
Rajul Agrawal, Dr. B. K. Chourasia

Post Graduate student, Associate Professor
Department of Mechanical Engineering
Jabalpur Engineering College
Jabalpur 482011, India.

Abstract- Ground heat exchangers (GHEs), also known as ground source heat exchangers or geothermal heat exchangers, have gained significant attention in recent years as sustainable and energy-efficient solution for heating and cooling buildings. This review paper provides a comprehensive analysis of GHEs, encompassing their design principles, performance evaluation methods, and diverse applications in residential, commercial, and industrial settings. The review discusses current challenges and future research directions in the field of GHEs, including the optimization of system design, operational strategies, and cost-effectiveness. It highlights the importance of standardized guidelines and regulations to ensure proper installation, maintenance, and monitoring of GHE systems.

Keywords: Ground heat exchangers, maintenance, monitoring, system design, geothermal heat exchangers, etc.

INTRODUCTION

A ground heat exchanger (also known as a ground source heat exchanger or geothermal heat exchanger) is a system that utilizes the relatively constant temperature of the ground to provide heating, cooling, or both, for residential, commercial, or industrial buildings. It takes advantage of the fact that the temperature below the Earth's surface remains constant throughout the year, typically between 5 to 20 degrees Celsius (41 to 68 degrees Fahrenheit) depending on the location.

The ground heat exchanger consists of a series of pipes or tubes buried underground, either horizontally or vertically, and a heat pump system. These pipes are made of high-density polyethylene (HDPE) or other suitable materials and are filled with a heat transfer fluid, usually a mixture of water and antifreeze.

During the winter, the fluid absorbs heat from the ground through the buried pipes and carries it into the heat pump. The heat pump then increases the temperature of the fluid further using a compressor and transfers the heat to the building's heating system. This process provides space heating for the building[1].

In the summer, the ground heat exchanger works in reverse. The fluid absorbs heat from the building's cooling system and carries it into the heat pump. The heat pump then transfers the heat to the ground, effectively cooling the building. The efficiency of a ground heat exchanger depends on the design, size, and location of the system. Horizontal ground heat exchangers require more space for installation but are suitable for areas with sufficient land availability. Vertical ground heat exchangers require drilling deep boreholes and are more suitable for areas with limited space. The ground composition and thermal conductivity also play a role in the system's performance [2].

Ground heat exchangers are considered a sustainable and renewable energy solution as they utilize the Earth's natural heat. They can significantly reduce energy consumption and greenhouse gas emissions compared to conventional heating and cooling systems. However, the installation costs can be relatively high, and the suitability of such a system depends on factors like site conditions, energy requirements, and local regulations. Consulting with a qualified professional is recommended for the design and installation of a ground heat exchanger system.

In the present paper, a review on ground heat exchangers has been carried out, which will play a crucial role in synthesizing existing knowledge, providing guidance for design and performance evaluation, showcasing technological advancements, identifying best practices, addressing policy considerations, and outlining future research directions. It will serve as a valuable resource for researchers, engineers, policymakers, and other stakeholders interested in geothermal heating and cooling technologies [3].

DIFFERENT TYPES OF GROUND HEAT EXCHANGERS

There are several types of ground heat exchangers (GHEs) used in geothermal heating and cooling systems. The main types include:
1. Horizontal Ground Heat Exchanger (HGHX): In this configuration, pipes or loops are installed horizontally in a shallow trench or a series of trenches. The depth of the trench typically ranges from 0.8 to 1.5 meters (2.6 to 5 feet). HGHX systems are suitable for areas with sufficient land availability.

2. Vertical Ground Heat Exchanger (VGHX): VGHX systems involve drilling boreholes vertically into the ground. The depth of the boreholes can vary depending on factors like the soil type, thermal conductivity, and required heat transfer capacity. Multiple pipes or loops are inserted into each borehole, and a grouting material is used to fill the gaps around the pipes, ensuring good thermal contact with the surrounding ground.

3. Pond/Lake Heat Exchanger: In this type of GHE, heat exchange takes place with a body of water, such as a pond or lake. Coiled pipes are submerged in the water, and heat is transferred between the water and the fluid circulating through the pipes. Pond/lake heat exchangers are suitable for locations with access to a water source.

4. Open Loop Ground Heat Exchanger: Open loop systems utilize groundwater as the heat exchange medium. Groundwater is pumped from a well or other water source, passed through a heat exchanger to extract, or reject heat, and then discharged back into the ground or another suitable outlet. Open loop GHEs require access to an adequate supply of groundwater and proper disposal options for the discharged water.

5. Standing Column Well (SCW): SCW systems are a type of vertical GHE that utilize a single borehole for both extraction and injection of groundwater. The same well is used for both water supply and disposal, resulting in a closed-loop system. The heat exchange occurs within the well itself, and the surrounding geologic formation serves as the heat source or sink.

6. Combination Systems: Combination systems integrate different types of GHEs to take advantage of their respective advantages and address site-specific conditions. For example, a hybrid system may combine horizontal and vertical GHEs or a combination of a horizontal GHE with a pond or lake heat exchanger. These systems offer flexibility in design and can optimize performance based on site characteristics.

The selection of the appropriate type of GHE depends on factors such as available land area, geology, hydrology, thermal conductivity of the soil, energy requirements, and local regulations. Consulting with a geothermal system designer or engineer is recommended to determine the most suitable GHE configuration for a specific project.[4-7]

Table 1 Previous research on GHE considering design and configuration.

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<th>Year</th>
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<th>Main findings</th>
<th>Outcomes measured</th>
<th>Detailed study design</th>
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<tr>
<td>2022</td>
<td>Saif H. Majeed, Amar S. Abdul-Zahra, D. G. Mutasher</td>
<td>Copper tubes were the best type of heat exchanger to be used in this regard.</td>
<td>The type of material of the pipe has a significant influence on both the heat transfer effectiveness and the system performance. Copper tubes were the best type of heat exchanger (type coil) to be used in this regard. The highest recorded values of the heat exchange rate were 5.81, 4.81, 2.72, 1.60, and 1.32 kw with an inlet temperature of 80°C and a flow rate of 5 l/min for the case of copper coil, copper 3u, galvanized 3u, pvc profile, and pvc 3u, respectively.</td>
<td>Heat transfer, effectiveness system, performance, heat exchange rate</td>
<td>Experimental</td>
</tr>
<tr>
<td>2021</td>
<td>S. Koohi-Fayegh, M. Rosen</td>
<td>The ground provides a better source/sink for heat than outside air for heat pump efficiency.</td>
<td>Ground heat exchangers can be used to store heat in the ground during summer for use in winter, increasing efficiency and reducing environmental impact. Several heat transfer models exist for ground heat exchangers, which usually consist of a series of vertical or horizontal underground pipes. Design software for vertical ground heat exchangers is available to help optimize their performance and characteristics.</td>
<td>A review of analytical and numerical models for heat transfer in vertical heat exchangers</td>
<td>A review</td>
</tr>
<tr>
<td>2021</td>
<td>Giouli Mihalakakou, Manolis Souliotis, Maria Papadaki, George Halkos</td>
<td>System design parameters are most important on the thermal efficiency of the system.</td>
<td>Earth-to-air heat exchangers can significantly reduce heating/cooling energy loads and improve indoor thermal comfort conditions. System design parameters, especially</td>
<td>Thermal performance of earth to air heat exchanger</td>
<td>A review</td>
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<td>Authors</td>
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<td>John Paravantis, Sofoklis Makridis, Spiros Papaefthimiou</td>
<td>Impact of main characteristics on thermal efficiency</td>
<td>length and burial depth, have the most important influence on the thermal efficiency of the system. More experimental work, including laboratory simulators, is needed to further assess the economic feasibility of earth-to-air heat exchangers.</td>
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<tr>
<td>Hoon Ki Choi, Geun Jong Yoo, Jae Hun Pak, Changhee Lee</td>
<td>2018 Branch tube type ground heat exchangers are suggested for increasing heat transfer efficiency.</td>
<td>The branch tube type ground heat exchanger has better heat transfer performance than the u-tube type. Increasing the number of branch tubes improves the heat transfer performance. The branch tube type yields higher pressure drop than the u-tube type for the same mass flow rate of circulating fluid.</td>
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<td>Tian yan, xinhua xu</td>
<td>2018 Ground heat exchangers can be used in a passive or active way.</td>
<td>Ground heat exchangers can be classified into water- or air-based ground heat exchanger according to the heat transfer medium. Ground heat exchangers can be used in a passive or active way. Various technologies can be integrated with ground heat exchangers to improve efficiency and reduce cost.</td>
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<tr>
<td>A. Shtym, i. Zhurmilova</td>
<td>2017 The vertical ground heat exchanger has the advantage over the horizontal one as it is less dependent on seasonal fluctuations of the ambient temperature and solar radiation.</td>
<td>• vertical ground heat exchangers have the advantage over horizontal ones due to their lower dependence on seasonal fluctuations and solar radiation, and their smaller area requirement. • installation of ground heat exchangers in consumable pipelines can be calculated, and the cost of construction works required for using such an energy source can be determined. • horizontal and vertical ground heat exchangers can be compared in terms of their features and types.</td>
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<tr>
<td>Bahman zohuri</td>
<td>2017 Heat exchangers have widespread industrial and domestic applications.</td>
<td>• heat exchangers are heat transfer devices that exchange heat between two or more process fluids. • heat exchangers have widespread industrial and domestic applications. • many types of heat exchangers have been developed for use in various industries.</td>
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<tr>
<td>Ravi ranjan manjun, v. Bartaria</td>
<td>2016 The closed loop system may be more effective (while the air temperature extremes) as an open system.</td>
<td>• earth air heat exchangers (eahees) are an effective passive heating/cooling medium for buildings. • there are two types of eahees: closed and open systems. • the undisturbed temperature of the ground is important for a correct interpretation of the geothermal heat exchanger.</td>
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| 2016 | Suresh Kumar Soni, Mukesh Pandey, Vishvendra Nath Bartaria | The power consumption compared to base mode (i.e., Conventional air conditioner) reduces when horizontal and vertical direct expansion ground coupled heat pump systems are used.                                             | - direct expansion ground coupled heat pump systems can significantly improve the performance of conventional air conditioners.  
- horizontal and vertical direct expansion ground coupled heat pump systems reduce power consumption compared to the base mode.  
- vertical configured buried copper tubes provide more economic feasibility than horizontal.                                             | Experimental          |
| 2015 | Antonio Capozza, Angelo Zarrella, Michele De Carli | The energy efficiency of the heat pump depends on the temperature of the heat carrier fluid on the ground side.                                                                                             | - the energy efficiency of the heat pump system is affected by the temperature of the heat carrier fluid on the ground side.  
- a detailed numerical simulation tool was used to analyze the effects of the heat imbalance on the heat pump entering fluid temperature over ten simulated years. | Long term analysis of 2 office buildings with unbalanced load profiles in Italy                                                                                                                     |
| 2011 | Lu xing, james r. Cullin, j. Spitler, piljae im, d. Fisher | A numerical model can be used to size these foundation heat exchanger systems.                                                                                                                               | - a numerical model has been developed to size foundation heat exchanger (fhx) systems.  
- the numerical model is validated with one year of experimental data collected at an experimental house.  
- the model shows good agreement with the experimental data, with minor discrepancies due to approximations. | Experimental          |
| 2009 | S. Javed, P. Fahlen, J. Claesson                 | The ground may be used as a heat source, a heat sink, or as a heat storage medium by means of vertical ground heat exchangers.                                                                                  | - various analytical and numerical models of varying complexity have been developed and used to predict heat transfer in vertical ground heat exchangers.  
- this paper provides a state-of-the-art review of analytical and hybrid models for the vertical ground heat exchangers.  
- the paper highlights the strengths and limitations of these models from design and research points of view. | A review of scientific work                                                                                                                                             |
| 2007 | Georgios. Florides, soteris. Kalogirou          | The geometrical characteristics of the system are input data for ground heat exchangers.                                                                                                                        | - ground heat exchangers are an effective way to exploit the heat capacity of the ground. several calculation models exist for ground heat exchangers, considering geometrical characteristics, thermal characteristics of the ground and pipe, and undisturbed ground temperature. | Efficiency of heat exchanger system  
- temperature variation around the pipes  
- temperature variation in the ground                                                                                           |
ADVANCEMENTS IN HORIZONTAL GROUND HEAT EXCHANGERS

Advancements in horizontal ground heat exchangers (GHEs) have aimed to enhance their performance, efficiency, and ease of installation. Some notable advancements in this area include:

1. Improved Pipe Materials: The development of high-density polyethylene (HDPE) pipes with enhanced thermal conductivity has improved heat transfer efficiency in GHE systems. These pipes exhibit higher resistance to thermal deformation and offer improved durability, minimizing the risk of leaks or pipe failure.

2. Enhanced Pipe Configurations: Advancements in pipe layout and configuration have optimized the performance of horizontal GHEs. Innovative designs, such as serpentine or spiral configurations, increase the contact area between the pipes and the surrounding soil, promoting better heat transfer. This results in improved system efficiency and reduced installation footprint.

3. Enhanced Heat Transfer Fluids: Research has focused on developing more efficient heat transfer fluids for GHE systems. Novel fluid compositions and additives have been explored to improve heat conductivity, reduce pressure drop, and prevent pipe fouling or corrosion. These advancements aim to enhance the overall thermal performance of the GHE system.

4. Enhanced Ground Coupling: Techniques such as grouting or backfilling with thermally enhanced materials have been investigated to improve the thermal contact between the pipes and the surrounding soil. This optimization minimizes thermal resistance and enhances heat transfer, leading to improved system efficiency.

5. Monitoring and Control Systems: Advanced monitoring and control systems have been developed to optimize the operation of horizontal GHEs. These systems integrate sensors and data analytics to monitor temperature differentials, flow rates, and energy consumption. This real-time data enables efficient system operation, predictive maintenance, and potential energy savings.[8-10]

6. Numerical Modeling and Simulation: The use of advanced numerical modelling and simulation techniques has enabled more accurate prediction of the performance of horizontal GHEs. These models consider factors such as soil properties, groundwater flow, and thermal characteristics to optimize design parameters, pipe spacing, and layout. This helps to maximize heat transfer efficiency and system performance.

7. Integration with Renewable Energy Sources: Horizontal GHEs are increasingly being integrated with renewable energy sources, such as solar panels or wind turbines, to provide a more sustainable and energy-efficient heating and cooling solution. This integration allows for the utilization of renewable energy for GHE system operation, reducing reliance on conventional energy sources.[11]

These advancements collectively contribute to improved efficiency, enhanced performance, and increased applicability of horizontal GHE systems. They enable greater utilization of geothermal energy and promote the adoption of sustainable heating and cooling solutions in various residential, commercial, and industrial applications.[14,17]

Table 2 Recent studies on advancements in horizontal ground heat exchangers

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<tr>
<th>Year</th>
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<th>Main findings</th>
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<th>Detailed study design</th>
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<tr>
<td>2021</td>
<td>K. Balaji</td>
<td>Open-loop and closed-loop pipe networks are the most common ground heat exchanging methods.</td>
<td>• The integration of shallow geothermal energy (SGE) with heat pumps using pipe networks is extensively reviewed. • Factors influencing the ground heat exchanger’s performance such as heat transfer fluid (HTF), groundwater flow, and soil properties are discussed in detail. • This paper highlights the recent research findings and potential research points in the ground heat exchanger.</td>
<td></td>
<td>comprehensive review</td>
</tr>
<tr>
<td>2019</td>
<td>Arif Widiatmojo, S. Gaurav, T. Ishihara, A. Tomigashi, K. Yasukawa, Y. Uchida, Shohei Kaneko, M. Yoshioka</td>
<td>The high hydraulic resistance of installed capillary mat heat exchangers may become the major disadvantage of the capillary mat.</td>
<td>• The capillary mat heat exchanger required 6% higher electricity consumption compared to the slinky pipe heat exchanger. • The results suggest the potential use of capillary mat as an alternative to slinky heat exchanger. • The high hydraulic resistance of installed</td>
<td>Electricity Consumption •Performance of Capillary Mat In Comparison To Slinky Pipe •Hydraulic Resistance Of Installed</td>
<td>comparison of 2 different heat exchangers, namely, the capillary mat and the widely used slinky pipe</td>
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<tr>
<td>Year</td>
<td>Authors</td>
<td>Abstract summary</td>
<td>Main findings</td>
<td>Outcomes measured</td>
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<td>2018</td>
<td>Jiajia Gao, Anbang Li, Xinhua Xu, Wenjie Gang, Tian Yan</td>
<td>Ground heat exchangers can be used in a passive or active approach.</td>
<td>• Ground heat exchangers can be classified into water-based and air-based ones based on the heat transfer medium, and can be used in a passive or active approach. • Ground heat exchangers can be integrated with various cooling and heating technologies, such as solar thermal collectors, cooling towers, nocturnal radiative cooling technology, and solar chimney. • Ground heat exchangers can help realize zero energy buildings, providing a promising solution to improve energy efficiency of buildings.</td>
<td>Capillary Mat Heat Exchangers</td>
<td>a literature review</td>
</tr>
<tr>
<td>2016</td>
<td>Michiya Suzuki, Kazuyuki Yoneyama, Saya Amemiya, Motoaki Oe</td>
<td>The diameter of the spiral-type heat exchanger is determined to reduce the construction cost.</td>
<td>• A spiral-type heat exchanger for a ground-source heat pump system has been developed to perform intensive heat-exchange in the aquifer layer near the ground surface. • The performance of the heat exchanger has been simulated under various flow rates and soil conditions using the numerical simulator “TOUGH2/EOS1.” • The cost-effectiveness of the spiral-type exchanger has been made clear.</td>
<td>•Heat Exchange Capacity Per Unit Length •Performance of The Heat Exchanger Under Various Flow Rates and Soil Conditions •Cost Effectiveness Of The Spiral Type Exchanger</td>
<td>experimental</td>
</tr>
<tr>
<td>2015</td>
<td>Suresh Kumar Soni, Mukesh Pandey, Vishvendra Nath Bartaria</td>
<td>The performance of both types of ground-coupled heat exchanger systems is reviewed.</td>
<td>• Ground coupled heat exchangers (GCHEs) are used for space conditioning, water heating, agricultural–drying, bathing, and swimming. • GCHEs reduce cooling load in summer and heating load in winter, and can conserve significant amounts of primary energy. • Experimental and modelling studies have been conducted on both earth–air heat exchanger (EAHE) and ground source heat pump (GSHP) systems, and their merits and demerits have been identified.</td>
<td>•Cooling Load Reduction in Summer •Heating Load Reduction in Winter •Primary Energy Conservation •Emission Reduction •Performance of Earth–Air Heat Exchanger Systems</td>
<td>a review of experimental and modelling studies</td>
</tr>
<tr>
<td>2011</td>
<td>A. Benazza, Eduardo Blanco, M.</td>
<td>A typical ground-coupled heat exchanger consists</td>
<td>• A numerical simulation was carried out to investigate the performance of a horizontal</td>
<td>•Heat Exchanger Efficiency</td>
<td>A numerical investigation</td>
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<tr>
<td>Year</td>
<td>Authors</td>
<td>Abstract summary</td>
<td>Main findings</td>
<td>Outcomes measured</td>
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<tr>
<td>2010</td>
<td>Aichouba, José Luis Río, Samir Laouedj</td>
<td>on a set of pipes buried vertically or horizontally in the ground and coupled to a heat pump.</td>
<td>ground coupled heat exchanger. • The influences of thermal conductivities and geometrical parameters on the heat exchanger efficiency were studied. • The results showed that the heat exchanger efficiency was affected by the climatic conditions, thermal conductivities, and geometrical parameters.</td>
<td>Temperature Distribution Of The 1 Or 2 Dimensional Cylindrical Heat Source Models With Infinite And Finite Length</td>
<td>Detailed study design</td>
</tr>
<tr>
<td>2010</td>
<td>Lin Yun</td>
<td>A solid cylindrical heat source model is proposed to describe the heat transfer process of the spiral coil ground heat exchangers.</td>
<td>• A solid cylindrical heat source model is proposed to describe the heat transfer process of the spiral coil ground heat exchangers. • Analytical solutions have been derived, applicable for temperature distribution of the one-or two-dimensional cylindrical heat source models with infinite and finite length. • Geometrical and physical parameters which impact on this heat transfer process have been analysed and discussed accordingly.</td>
<td>Integral Average Temperature On Cylindrical Surface</td>
<td>Detailed study design</td>
</tr>
<tr>
<td>2004</td>
<td>Zhao Jun</td>
<td>The heat transfer performance of ground exchanger is studied for different soil, different backfill material and different pipe quantity.</td>
<td>• Different buried methods of ground heat exchangers have different heat transfer performance. • Heat transfer performance is affected by soil type, backfill material, and pipe quantity. • Single U-pipe with concrete backfill has the highest heat transfer performance.</td>
<td>Heat Transfer Performance of Ground Exchanger</td>
<td>Detailed study design</td>
</tr>
<tr>
<td>2004</td>
<td>LIU Dong-sheng, SUN You-hong, Gao Ke, WUXiao-hang</td>
<td>Ground heat exchanger is the key technique of ground source heat pump.</td>
<td>• Ground Source Heat Pump technique is a renewable energy system that uses the heat stored in the ground to provide heating and cooling. • Ground heat exchanger is the key technique of ground source heat pump and its patterns are discussed. • Software is helpful to design ground heat exchanger and its market is becoming more and more extensive.</td>
<td>Experimental study</td>
<td>Detailed study design</td>
</tr>
<tr>
<td>2004</td>
<td>Wang Xiaowei</td>
<td>Ground-coupled heat pump systems have great potential for energy conservation in buildings.</td>
<td>• Drilling methods and machineries, pipe preparation and borehole backfilling are essential for the installation of vertical ground loops. • Ground heat exchangers are an important component of ground-coupled heat pump systems. • Ground-coupled heat pump systems have great potential for energy conservation in buildings.</td>
<td></td>
<td>Detailed study design</td>
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<tr>
<td>2004</td>
<td>Zhu Ying-chun</td>
<td>The results indicated can be implied in</td>
<td>• Engineering drilling, grouting engineering for backfilling material and inserting U-type pipes into the bore holes are</td>
<td></td>
<td>Detailed study design</td>
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<tr>
<td>Year</td>
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| 1998 | Gerrit Draayer, J. V. Dijk | The secondary loop is a heat pump between the primary heat exchanger, compressor and condenser. | • Ground heat exchangers can be used to transfer heat from the ground to a building.  
• The system consists of three loops: a primary loop with a U-shaped tube buried in the ground, a secondary loop with a heat pump, and a final loop with radiators.  
• The system is efficient and cost-effective, making it a viable option for heating buildings. | | |
| 1990 | Otto J. Svec | A horizontal ground heat exchange system used in an experimental Ground Source Heat Pump installation demonstrated its excellent performance. | • Spiral ground heat exchangers made of copper and high-density polyethylene tubing can be used in GSHP systems to activate a large mass of soil.  
• Monitoring of the system during the 1988/89 winter season demonstrated its excellent performance.  
• Horizontal GSHP systems may be more economical than vertical GSHP systems in most practical situations. | •Performance of the Ground Heat Exchange System  
•Potential Savings on Initial Installation Costs  
•Economy of Horizontal GSHP Systems Compared to Vertical GSHP Systems | experimental |
| 1989 | O. Svec, J. Palmer | A high-efficiency ground heat exchanger has been developed for use with ground-source heat pumps. | • A high-efficiency ground heat exchanger has been developed for use with ground-source heat pumps.  
• Thermal performance of a full-scale prototype indicated that this heat exchanger can achieve very high heat extraction rates if subfreezing operating temperatures are used.  
• For sensitive soil types, such as Leda clay, substantial settlement occurred after the first freeze-thaw cycle due to initial collapse of the soil structure. | •Heat Extraction Rates  
•Settlement of Soil Structure | |
CONCLUSION AND FUTURE RESEARCH

As the review carried out it can be observed that the research in ground heat exchangers (GHEs) is crucial to further advance the technology, improve its performance, and address various challenges associated with its implementation. Some key areas that warrant research in GHEs include:

- **Thermal Performance Optimization:** There is a need for research to optimize the thermal performance of GHE systems. This involves studying factors such as pipe design, spacing, and configuration to maximize heat transfer efficiency, minimize pressure drop, and reduce thermal losses. Advanced numerical modelling and simulation techniques can be employed to analyse and optimize these parameters.

- **Ground Thermal Properties and Characterization:** Research is needed to improve our understanding of the thermal properties of different soil types and their impact on GHE performance. This includes studying the influence of factors like soil moisture content, porosity, and thermal conductivity on heat transfer rates. Accurate characterization of the ground thermal properties can lead to better design and sizing of GHE systems.

- **Integration with Renewable Energy Sources:** Research can focus on exploring the integration of GHE systems with renewable energy sources, such as solar panels, wind turbines, or waste heat recovery systems. Investigating the optimal combination of GHEs with other renewable energy technologies can enhance system efficiency, reduce environmental impact, and contribute to a more sustainable energy mix.

- **Hybrid GHE Systems:** There is a need for research on hybrid GHE systems that combine different types of GHE configurations or integrate GHEs with other heat transfer technologies. Examining the performance, design considerations, and operational strategies of hybrid GHE systems can lead to improved overall system efficiency and flexibility.

- **Long-Term Performance and Reliability:** Long-term performance and reliability of GHE systems require further investigation. Research can focus on monitoring the performance of GHEs over extended periods, assessing factors such as thermal degradation, ground movement effects, and long-term pipe integrity. This research can help develop guidelines for maintenance, system optimization, and ensuring the longevity of GHE systems.

- **Environmental Impacts and Sustainability:** Research should continue to explore the environmental impacts and sustainability aspects of GHE systems. This includes assessing the overall carbon footprint, energy consumption, and potential groundwater contamination risks associated with GHE installation, operation, and decommissioning. Developing environmentally friendly installation techniques and investigating the potential for GHE systems to contribute to carbon neutrality are areas of interest.

- **Cost Reduction and Economics:** Further research is needed to explore cost reduction strategies, improve cost-effectiveness, and enhance the economic viability of GHE systems. This can involve analyzing the life cycle costs, exploring innovative installation methods, assessing financing models, and studying the scalability of GHE technology. Research in these areas can enhance the performance, reliability, and efficiency of GHE systems, promote their wider adoption, and contribute to sustainable and energy-efficient heating and cooling solutions for buildings and various applications.

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11. Benazza, Eduardo Blanco, M. Aichouba, José Luis Río, Samir Laouedj Numerical Investigation of Horizontal Ground Coupled Heat Exchanger 10.1016/J.EGYPRO.2011.05.004
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