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Performance Comparison of Single and Double U-Tube Borehole Heat Exchangers in Ground Source Heat Pump Systems

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***Abstract*—** As global energy demand for heating and cooling continues to rise, largely driven by increasing temperatures and reliance on air conditioning, sustainable alternatives such as ground source heat pump (GSHP) systems are critical to reducing dependence on fossil fuels and mitigating grid instability. This study develops a numerical model to evaluate the thermal performance of single and double U-tube borehole heat exchangers (BHEs), namely sBHE and dBHE, integrated with a heat pump. The model examines the impact of borehole depth, mass flow rate of the circulating fluid, and heating and cooling loads of a building on system efficiency. Three different cases of dBHE consistently outperform the base case of a 75-m sBHE with a total mass flow rate of 0.2 kg/s and a constant building demand of 3.52 kW (1 ton) for heating and cooling. These results are obtained under identical soil, grout, pipe and working fluid thermal properties for all cases, including the base case, as well as identical borehole size, U-tube size and shank spacing. In Case 1, a 75-m dBHE with a 50% reduced mass flow rate (0.1 kg/s of total flow rate, i.e., each U-tube with 0.05 kg/s) improves entrance water temperature (EWT) to the heat pump from -0.13°C to 3.22°C in heating mode and from 30.5°C to 25.7°C in cooling mode, while increasing heating coefficient of performance (COP) by 2.8% and cooling COP by 10.9%. In Case 2, when subjected to higher building loads (4.22 kW (1.2 tons) instead of 3.52 kW), a dBHE can still sustain system efficiency for both heating and cooling modes, while increasing heat extraction by 25.2% and heat rejection by 21.6%. In Case 3, a 60-m dBHE can achieve comparable performance to the 75-m sBHE, with a minor 0.6% increase in heating COP and less than a 2% decrease in cooling COP, suggesting that the depth of a dBHE can be reduced by up to 20% without sacrificing performance. These findings highlight the superior efficiency, adaptability, and cost-saving potential of dBHE for GSHP applications, enabling optimized performance across various design constraints.

Keywords-ground source heat pump (GSHP); single U-tube borehole heat exchanger (sBHE); double U-tube borehole heat exchanger (dBHE); heating and cooling coefficient of performance (COP); transient heat transfer; Crank-Nicolson method; borehole thermal energy storage

I. INTRODUCTION

Heating and cooling account for a significant portion of global energy consumption in building sector, with space heating alone representing nearly 50% of total building energy demand [1]. Currently, natural gas dominates the heating sector, supplying 42% of global heating demand, with even higher shares in regions such as the United States (60%) and the European Union (40%). At the same time, space cooling demand has been rising at an annual rate of 4% since 2000, driven by global temperature increases and the growing reliance on air conditioning systems. As of 2022, more than 1.5 billion residential air conditioning units were in operation worldwide, significantly contributing to peak electricity demand and grid instability [1].

In response to these challenges, the International Energy Agency (IEA) has emphasized the urgent need for energy-efficient and low-carbon heating and cooling solutions to reduce reliance on fossil fuels and mitigate environmental impacts. Achieving sustainability targets requires a combination of strategies, including building insulation improvements, high-efficiency HVAC systems, and the adoption of renewable-based heating and cooling technologies [1].

Among these solutions, ground source heat pump (GSHP) systems have gained increasing attention due to their ability to enhance energy efficiency and reduce carbon emissions. GSHPs, when coupled with BHEs, provide a sustainable alternative to conventional heating and cooling systems by utilizing the ground as a thermal energy storage medium. Unlike air source heat pumps, which experience efficiency losses due to fluctuating outdoor temperatures, GSHPs benefit from the

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relatively stable temperature of the ground, resulting in higher efficiency and reduced operational costs ([2]-[4]).

Ground source heat pumps demonstrate greater savings compared to air source heat pumps, primarily attributed to higher ground temperatures during winter as opposed to outdoor air temperatures [5]. Additionally, in cold regions, air source heat pumps often necessitate backup heating from a furnace or electricity, further enhancing the advantage of ground source heat pumps [5]. Consequently, ground source heat pumps can deliver more heat throughout the winter season than their air source counterparts [5]. GSHP systems can be integrated with ground heat exchangers of different pipe installations, including horizontal (continuous pipe loops stacked horizontally) and vertical (pipe loops placed vertically) configurations, where the latter is the most typical configuration. BHEs, as the fundamental component, are preferred due to their flexibility, high efficiency, high thermal capacity in limited space, and reduced land area requirements compared to horizontal ground heat exchangers ([6],[7]). However, it is worth noting that the installation cost of vertical ground heat exchangers, such as BHEs, is higher than that of horizontal configurations. Horizontal ground heat exchangers are more economical when ample land area is available [8].

Among the various U-tube configurations (single, double, triple, and multiple U-tubes), single and double U-tube BHEs are commonly integrated with GSHP systems for space heating and cooling applications. Research efforts have focused on analyzing the heat transfer performance, modeling, and performance comparison between these two common BHE configurations.

Over the last decade, several research investigations have examined the heat transfer performance of BHEs with different configurations. Researchers have developed various models to analyze heat transfer within BHEs. For example, Lee et al. [9] developed a three-dimensional numerical model to evaluate borehole ground heat exchanger performance, incorporating grout thermal capacitance and short-time-step fluid dynamics. Furthermore, Yang et al. [10] investigated the fluid temperature variation along the borehole length analytically as well as thermal interference between neighboring legs of the U-tube. Conti et al. [11] used quasi-three-dimensional approaches and effectiveness-NTU theory to create an analytical model for double U-tube BHEs.

In addition to sBHE modeling, research has also focused on comparative assessments of different BHE configurations. For instance, Zeng et al. [12] developed a quasi-three-dimensional analytical heat transfer model that compared sBHE and dBHE, considering thermal interference. Florides et al. [13] created a 3D conduction and convective heat transfer model to analyze the performance and ground temperature distribution of these BHEs. Adamovskýa et al. [14] conducted experiments comparing sBHE and dBHE, concluding that dBHE is more effective than sBHE, particularly in terms of temperature regulation, specific heat power and energy efficiency.

Sensitivity analyses have also been conducted to assess the impact of various parameters, including borehole geometrical parameters (depth, diameter, shank spacing), pipe material, pipe diameter, the thermal conductivity of grout and soil, fluid inlet temperature, and flow velocity on BHE performance ([15]-[19]).

Collectively, these studies emphasize the need for further research and optimization in integrating heat pump mechanisms with BHEs to effectively meet building load demands. This study develops a numerical model to simulate the thermal performance of a GSHP system with integrated BHEs, incorporating a heat pump mechanism to dynamically simulate heat injection and extraction based on building load demand and heat pump capacity. The model considers both single and double U-tube configurations, with water as the circulating fluid, and evaluates the effects of borehole length, mass flow rate, and the heat pump capacity. The Crank-Nicolson finite-difference method is used to solve the transient thermal responses of circulating fluid, grout and surrounding ground, ensuring numerical stability and accuracy. The findings provide insight into system performance under heating and cooling demands, contributing to the optimization of GSHP design for improved energy efficiency.

II. Methodology

This model builds upon the work of Kerme et al. [20], which developed a numerical approach for simulating BHEs with both single and double U-tube configurations. The primary objective of the original model was to determine the total heat injection/extraction rate per unit depth while predicting the working fluid temperatures as it circulates through the U-tube. The formulation is based on transient heat conduction and energy rate balance principles, assuming a homogeneous and isotropic ground with conduction as the sole heat transfer mechanism in the borehole region.

To enhance the existing model, this work integrates a heat pump, coupling it with the borehole thermal response to account for dynamic heating and cooling loads. The heat pump is modeled to respond to an hourly heating and cooling demand of 3.52 kW (1 ton), regulating heat extraction/injection from/to the ground accordingly. The governing equations are first discretized using the finite difference method, and then a Crank-Nicolson method, which is a second-order implicit finite-difference scheme, is implemented for time advancement that ensures numerical stability.

To develop this numerical model, the following key assumptions were made:

1. Material Properties: Physical properties (thermal conductivity, heat capacity, density) are assumed to be constant at an average value, independent of temperature.
2. Ground Homogeneity: The soil surrounding the borehole is assumed to have homogeneous thermal properties.
3. Heat Transfer Mechanism: Only thermal conduction is considered in both the grout and the surrounding ground.
4. No Groundwater Influence: The effects of underground water flow and groundwater advection are neglected.
5. Negligible Contact Resistance: The thermal resistance at the U-tube/grout interface and the borehole wall/soil interface is assumed to be negligible.

6. Boundary Conditions: The far-field ground temperature remains constant throughout the simulation.

7. Steady Mass Flow Rate: The working fluid in the U-tube maintains a constant mass flow rate. For dBHE, the mass flow rate is assumed to divide equally between double U-tubes.

Based on the above assumptions, the transient energy rate balance equations for the fluid flowing downward in tube-1 and fluid flowing upward in tube-3 of the first U-tube, the fluid flowing downward in tube-2 and fluid flowing upward in tube-4 of the second U-tube, the grout, and the surrounding ground elements are derived and then discretized using the finite difference method.

After the discretization, the Crank-Nicolson approach is applied to obtain the temporal solutions of the fluid, grout and ground node temperatures outside the borehole. For detailed derivation of the numerical method, please refer to [19] and [20].

The heat pump extracts or injects heat ($\dot{Q}_{BHE}$) based on the heating and cooling capacity of the heat pump ($\dot{Q}_{HP}$) when a building load is required:

$$\dot{Q}_{BHE} = \dot{Q}_{HP}\left(1 \mp \frac{1}{COP}\right) \quad (1)$$

where the negative (–) or positive (+) sign is for the heating or cooling mode, respectively. Correspondingly, COP is the heating or cooling COP.

For heating mode:

$$LWT = EWT - \frac{\dot{Q}_{BHE}}{\dot{m}C_f} \quad (2)$$

For cooling mode:

$$LWT = EWT + \frac{\dot{Q}_{BHE}}{\dot{m}C_f} \quad (3)$$

where LWT is the leaving water temperature from the heat pump to the BHE, EWT is the entrance water temperature to the heat pump from the BHE, $\dot{Q}_{BHE}$ is the heat extraction rate from the BHE in heating mode or the heat injection rate to the BHE in cooling mode, $\dot{m}$ is the mass flow rate of water in the BHE, and C_f is the specific heat capacity of water.

The heating and cooling COPs of a commercial heat pump used in the study are given, respectively, as follows:

$$COP_H = 0.0011\, EWT^2 + 0.0225\, EWT + 3.1716 \quad (4)$$

$$COP_C = -0.076495\, EWT + 5.6251 \quad (5)$$

where EWT is in °C.

III. Results

In this study, the base case consists of the heat pump integrated with a single U-tube borehole of 75 m depth, a mass flow rate of 0.2 kg/s, and a constant hourly building load of 3.52 kW (1 ton) which is also the heat pump capacity. Three main cases are analyzed in comparison to this base case:

Case 1: A double U-tube borehole with the same depth (75 m) and same building load (3.52 kW), operating at a reduced mass flow rate of 0.1 kg/s.

Case 2: A double U-tube borehole with the same depth (75 m) and mass flow rate (0.2 kg/s), designed to accommodate a higher hourly building load of 4.22 kW (1.2 tons) which is also the heat pump capacity.

Case 3: A double U-tube borehole with the same mass flow rate (0.2 kg/s) and same hourly building load (3.52 kW), but with a reduced borehole depth of 60 m to assess its performance at a shallower depth.

The main constant input parameters used in this study for all cases are summarized in Tables 1 and 2. For further details on parameter selections, dimensions and combined effect of significant influencing design parameters, please refer to reference [21].

TABLE 1. PARAMETERS USED IN ALL SIMULATION CASES

Parameter	Symbol	Value	Parameter	Symbol	Value
Half shank spacing of U-tube (m)	d	0.08697	Borehole radius (m)	r_b	0.1
U-tube pipe inner radius (m)	r_{pi}	0.01103	U-tube pipe outer radius (m)	r_{po}	0.01303
U-tube pipe thermal conductivity (W/m·K)	k_p	0.4	Soil thermal conductivity (W/m·K)	k_s	2.5
Soil specific heat capacity (J/kg·K)	C_s	2016	Soil density (kg/m³)	ρ_s	2000
Grout thermal conductivity (W/m·K)	k_b	0.5	Grout specific heat capacity (J/kg·K)	C_b	2200
Grout density (kg/m³)	ρ_b	1800	Fluid thermal conductivity (W/m·K)	k_f	0.6
Fluid specific heat capacity (J/kg·K)	C_f	4183	Fluid density (kg/m³)	ρ_f	997
Fluid viscosity (Pa·s)	μ_f	0.0008905	Undisturbed ground temperature (°C)	T_g	10

TABLE 2. PARAMETERS USED IN SPECIFIC SIMULATION CASES

Parameter	Symbol	Base	Case 1	Case 2	Case 3
Borehole		sBHE	dBHE	dBHE	dBHE
Borehole depth (m)	H	75	75	75	60
Total mass flow rate (kg/s)	$\dot{m}$	0.2	0.1	0.2	0.2
Building load (kW)	$\dot{Q}_{HP}$	3.52	3.52	4.22	3.52
Reynolds number	Re	12940	3237	6470	6470

Figure 1 illustrates the depth-averaged heat rejection per unit length for both single and double U-tube boreholes over a one-month duration (774 hours) with a constant fluid inlet temperature of 30°C to the boreholes. These results correspond to boreholes with a length of 75 m, similar to the base case without an integrated heat pump. The achieved steady depth-averaged heat rejection per unit length is 46.40 W/m for the single U-tube borehole and 79.06 W/m for the double U-tube borehole, with the latter demonstrating 1.7 times greater heat rejection.

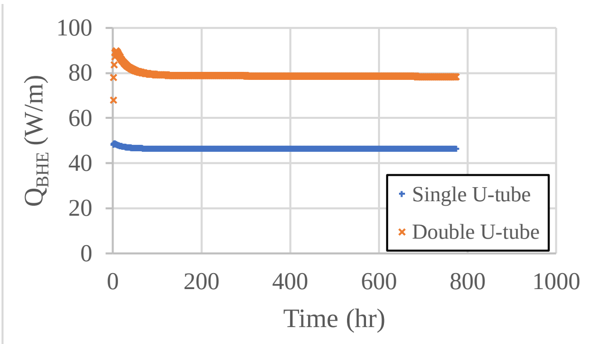

Figure 1. Depth-averaged heat rejection per unit length for single and double U-tube boreholes over one month.

Figure 2 presents the time-averaged heat rejection per unit length along borehole depth for both single and double U-tube boreholes under the same conditions. The double U-tube borehole has a higher time-averaged heat rejection of about 32 W/m more than the single U-tube borehole for all depths of borehole. However, as averaged over longer depth, the heat rejection per unit length of borehole decreases. For example, from 20 to 40 m depth, the heat rejection rate per unit length decreases by 7.75%, while the borehole depth increases by 100%. This means that overall heat rejection rate still increases by 84.5% (from 975 to 1798 W).

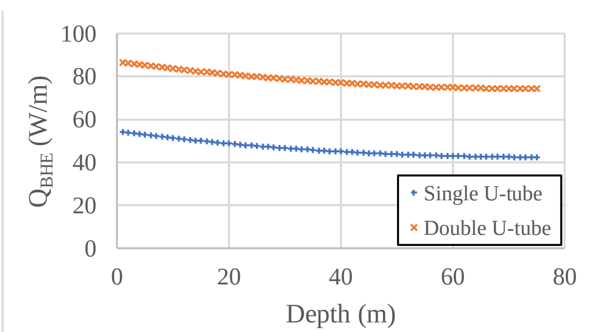

Figure 2. Time-averaged heat rejection per unit length along borehole depth for single and double U-tube boreholes.

With the integration of a heat pump, for each case, the system's performance is evaluated by analyzing key thermal and efficiency parameters over time. Figures 3 and 4 illustrate the EWT and LWT over time, showing how the thermal exchange varies for different configurations. Figure 5 presents the borehole heat transfer, comparing the heat rejection (positive) and extraction (negative) rates for each case. Finally, Figure 6 depicts the COP over time, highlighting the efficiency of the heat pump system under different borehole configurations, mass flow rates, and load conditions.

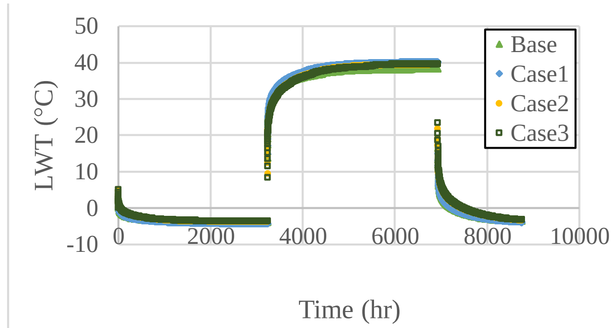

Figure 3. Leaving water temperature over one year.

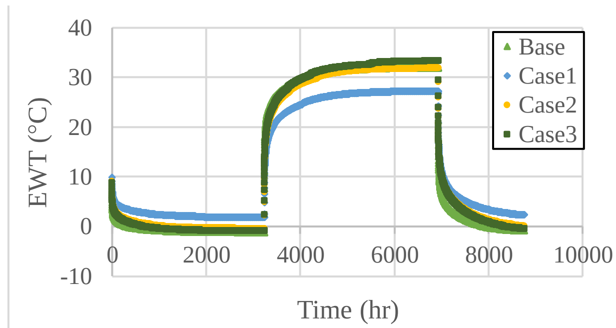

Figure 4. Entering water temperature over one year.

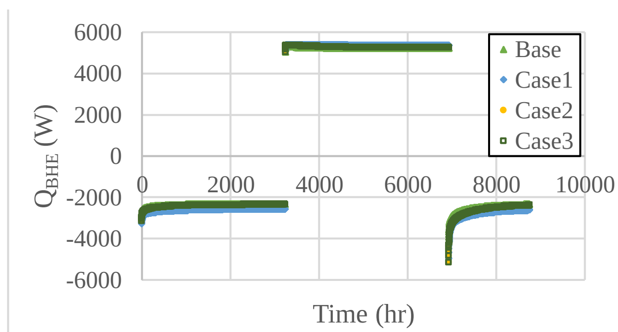

Figure 5. Heat rejection/extraction to/from the ground over one year.

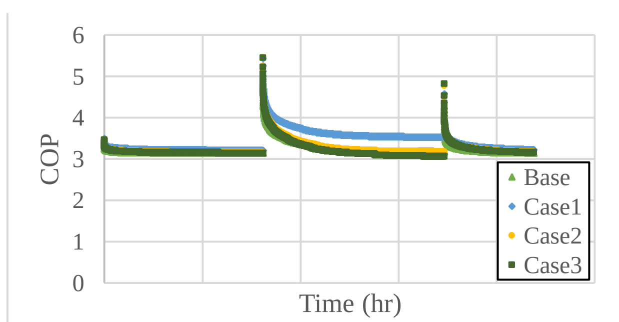

Figure 6. Coefficient of performance over one year.

The comparative results of the ground source heat pump system for the base case and all three study cases are summarized in Table 3.

TABLE 3. SIMULATION RESULTS.

Parameter	Symbol	Base	Case 1	Case 2	Case 3
EWT (heating) (°C)	EWT_H	-0.13	3.22	1.18	0.69
EWT (cooling) (°C)	EWT_C	30.53	25.66	29.93	31.11
LWT (heating) (°C)	LWT_H	-3.008	-3.2	-2.42	-2.26
LWT (cooling) (°C)	LWT_C	36.78	38.49	37.52	37.41
Water temperature difference (heating) (°C)	ΔT_H	2.88	6.44	3.62	2.97
Water temperature difference (cooling) (°C)	ΔT_C	6.25	12.83	7.6	6.3
Average heating COP	COP_H	3.17	3.26	3.2	3.19
Total heat extracted from the ground (kWh)	Q_H	12005	12418	14751	12151
Average heat extraction rate (W)	$\dot{Q}_{BHE,H}$	2406	2684	3014	2471
Average heat extraction rate (W/m)	$\frac{\dot{Q}_{BHE,H}}{H}$	32.1	35.8	40.2	41.2
Total supplement heating needed (kWh)	$Q_{s,H}$	223	0	36.7	103
Average cooling COP	COP_C	3.29	3.65	3.33	3.24
Total heat rejected to the ground (kWh)	Q_C	16595	16442	20157	16854
Average heat rejection rate (W)	$\dot{Q}_{BHE,C}$	5228	5366	6356	5270
Average heat rejection rate (W/m)	$\frac{\dot{Q}_{BHE,C}}{H}$	69.7	71.5	84.7	87.8
Total supplement cooling needed (kWh)	$Q_{s,C}$	0	0	0	0

A dBHE system with a reduced mass flow rate (0.1 kg/s total) at 75 m exhibited significant efficiency gains. The EWT in heating mode improved from -0.13°C to 3.22°C, while in cooling mode, it dropped from 30.53°C to 25.66°C, indicating better thermal regulation. Additionally, the heat extraction rate ($\dot{Q}_{BHE,H}$ or $\frac{\dot{Q}_{BHE,H}}{H}$) increased by 11.6%, and the cooling heat rejection rate ($\dot{Q}_{BHE,C}$ or $\frac{\dot{Q}_{BHE,C}}{H}$) improved by 2.6%, despite the 50% reduction in mass flow rate. The heating COP increased by 2.8% and the cooling COP by 10.9%, effectively eliminating the need for supplemental heating. Lower required mass flow rate, coupled with lower pressure drop, will lead to lower pumping power requirement which result in higher overall system performance.

For a higher building load demand (4.22 kW instead of 3.52 kW) with a dBHE at 75 m and total mass flow rate of 0.2 kg/s, the system maintained about the same COP, with EWT in heating at 1.18°C and in cooling at 29.93°C. The heat extraction rate increased by 25.2%, while cooling rejection rate increased by 21.6%. Also, the system maintained a similar performance, with a 0.95% increase in heating COP (from 3.17 to 3.2) and a 1.22% improvement in cooling COP (from 3.29 to 3.33), demonstrating that the double borehole configuration can support higher loads while maintaining performance.

When analyzing shallower borehole configurations, a 60 m dBHE with 0.2 kg/s flow rate provided comparable performance to the sBHE at 75 m and mass flow rate of 0.2 kg/s (base case), with a minor 0.6% increase in heating COP and a less than 2% decrease in cooling COP. This suggests that borehole depth can be reduced by up to 20% without sacrificing performance, leading to potential cost savings.

Furthermore, the need for supplemental heating was entirely eliminated for Case 1, while in Case 4, the supplemental heating demand was reduced by 53.8% compared to the base case. This highlights the superior thermal performance and efficiency of a double U-tube borehole, even at reduced depths.

These findings confirm that a GSHP system with double U-tube boreholes not only improves system performance but also offers significant flexibility in design, allowing for reductions in borehole depth and/or mass flow rate while being capable of serving higher building load demands, all while maintaining or exceeding the performance of single U-tube borehole systems.

IV. CONCLUSION

By developing a dynamic simulation model of single and double U-tube borehole that integrates a heat pump, this study demonstrates that a GSHP system with a dBHE configuration consistently outperforms a system with sBHE in terms of heat extraction/rejection, heat pump COP, and system thermal performance. The results indicate that reducing the mass flow rate in a dBHE system enhances efficiency, as measured by an increase in the heat pump COP, while maintaining or even improving performance compared to the base case of sBHE, which is evaluated based on similar EWT/LWT, increased heat extraction/rejection, and the system's ability to meet higher building load demands without requiring additional supplemental heating. Notably, Case 1 (dBHE at 75 m with half the mass flow rate (0.1 kg/s total)) has significantly improved EWT, increased heat extraction and rejection rates, and eliminated the need for supplemental heating, proving its superior thermal performance.

Additionally, when subjected to a higher building load (20% more), the double U-tube borehole system is able to sustain its efficiency, demonstrating its ability to support greater thermal demands while maintaining heating and cooling performance. Moreover, for Case 4 with a shallower borehole (i.e., 60 m depth), it was found to provide comparable performance to a 75-m single U-tube borehole system with about 54% reduction in supplemental heating, indicating that the borehole depth can be reduced by up to 20% without significant losses in heat pump COP. This finding has major implications for potential in reducing installation (such as, shorter borehole length with the same building load or higher building load with the same borehole length) and operation (reduced pumping energy) costs while preserving system effectiveness in terms of heat pump COP.

Overall, these results confirm that GSHP systems with double U-tube boreholes provide a more efficient and flexible alternative to single U-tube borehole systems, enabling reductions in borehole depth and/or mass flow rate while maintaining or exceeding thermal performance. These findings underscore the potential of optimized GSHP design and operation to enhance overall energy efficiency, reduce operational costs, and/or support higher building load demands, contributing to sustainable and cost-effective geothermal heating and cooling solutions.

The above conclusion is preliminary, as it is only based on one set of soil, grout and ground thermal properties. Further study is required in order to study the impacts of different soil, grout and ground thermal properties.

V. Acknowledgment

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