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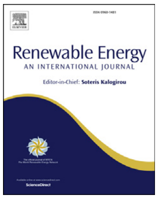

Experimental study to investigate the effect of water impregnation on thermal performance of earth air tunnel heat exchanger for summer cooling in hot and arid climate

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ABSTRACT

An EATHE system performs well for short periods but its thermal performance gets deteriorated during long continuous operation due to sub-soil thermal saturation in the vicinity of buried pipe. Effect of soil thermal saturation can be reduced to some extent in longer EATHE pipe but it is uneconomical. In the present study sub-soil moisture content is increased to enhance soil thermal properties and its effect on EATHE thermal performance and pipe length requirement for certain temperature drop has been investigated experimentally for summer cooling in hot and arid climate. In the study, two identical experimental set-ups have been developed at Ajmer city (India). A water impregnation system has been introduced to maintain different soil moisture contents in the close proximity of EATHE pipe. Knee point is obtained at a length of 29 m, 28 m, 27 m and 26 m from pipe inlet section with 5%, 10%, 15% and 20% moisture in sub-soil respectively, as compared to 41 m length in dry soil, after 10 h of continuous operation. The average heat transfer rate and COP increased by 24.1% and 24.0% respectively for 20% moisture content at 30 m EATHE pipe length as compared to dry system.

1. Introduction

Global primary energy demand is increasing day by day, and one-third of total energy demand is required for space heating and cooling. The renewable energy has assumed significance in the wake of dwindling reserves of fossil fuels as well as their steeply increasing prices along with serious environmental issues. Owing to this, most of the countries are turning towards passive and low-grade energy systems for meeting building cooling and heating needs. The Earth air tunnel heat exchangers (EATHE) employs sub-soil as a heat source/sink to transfer heat to/from fluid flowing through the buried pipes.

Performance of earth air tunnel heat exchanger (EATHE) system deteriorates during long continuous operation because of soil thermal saturation and moisture transfer away from the heat source in the sub-soil layers. This moisture transfer reduces sub-soil thermal conductivity and slows down heat dissipation rate between soil layers and results in sub-soil thermal saturation.

Efforts were made to mitigate soil thermal saturation to certain extent by operating the EATHE system in different intermittent modes so that soil layers get sufficient time for regeneration [1,2]. Goswami and Ileslamlou [3] observed that during shut-off period soil moisture diffused back towards the heat source and thereby regenerated the soil. However, during daily day time EATHE operation, soil temperature on a successive day is found to be slightly higher than the previous day and affected the outlet air temperature [4]. Mathur et al. [5] observed in the study that at the end of summer season, sub-soil became saturated and found to be unsuitable for cooling in the next summer. To resolve this problem by heat removal from the underground soil they used night purging

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Abbreviations: COP, Coefficient of Performance; EATHE, Earth Air Tunnel Heat Exchanger; GCHE, Ground Coupled Heat Exchanger; GHE, Ground Heat Exchanger; GSHE, Ground Source Heat Exchanger; GSHP, Ground Source Heat Pump; HDPE, High-Density Polyethylene; HGCHE, Horizontal Ground Coupled Heat Exchanger; PUF, Polyurethane Foam; PVC, Poly Vinyl Chloride; RH, Relative Humidity; RPM, Rotations Per Minute; RTD, Resistance Temperature Detectors.

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Nomenclature

T_{soil}	Temperature of soil, °C
T_{amb}	Ambient air temperature, °C
D_{t1} to D_{t8}	Temperature of air along the EATHE pipe length for dry EATHE, °C
W_{t1} to W_{t8}	Temperature of air along the EATHE pipe length for wet EATHE, °C
Q	Heat transfer rate from air to soil, watt
A_s	Surface area of EATHE pipe, m^2
W	Electricity consumption of blower, watt
$\dot{m}$	Mass flow rate of air through the pipe, kg/s
ρ	Density of air, kg/m^3
A_{cs}	Cross-sectional area of EATHE pipe, m^2
V	Velocity of air in EATHE pipe, m/sec
C_p	Specific heat of air, J/kg K
T_{inlet}	EATHE inlet air temperature, °C
T_{oulet}	EATHE outlet air temperature, °C
d	Diameter of EATHE pipe, m
L	Length of EATHE pipe, m

during summer, and day/night operation during winter. Winter day/night operation provided better soil condition for next summer along with space heating. Zeng et al. [6] studied ground source heat pump (GSHP) performance in three different modes (operation for 8 h, 12 h, and 24 h) in karst areas and observed that intermittent mode was beneficial in terms of heat recovery of temperature fields. It was also found that by increasing recovery time from 0 to 16 h, the COP of the system increased by 22.4%.

Few researchers observed that effect of soil thermal saturation can be reduced by increasing EATHE pipe length because longer pipe provides more area to dissipate heat [7–9] but land area requirement enhances along with higher excavation cost, pipe cost and pumping power, which reduces the economic viability of EATHE system.

Intermittent EATHE operation reduces soil thermal saturation to certain extent but is unuseful for applications needing a continuous operation. Use of longer EATHE pipe involves extra cost and night purging operation requires additional blower power. Thus, some feasible solution needs to be explored for long continuous EATHE operation.

It has been observed by various researchers that the performance of under ground heat exchanger highly depends on sub-soil thermal properties. Thermal conductivity is the most important sub-soil property for heat transfer and it primarily depends on moisture content, density and mineralogical composition of the soil. Efforts should be made to improve underground soil thermal properties [5,10]. Allan and Kavanaugh [11] used high thermal conductivity backfilling material in the GSHP studies, which resulted in reduced bore length up to 37%. Wang et al. [12] studied the effect of soil type and porosity in a simulation analysis of GHE and observed faster heat diffusion in the sand than that with loam and clay. However, the moisture diffusion ability was lowest in loam. Abu-Hamdeh [13] investigated the effect of density and water content on soil thermal properties and noticed higher thermal diffusivity in sandy soil than clay soil.

The heat transfer in soil occurs by simple conduction and moisture diffusion as liquid and vapour, through air filled pores [14]. Moya et al. [15] noticed that when heat flux is activated, moisture is pushed away from the heat source due to vapour flux and when heat source is deactivated, the vapour flux is stopped and capillary action sucks liquid back towards the heat source. The soil moisture and temperature concentration gradient distribution govern the rate of heat transfer in sub-soil [16,17]. Liu et al. [18] developed a mathematical model for simultaneous heat and moisture transfer in the porous soil with dry surface layer at the top and observed that the temperature and temperature gradient play a significant role in soil moisture transport. Tarnawski and Leong [19] observed that unsaturated soil offers high thermal resistance, which hampers heat injection into the surrounding soil and results in diminished thermal performance of GHE in unsaturated soil. At the installation depth of horizontal GHE soil is usually unsaturated and both heat and moisture transfer occur simultaneously, but very few researchers considered the effect of moisture migration with heat transfer in sub-soil near EATHE pipe [20–22].

An inner heat source model simulating heat and water transfer in sub-soil was developed by Li et al. [23] using Autough2 software and observed that the soil with high thermal conductivity and high specific heat is most favourable for burying underground heat exchangers. Results showed that the soil temperature rise in an intermittent mode (operation ratio of 1:1) is only 25–30% of that obtained in continuous mode with different soils. Leong et al. [24] evaluated the effect of soil types and soil moisture content on thermal performance of GSHP by considering three soils namely sand, silty loam and silty clay with five different degrees of saturation (0, 12.5, 25, 50 and 100%) using simulation. The result showed that soil moisture content strongly influenced the performance of ground source heat pump and its COP increased up to 35% when soil moisture increased from 0 to 12.5%. Soil water content above 25% led to further better heat pump performance while the effect of moisture content above 50% was relatively insignificant. In the study, the amount of heat extracted from the ground was the highest for sand, followed by silty loam and silty clay.

Remund et al. [25] developed heat and water transfer model to evaluate the performance of underground heat exchanger in an unsaturated Sharpsburg silty clay soil. In the simulation, initially, the performance of ground heat exchanger was studied at three different initial water contents of soil (0.175, 0.250 and 0.350 m^3/m^3) and then water content levels were maintained constant at the pipe wall surface and compared the performance of ground heat exchanger with initial water contents performance. Results indicated that the heat transfer increased up to 24% with water addition of 0.350 m^3/m^3 and hourly water addition required was 0.0012–0.0314 L/meter length of heat exchanger. Inoue et al. [26] numerically studied the effect of water injection on the performance of GHE in vertical ground source heat exchanger. Sensitivity analysis results showed that the heat exchange rate was 1.7 times higher when 18 °C water was injected at 1 L/min in well compared to well without water injection.

Gao et al. [27] propounded a novel approach in which a horizontal ground coupled heat exchanger (HGCHE) is submerged under the rain garden where the moisture in the sub-soil reached by percolation. In the experimental study they used sandy soil container and observed that water impregnation in sub-soil was possible during heat transfer between soil and fluid. They also observed that soil in the vicinity of horizontal pipe wall became dry due to moisture diffusion due to the presence of large temperature difference. Go et al. [28] investigated the effect of rainfall infiltration on the thermal performance of shallow trenches using infiltration analyses and found augmented thermal efficiency with rainfall infiltration in the unsaturated ground. It was also observed that in saturated ground when ground water advection velocity increased, the performance of HGCHE got enhanced because ground water advection attenuated temperature increment of sub-soil in the vicinity of the heat source and increased heat transfer between heat source and soil. Moreover, the effect of