contributes a dominant share of total thermal resistance, with some studies indicating it can account for more than 65% of overall borehole resistance. This highlights that improving pipe or soil properties alone is insufficient unless backfill performance is also optimised. As a result, backfill selection is identified as a critical design parameter in GSHP systems.

Table 6. Summary of studies on backfill materials and thermal performance of borehole heat exchangers

Study	Methodology	Material / Focus	Key Findings	Key Implication
Lee et al. 2010[13]	Experimental	Silica sand and graphite grout	Conductivity up to 3.5 W/m.K	Hybrid fillers enhance grout performance
Wang et al. 2016[14]	Experimental	Sand, clay, loam	Sand shows highest conductivity and lower contact resistance	Coarse soils preferred
Choi and Ooka 2016[15]	Experimental	Gravel vs. cement grout	Gravel reduces resistance under certain conditions	Coarse aggregates enhance heat transfer
Cao et al. 2018[16]	Experimental	Organic soil, clay, silt, sand	Sand exhibits the best geothermal suitability	Soil type selection is important
Al-Ameen et al. 2018[17]	Experimental	Metallic particle-enhanced grout	Heat transfer improved up to 77%	Advanced composites significantly boost performance

In addition, natural soil and moisture conditions significantly influence thermal behaviour. Coarse-grained soils such as sand consistently outperform fine-grained soils (clay and silt) due to higher conductivity and lower contact resistance. Moisture content further enhances thermal performance, with wet backfill mixtures showing notably improved conductivity and reduced borehole length requirements. From a practical standpoint, improved backfill materials can lead to reduced borehole length, lower installation costs, and improved energy efficiency, reinforcing their importance in system optimisation. Overall, the findings confirm that optimising backfill and grout materials is one of the most effective strategies for improving GSHP efficiency, with performance strongly dependent on thermal conductivity, moisture conditions, and additive composition.

(v) Fluid Velocity

Table 7 shows the influence of fluid flow within HDPE pipes on the thermal performance of GHEs.

Table 7. Summary of studies on flow velocity and thermal performance of borehole heat exchangers

Study	Methodology	Focus	Key Findings	Key Implication
Zhang et al. 2018 [18]	Numerical (transient)	Variable vs. constant flow	Adaptive flow control stabilises temperatures and improves long-term performance	Flow modulation enhances system efficiency
Yang et al. 2021 [19]	CFD simulation	Internal convective heat transfer	Velocity strongly influences thermal gradients within pipes	Optimal flow selection is critical for uniform heat transfer

Malek et al. 2021 [20]	Coupled thermo-hydraulic modelling	Large borehole field optimisation	Flow optimisation reduces pumping energy by 20% without loss in heat transfer	Energy-efficient operation through velocity control
Liang et al. 2022 [21]	Numerical and experimental	Freezing risk vs. velocity	Low velocity causes local freezing; moderate velocity improves stability	Proper velocity prevents freezing in cold regions

The reviewed studies collectively indicate that fluid flow rate and velocity are key operational parameters governing the thermal performance and energy efficiency of borehole heat exchanger (BHE) systems. Their influence extends to heat transfer rates, thermal stability, pumping energy demand, and long-term system reliability. A central finding across the literature is that flow optimization significantly improves system performance compared to constant high-flow operation. Adaptive flow strategies help stabilize fluid and ground temperatures, reduce thermal fluctuations, and enhance long-term operational efficiency. This demonstrates that dynamic control strategies are more effective than fixed operating conditions. Another consistent outcome is that an optimal velocity range exists, balancing heat transfer enhancement and pumping energy consumption. While increased flow velocity reduces thermal resistance by improving convection within the pipes, excessively high velocities lead to higher pumping power requirements without proportional thermal benefits. Studies report that optimized velocity control can reduce energy consumption by around 20% while maintaining adequate heat transfer performance, highlighting a clear thermo-hydraulic trade-off. The literature also shows that soil thermal properties significantly influence the effectiveness of flow control strategies. In higher-conductivity soils, the impact of velocity changes is more pronounced, whereas in low-conductivity soils, the system is less sensitive to flow variations. This indicates that hydraulic design must be coupled with site-specific geological conditions for optimal performance. In cold-region applications, flow velocity plays a critical role in preventing freezing around boreholes. Low velocities increase the risk of localized freezing due to insufficient heat replenishment, while moderate velocities enhance thermal stability and ensure safe operation under seasonal or sub-zero conditions. Overall, the findings confirm that flow rate optimization is essential for achieving energy-efficient and thermally stable GSHP operation. Proper velocity control not only improves heat transfer uniformity but also reduces operational costs and enhances system reliability, making it a critical component of GSHP system design and thermal operation.

(vi) Soil thermal properties

Table 8 presents a review of studies on the influence of soil thermal properties on the thermal potential of GHEs. The reviewed studies consistently demonstrate that soil thermal and hydrogeological properties are the dominant factors governing the performance of borehole heat exchangers (BHEs), with moisture content, saturation level, soil type, and groundwater interaction playing central roles in heat transfer efficiency and long-term system stability. A key finding across the literature is that soil thermal conductivity strongly controls heat exchange performance, with sandy and coarse-grained soils generally outperforming clay and fine-grained soils due to higher permeability and lower thermal resistance. Improvements in heat transfer of approximately 8-40% are reported in sandy or saturated conditions compared to clayey or unsaturated soils, highlighting the importance of soil texture and structure. Moisture content emerges as a critical governing parameter, often having a stronger influence than density or mineral composition. Increased saturation consistently enhances thermal conductivity and reduces thermal resistance, improving system efficiency. However, spatial variability in moisture can significantly alter apparent thermal conductivity, indicating that soil heterogeneity must be explicitly considered in design and parameter estimation. Several studies emphasize that freeze-thaw cycles and groundwater interactions significantly affect thermal behaviour, particularly in cold or saturated environments. High-conductivity soils and groundwater flow improve thermal stability and reduce seasonal temperature fluctuations, but advective heat transfer can also distort thermal response test (TRT) interpretations if not properly accounted for. Another important outcome is that soil heterogeneity and simplification in modelling can lead to significant design errors, including underestimation of borehole length by up to 15%. This highlights the limitations of uniform soil assumptions in conventional GSHP design methodologies. Overall, the literature confirms that accurate soil characterization is the most critical and also the most uncertain input in BHE system design. Thermal conductivity and moisture dynamics must be carefully assessed to ensure reliable performance prediction and optimal system sizing, especially in variable or cold-region environments.

Table 8. Summary of studies on the effect of soil thermal properties on the GHE performance

Study	Methodology	Focus	Key Findings	Key Implication
Cao et al. 2018 [16]	Experimental (A-DTS)	Moisture variability in soils	Small moisture variations significantly alter conductivity	Spatial heterogeneity must be considered
Agrawal et al. 2020 [22]	Experimental	Wet vs. dry sand-bentonite	Wet soils show higher conductivity and lower resistance	Moisture enhances heat exchange efficiency
Malek et al. 2021 [20]	Experimental	Soil density, moisture, mineralogy	Moisture has the strongest influence on conductivity; density secondary	Moisture control is critical for thermal design
Aizzuddin et al. 2021[23]	Experimental	Tropical soil conditions	Soil $k = 1.5-5$ W/m.K optimizes GSHP performance	Site-specific soil characterization is essential
Li et al. 2020 [24]	Numerical	Kaolin-amended sand	Improved moisture retention and stable thermal conductivity	Soil additives enhance long-term performance

CONCLUSIONS

The reviewed literature demonstrates that the performance of ground source heat pump (GSHP) and ground heat exchanger (BHE) systems is governed by a strongly coupled interaction of subsurface conditions, system design, materials, and operational strategy, rather than any single controlling parameter.

1. Geometrical and structural factors influence GHE performance, but their impact is generally secondary to subsurface thermal and hydrogeological conditions. Configurations such as double U-tubes and pile systems perform better due to increased heat transfer area, yet most geometric parameters show diminishing returns beyond optimal ranges.
2. Thermal operation strategy plays a crucial role in long-term system stability. Intermittent operation, flow modulation, and load balancing improve efficiency, reduce thermal drift, and can partially offset limitations, arising from non-optimal design.
3. Material properties such as backfill and pipe conductivity significantly affect thermal resistance. High-conductivity grouts and advanced composite pipes enhance heat transfer, but their effectiveness depends strongly on optimized geometry and site conditions.
4. An integrated design approach is essential for high-performance GSHP systems. Optimal efficiency is achieved by balancing geometry, materials, subsurface conditions, and operational control, ensuring thermal, hydraulic, economic, and site constraints are simultaneously satisfied.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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