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Thermal Performance Assessment of Earth Air Tunnel Heat Exchanger System Enhanced with Water Impregnation Using Computational Fluid Dynamics

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Abstract - Geothermal energy offers a readily accessible and environmentally friendly source of low-grade thermal energy, particularly for building applications. Utilisation methods such as ground source heat pumps and earth-to-air heat exchangers (EATHE) have been employed to achieve energy-efficient cooling and heating. EATHE systems, which consist of underground heat exchangers utilising buried pipes, effectively exchange heat with the ground to cool or warm air passing through them. During summer and winter, hot or cold outdoor air is circulated through these pipes, exchanging heat with the surrounding soil. Consequently, the outlet air temperature from the EATHE system can significantly differ from the ambient air temperature. In the summer, if the outlet air temperature is sufficiently low after the heat exchange process, it can be directly used for space cooling, contributing to energy savings. Enhancing the moisture content of the soil can further improve the effectiveness and performance of the EATHE system. This can be achieved by introducing a wet configuration of the system. The earth-to-air heat exchanger configurations can reduce energy consumption for space conditioning, with the wet configuration enhancing the system's efficacy. The study employs computational fluid dynamics (CFD) simulations using ANSYS FLUENT software to model and analyse different configurations of the EATHE system. The results are compared and validated against experimental data, demonstrating the impact of soil moisture content and airflow velocity on the system's performance.

Keywords:- Geothermal energy, Earth-to-air heat exchanger, Moisture content, Computational fluid dynamics, Energy efficiency, Space conditioning

1. INTRODUCTION

Geothermal energy, derived from the heat stored beneath the Earth's surface, is increasingly recognised as a valuable renewable energy resource with vast potential for providing sustainable solutions to meet the world's growing energy demands. Unlike traditional fossil fuels, geothermal energy offers a clean and environmentally friendly alternative, characterised by its low carbon footprint and virtually limitless supply. Among the various applications of geothermal energy, one area of particular interest is its utilisation for building heating, ventilation, and air conditioning (HVAC) systems. In recent years, there has been a growing emphasis on developing energy-efficient HVAC technologies to reduce reliance on conventional heating and cooling methods, which often contribute to greenhouse gas emissions and environmental degradation. Geothermal-based

HVAC systems offer a promising solution to this challenge, leveraging the Earth's natural heat reservoirs to provide sustainable heating and cooling solutions for residential, commercial, and industrial buildings. One of the key technologies employed in geothermal HVAC systems is the earth-to-air heat exchanger (EATHE), also known as ground-coupled heat exchangers or ground-source heat exchangers. EATHE systems harness the stable temperatures of the Earth's subsurface to exchange heat with the ambient air, thereby providing a cost-effective and energy-efficient means of conditioning indoor spaces. By utilising buried pipes or ducts, EATHE systems facilitate heat transfer between the ground and the air, allowing for the preheating or precooking incoming ventilation air, depending on the season. An EATHE system typically involves circulating outdoor air through buried pipes or ducts, where it exchanges heat with the surrounding soil before being introduced into the building's HVAC system. During the winter months, the relatively warmer temperatures of the Earth's subsurface help to preheat the incoming ventilation air, reducing the load on conventional heating systems.

Conversely, in the summer, the cooler temperatures of the ground can be utilised to cool the incoming air, thus alleviating the burden on air conditioning systems. This process, known as free cooling or free heating, offers significant energy savings compared to traditional HVAC systems, making EATHE systems an attractive option for sustainable building design and operation. In addition to their energy efficiency benefits, EATHE systems also offer several environmental advantages. By reducing the demand for fossil fuel-based heating and cooling, these systems help to mitigate greenhouse gas emissions and combat climate change. Furthermore, EATHE systems have a minimal impact on the surrounding environment, requiring only a modest land area to install buried pipes or ducts. The effectiveness of EATHE systems can be further enhanced by optimising various design parameters, such as soil moisture content, pipe configuration, and airflow velocity. Increasing the moisture content of the soil, for example, can improve heat exchange efficiency by enhancing thermal conductivity and reducing thermal resistance. Computational fluid dynamics (CFD) simulations offer a powerful tool for modelling and analysing the performance of EATHE systems under different operating conditions, providing valuable insights for system design and optimisation. In light of these considerations, this study aims to investigate the thermal performance of EATHE systems using CFD simulations, focusing on the impact of soil moisture content on system efficiency and effectiveness. By comparing simulation results with experimental data, this research seeks to provide a comprehensive understanding of the factors influencing the performance of EATHE systems and their potential for sustainable building HVAC applications.

2. LITRERATURE SURVEY

In order to provide soil layers enough time for regeneration, efforts were undertaken to minimise soil thermal saturation to some extent by running the EATHE system in various intermittent modes [1,2]. According to Goswami and Ileslamlou [3], soil moisture regenerated the soil throughout the shut-off interval by diffusing back towards the heat source. Nevertheless, during regular daytime EATHE operation, it is discovered that the soil temperature on a subsequent day is marginally higher than the day before, impacting the output air temperature [4]. In their investigation, Mathur et al. [5] noted that subsoil got saturated at the end of summer and was deemed inappropriate for cooling the next summer. In summer, they employed night purging; in winter, they used day/night operations to remove heat from the subsurface soil. Better soil conditions and room heating were given by the winter day/night operation for the following summer. In karst regions, Zeng et al. [6] investigated the performance of ground source heat pumps (GSHPs) in three distinct modes (running for eight hours, twelve hours, and twenty-four hours). They found that the intermittent mode was advantageous for temperature field heat recovery.

Additionally, it was discovered that the system's COP rose by 22.4% when the recuperation time was extended from 0 to 16 hours. Some researchers have found that extending the length of an EATHE pipe can lessen the effect of soil thermal saturation because longer pipes have more area to dissipate heat [7-9]. However, this increases the requirement for land area and raises the cost of excavation, pipework, and pumping power, all of which lower the EATHE system's economic viability. A certain amount of soil thermal saturation is reduced by intermittent EATHE operation, but it is useless for applications requiring continuous operation. Longer EATHE pipes are more expensive, and nighttime purging operations demand more blower power. For EATHE to operate continuously for an extended period of time, a workable solution must be investigated. Researchers have noted that the subsoil's thermal characteristics significantly impact the performance of an underground heat exchanger. Therm conductivity is the most significant sub-soil attribute for heat transmission, mostly determined by the soil's density, moisture content, and mineralogical makeup. Enhancing the thermal characteristics of subterranean soil should be a priority [5,10]. In the GSHP tests, Allan and Kavanaugh [11] employed high thermal conductivity backfilling material, which led to a 37% reduction in bore length. In a simulated investigation of GHE, Wang et al. [12] looked at the impact of soil type and porosity and found that heat diffused more quickly in sand than in loam and clay. However, loam has the least capacity to diffuse moisture. In his investigation on the impact of water content and density on soil thermal characteristics, Abu-Hamdeh [13] found that sandy soil had a greater thermal diffusivity than clay soil.

In soil, heat is transferred via air-filled pores by simple conduction and moisture diffusion as liquid and vapour [14]. Vapour flux causes moisture to be pushed away from the heat source when heat flux is active, and capillary action causes the liquid to be drawn back towards the heat source when heat flux is deactivated, as observed by Moya et al. [15]. The heat transmission rate in the subsoil is controlled by the temperature concentration gradient distribution and soil moisture content [16, 17]. A mathematical model for the simultaneous transmission of heat and moisture in porous soil with a dry surface layer at the top was created by Liu et al. [18], who also noted that temperature and temperature gradient are important factors in the movement of soil moisture. Unsaturated soil has a high degree of thermal resistance, which prevents heat from being injected into the surrounding soil and lowers the thermal performance of GHE in unsaturated soil, according to Tarnawski and

Leong [19]. Few studies have examined the relationship between moisture migration and heat transfer in the subsoil near EATHE pipes. Generally, the soil is unsaturated at the installation depth of horizontal GHE, and heat and moisture transfer occur concurrently [20–22].

3. METHODOLOGY

The ANSYS version 15.0.7 was used to create the geometric model of the rudimentary EATHE system. The produced model is meshed using ANSYS ICEM CFD. A geometrical model has been constructed for a dry tunnel with a pipe length of 68.9 metres and a diameter of 0.01 metres. The soil volume around the pipe is a concentric cylinder with a length of 65.2 metres and a diameter of 0.1 metres. The air entrance is at one end of the pipe, while the exit is at the other. In the experimental section, the outlet is insulated, meaning that no heat transfer is considered at the outlet. In order to maintain consistent conditions during the simulation research, we eliminated the dirt from the outlet section of the pipe, as seen in Figure 1.

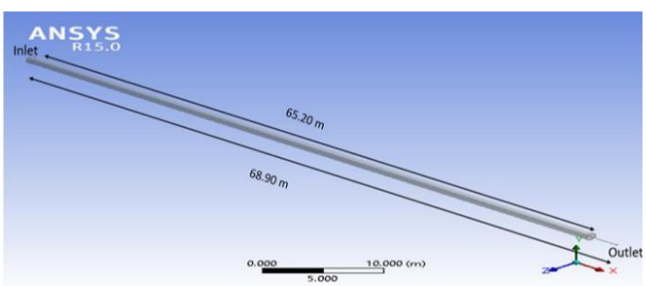

Figure 1. Physical geometry details of the EATHE system

To enhance heat transfer within the PVC pipe wall and the surrounding soil, they were "coupled," with their initial temperatures determined through experimental measurements. The air inlet boundary condition was set as "Velocity Inlet," maintaining a steady flow of 5 m/s. The air exit was assigned a "Pressure Outlet" condition as the air is compressible. Using ANSYS version 22, a geometric model of the basic EATHE system was constructed. ANSYS ICEM CFD was utilised to mesh the model. The geometric model comprised a basic, dry tunnel with a pipe length of 68.9 m and a diameter of 0.01 m. The soil volume was represented as a concentric cylinder encompassing a pipe with a length of 65.2 m and a diameter of 0.1 m. The air intake was positioned at one end of the pipe, while the outflow was at the other.

In the CFD simulation, several assumptions are made to ensure accurate representation throughout the operation. Firstly, it is assumed that the thermophysical characteristics of air, PVC pipe, and soil remain constant. Additionally, the output section of the simulation does not consider heat transmission, while vertical pipes are adequately insulated. Furthermore, perfect thermal contact is assumed between the buried pipe and the surrounding soil. The airflow within the test section is assumed to be fully developed, and the pipe surface does not exhibit any slip condition for velocity.

Moreover, uniform air mixing within the EATHE system is presumed along the length of the pipe. The ground layers are assumed to have uniform heat conductivity, and the soil surrounding the pipe is considered isotropic. Due to the thinness of the pipe, its heat resistance is essentially negligible. The cross-section of the pipe is assumed to be consistently round. Finally, it is assumed that the thermal influence of the Earth surrounding the pipe becomes insignificant after a distance of "10r" from the outer surface, where "r" represents the pipe radius. These assumptions collectively form the basis for the CFD simulation, providing a framework for accurate analysis and predicting thermal behaviour within the system.

Table 1. Physical and thermal properties of materials used in simulation

Parameter	Material		
	Air	Soil	PVC
Density (kg m^{-3})	1.225	2050	1380
Specific heat capacity (J kg^{-1} K^{-1})	1006	1840	900
Thermal conductivity (W m^{-1} K^{-1})	0.0242	0.52	0.19

Table 2. Physical and thermal properties of soil with different moisture content used in the simulation

	Dry soil	5 % moisture soil	10 % moisture soil	15 % moisture soil	18 % moisture soil
Density (kg m^{-3})	2050	2152.5	2255	2357.5	2421
Specific heat capacity (J kg^{-1} K^{-1})	1840	1785	1719	1657	1624
Thermal conductivity (W m^{-1} K^{-1})	0.52	0.74	0.9179	1.325	1.61

4. RESULT AND DISCUSSION

Previous research has established that hot fluid, such as air, loses heat to the surrounding soil as it traverses through an underground conduit. Moisture in the soil can further influence heat transmission by increasing thermal resistance through evaporation. In light of this, we developed four distinct models of the Earth-Air Tunnel Heat Exchanger (EATHE) system, each representing varying soil moisture levels—dry soil, soil with 5% moisture content, soil with 10% moisture content, and soil with 15% moisture content. These models were created to investigate the impact of soil saturation on heat exchange. Subsequently, simulations were conducted for each scenario over one hour, six hours, and eleven hours, with the resulting data compared against experimental observations. This comprehensive approach allowed for a thorough examination of how soil moisture levels affect the performance of EATHE systems and provided valuable insights into optimising their efficiency.

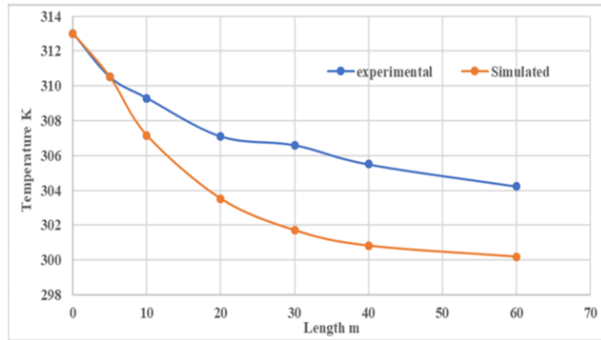

Figure 2. Variation of Temperature with length of dry soil for 1 hour of operation

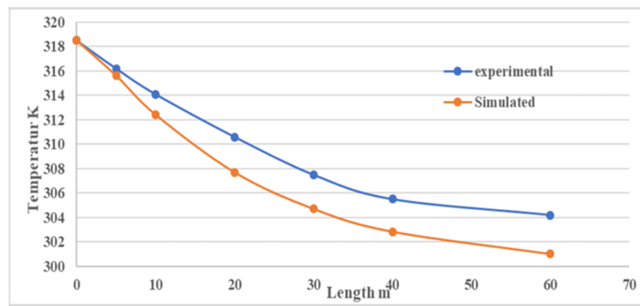

Figure 3. Variation of Temperature with length of dry soil for 6 hours of operation

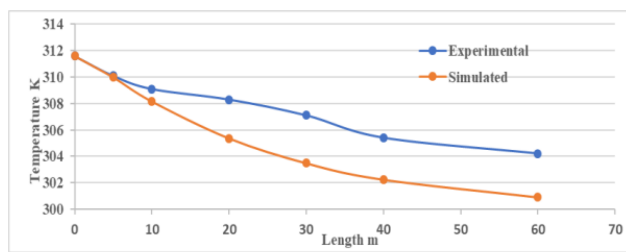

Figure 4. Variation of temperature with length of dry soil for 11 hours of operation

Incoming air at 311.6 K is the medium for heat transmission through dry soil, characterised by a thermal conductivity of 0.52 W/m-K. Figure 3 displays the temperature monitoring at different pipe lengths, with the resulting data compared to experimental observations. Upon comparison, a slight disparity between the outlet temperature of the experiment and the simulated outcome is noted, with an error percentage of 1.08%. This small deviation warrants further examination to ensure the accuracy of the simulation and to identify any factors contributing to the variance between the experimental and simulated results.

3. CONCLUSION

In conclusion, using earth-to-air heat exchanger (EATHE) systems represents a promising approach for harnessing geothermal energy to provide energy-efficient cooling and heating solutions for buildings. By leveraging the thermal properties of the ground, EATHE systems can effectively exchange heat with the surrounding soil, enabling the cooling or warming of outdoor air before it is circulated into indoor spaces. The effectiveness of EATHE systems can be further enhanced by increasing the soil moisture content, which improves heat exchange capabilities. Computational fluid dynamics (CFD) simulations have been instrumental in modelling and analysing different configurations of EATHE systems, providing valuable insights into their performance. Results from simulations, coupled with experimental validation, highlight the significant impact of soil moisture content and airflow velocity on the efficiency of EATHE systems. Overall, EATHE systems offer a sustainable and environmentally friendly solution for reducing energy consumption and enhancing building comfort, contributing to a greener future.

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