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Effect of soil moisture contents on thermal performance of earth-air-pipe heat exchanger for winter heating in arid climate: In situ measurement

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ABSTRACT

Earth-air-pipe heat exchanger (EAPHE) system is a passive system but requires long pipes for heat transfer and its performance also gets deteriorated during continuous operation. In this study, the moisture content of sub-soil is increased in the close vicinity of EAPHE pipe and its influence on thermal performance and pipe length requisite for certain temperature rise in winter season have been determined. The system comprises of two identical set-ups of EAPHE system buried at a depth of 3.7 m (one for dry soil, other for wet soil). A unique water impregnation system is presented to maintain different soil moisture content levels in the close vicinity of EAPHE pipe. The knee point for dry EAPHE system is obtained at a pipe length of 40 m from inlet section while in wet EAPHE system knee point is obtained at 28 m, 27 m and 26 m with 5%, 10%, and 15% soil moisture levels respectively, after 12 h of continuous operation. The average heat transfer rate and coefficient of performance increase up to 26.0% and 26.1% respectively, for 15% moisture content at 30 m length of EAPHE pipe as compared to dry system.

1. Introduction

Energy requirement is growing day by day across the globe and fossil fuel reserves will not be ample to satisfy the global energy demands in future. Out of total energy demand, nearly one-third energy is obligatory for space heating and cooling. Conventional heating and cooling systems are energy intensive and cost of fossil fuel-based energy is increasing continuously. All these concerns have raised the interest of the researchers and scientists towards utilising the renewable energy based systems at a large scale for heating and cooling of the building. Renewable and passive systems can reduce the building's cooling and heating energy demand. The earth-air-pipe heat exchanger (EAPHE) is also a promising system to provide both heating/cooling effects and includes the benefits of reduced energy consumption as well as lower greenhouse gas emission.

Due to large thermal inertia of soil, the variations in the temperature at the ground surface do not penetrate deep into the soil and soil at a depth of 3–4 m below the ground surface has more or less a constant temperature all through the year; which is significantly lower in summer/higher in winter, than the ambient air temperature (Misra et al., 2013b, 2013a). This temperature difference can be employed for pre-cooling/heating the ambient air in summer/winter by using earth-air-pipe heat exchanger (Bharadwaj and Bansal, 1981; Bisoniya et al., 2013; Jacovides et al., 1996).

Fazlikhani et al.(2017) considered two different climates (hot-arid and cold climate) to evaluate the effect of climatic conditions on the performance of EAHE system. It was found that in the winter season, air temperature rises to 11.2 °C and 17.2 °C in hot-arid and cold climates, respectively. Whereas, in summer, air temperature drop is up to 11.4°C and 11.1°C in hot-arid and cold climates, respectively. It was also observed that EAHE could be used for 294 days and 225 days of the year for hot-arid climate and cold climate, respectively.

Bansal et al. (2009) carried out a numerical study on EATHE system during the winter season and found that 23.4 m long EATHE system can increase air temperature in the range of 4.1–4.8 °C for the flow velocities of 2–5 m/s. Jakhar et al. (2015) coupled EATHE with a solar air heating duct to enhance the performance of EATHE system in winter season for arid climate of Ajmer (India). Results revealed that when EATHE system was coupled with solar air heating duct, its heating capacity increased by 1217.6–1280.7 kW h and COP increased up to 4.57. Kaushal et al. (2015) investigated an EAHX coupled with single pass solar air heater (SAH) and observed that performance of hybrid

Abbreviations: EAPHE, earth-air-pipe heat exchanger; GCHE, ground-coupled heat exchanger; GSHE, ground source heat exchanger; PUF, polyurethane foam; PVC, poly vinyl chloride; RH, relative humidity; RTD, resistance temperature detectors; SWTS, sub-soil water trickling system

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Nomenclature

Tinlet	EAPHE inlet air temperature, °C
T_{oulet}	EAPHE outlet air temperature, °C
T_{amb}	Atmospheric air temperature, °C
T_{soil}	Temperature of soil, °C
D_{t1} to D_{t8}	Air temperature along the length of pipe for dry EAPHE, °C
W_{t1} to W_{t8}	Air temperature along the length pipe for wet EAPHE, °C
A_s	Surface area of EAPHE pipe, m^2
Acs	Cross-sectional area of EAPHE pipe, m2
$\dot{m}$	Air flow rate in the pipe, kg/s
D	Diameter of EAPHE pipe, m
L	Length of EAPHE pipe, m
V	Air flow velocity in EAPHE pipe, m/sec
W	Electricity consumption of blower, watt
C_p	Specific heat of air, J/ kg K
ρ	Density of air, kg/m^3

EATHE is three times greater than simple EATHE.

Ghosal et al. (2005) integrated of ground air collector (GAC) and earth air heat exchanger (EAHE) for heating of greenhouse in the composite climate of India and compared the thermal performance of these two systems. It was observed that the during the winter period, GAC system is more effective than the EAHE system for greenhouse heating. Nayak and Tiwari (2009) developed a simplified mathematical model to evaluate the effectiveness of EAHE and Photovoltaic/thermal (PV/T) for heating and cooling of a greenhouse. It was observed that air temperature inside the greenhouse could be increased by around 7–8 °C during the winter season, by using of PV/T air collector during daytime and EAHE in the nighttime. Shukla et al. (2005) developed a quasi-steady state mathematical model to calculate seasonal cooling and heating potential of EAHE system for techno-economic analysis. The simple payback period was found 2.48 years, and it was concluded that the use of an EAHE system is very cost-effective along with a conventional air conditioner system for building heating/cooling.

Misra et al. (2013b) carried out a CFD modelling to investigate the influence of duration of operation and soil thermal conductivity on thermal performance of EATHE system for winter heating. It was observed that thermal performance of EATHE is significantly affected by duration of its continuous operation and soil thermal conductivity. Rouag et al. (2018) developed a transient semi-analytical model to predict the deterioration in thermal performance of EAHE system due to the duration of operation. They also observed that the soil radius (thickness of soil around the EAHE pipe) does not only depend on duration of operation, but it also depends on thermal diffusivity of soil, pipe diameter and inlet air temperature. Zeng et al. (2017) considered three different modes (operation for 8 h, 12 h, and 24 h) in karst areas to examine the performance of ground-source-heat- pump (GSHP) and they found that intermittent mode was advantageous for heat recovery of sub-soil. It was noticed that the COP of the system improved by 22.4% by increasing the time of recovery from 0 to 16 h. During long continuous operation, performance of EATHE system declines due to thermal saturation of soil in the vicinity of EATHE pipe. The thermal saturation of soil at the proximity of EATHE pipe can be reduced by running the EATHE system intermittently, thus, soil layers get adequate time for regeneration (Mathur et al., 2015a, 2015b).

Song et al. (2006) investigated the influence of soil thermal conductivity on the performance of GSHP and found that by increasing soil thermal conductivity from 1.1 W/m-K to 2.5 W/m-K, the heat transfer capacity increased by 100.8%. In a parametric study, Rosa et al. (2018) found that the air temperature drop/rise in EAHE system is proportional to the length of pipe and thermal conductivity of ground and inversely proportional to the diameter of pipe and air flow velocity.

The heat transfer in ground heat exchanger primarily depends on thermal conductivity of soil, thereby, rendering it a crucial property for ground-coupled heat exchangers (Darkwa et al., 2011). The soil thermal conductivity mainly depends on moisture contents, dry density, particle size, packing geometry and soil mineralogy etc. (Johansen, 1977).

The moisture content of soil greatly affects its thermal conductivity (Demir et al., 2009). The voids in the soil get filled with water, which subsequently increases the bridging between the soil particles thus, improving the thermal conductivity.

Sodha et al. (1990) investigated the EAHE pipe length required in cooling mode with different ground surface treatments for composite climate of Delhi (India) and observed that the dry sunlit surface required long tunnel for meeting the cooling load requirements, whereas, the wet shaded surface required the shortest one. From the parametric study, Puri (1987) observed that development of temperature profiles is faster in soil with high moisture contents compared to soil with low moisture contents.

Hsu et al. (2018) integrated the EAHE system with water-filled raft foundation to take the benefit of stable temperature and water of raft foundation of the building. It was observed that performance of this integrated system is equivalent to a real field based EAHE system at 2 m depth. It was also observed that the integrated system resulted into the lesser cost of installing the EAHE system.

Gao et al. (2016) proposed a novel method of submerging a horizontal ground-coupled heat exchanger (GCHE) underneath the rain garden, where due to percolation, the moisture contents of sub-soil increased. They found that the water can be impregnated to underground sub-soil during heat transfer process between fluid and soil. They also noticed that soil became dry in the proximity of pipe wall because of large temperature difference between layers of underground soil. Go et al. (2015) used infiltration analyses to study the impact of rainfall infiltration on thermal performance of shallow trenches. It was observed that in the unsaturated ground, the thermal efficiency of horizontal ground heat exchanger improved with infiltration of rain water. Platts et al. (2015) enveloped the ground heat exchanger pipe and water-saturated quartz sand by means of a polyethylene membrane to preserve moisture in the sand. From the numerical study, it was found that performance of horizontal GHE with this “Membrane Conduction Augmentation System” (MCAS) is better than “direct burial” (DB) horizontal GHE system.

Gan (2018) developed a new method to create moisture and temperature profiles in soil with spatially & temporally varying properties and the effects of primary conditions of soil and coupled heat and moisture transfer was evaluated on the thermal performance of a horizontal ground-coupled heat exchanger for a GSHP system. It was observed that for the estimation of heat transfer through a ground heat exchanger, the maximum deviation between models with and without considering moisture transfer were 17%, 18% and 24% in clay sand, sandy soils and loamy sand, respectively. It was concluded that for precise calculation of the thermal performance of a shallow depth ground-coupled heat exchanger, it is essential to consider coupled heat and moisture transfer process.

Cao et al. (2018) proposed a method for evaluating the performance of ground-heat-exchanger by applying the active-distributed-temperature-sensing (ADTS) technology, which interprets moisture of soil by a thermal response induced by the active electrical current. By using this method, they developed a relationship between thermal conductivity and soil moisture content of clay, silt, sand and organic soil. They reported that soil moisture content has a substantial impact on thermal conductivity of dry soil, but its impact is less on wet soil.

Soil thermal conductivity increases with an increase in soil density. By increasing unit weight of soil (or mass density), the contact area among the particles increases as more soil particles are filled in a unit