EXPERIMENTAL AND NUMERICAL ANALYSIS OF SOIL-TO-AIR HEAT EXCHANGER SYSTEM FOR DOMESTIC BUILDINGS

by

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Soil-to-air heat exchanger concept is one of the efficient methods to reduce the cooling effort required for any air conditioning system. In this paper, a theoretical model of soil-to-air heat exchanger has been developed to predict the air temperature in the outlet of the system during a hot atmospheric condition. This theoretical model is used to predict the sub-soil temperature for a specific ambient condition in a southern part of India and also compared with the measured sub-soil temperature. Performance of the soil-to-air heat exchanger system has been calculated during peak hours in summer and found to have the potential to reduce the energy required to cool the building.

Key words: *soil-to-air heat exchanger, domestic buildings*, *sub-soil temperature, air cooling*

Introduction

In recent years, the usage of air conditioning has drastically increased for domestic applications rather than official/industrial usage. This causes concern over the depletion of the ozone layer and global warming, as the air conditioner releases chlorofluorocarbons. In spite of its usage, several researches have been initiated to reduce its effect on global warming [1]. The concept of soil-to-air heat exchanger (SAHE) is gaining importance in the present energy scenario and related environmental effects [2, 3]. The SAHE is a reliable alternative to the air conditioning systems that circulate the external air to flow through underground soil where seasonal temperature variations are observed. In terms of reducing the energy demand and environmental issues, lots of researchers are investigating SAHE [4-9]. This paper focuses on the reduction of the energy demand in summer air conditioning system using SAHE.

In this system, air is the cooling medium which takes the hot outdoor air through a pipe which is buried in the soil with a relatively lower temperature. Heat transfer from the air to the soil takes place in the buried pipe and the air can be fed to the room directly or can be further cooled through another air conditioning system thus reducing the energy required for air conditioning. Several studies have been carried out by researchers on thermal comfort in tropical climate areas while studies on indoor thermal comfort are very limited.

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Bansal *et al.* [5] developed a computational model based on CFD to predict the thermal performance and cooling capacity of SAHE used to reduce the cooling load of buildings in summer. The developed model was validated with experimental investigations on a set-up established in the western part of India. Ghosal *et al.* [4, 6] developed a model to test the year-round effectiveness of a SAHE system coupled with a greenhouse located in the Indian Institute of Technology, Delhi, India and concluded that SAHE is more effective in winter than in summer.

Al-Ajmi *et al.* [7] built a model to investigate the cooling potential of SAHE in buildings in the desert region of Kuwait and the model was compared with other published models; it also highlights the effectiveness of SAHE based on the cooling load, indoor temperature reduction and cooling energy demand. De Paepe and Janssens [10] used a 1-D analytical method to analyze the influence of the design parameters of SAHE which can be used to determine its characteristics. Bisoniya *et al.* [13] developed a 1-D model of the SAHE systems that can be used by designers on the calculation of the design parameters. Vaz *et al.* [14] presented a numerical study of SAHE used for heating and cooling buildings and validated it with experiments conducted in southern Brazil. Florides and Kalogirou [15] has done a systematic review on the system, models and applications of ground heat exchangers.

Only few studies on the applicability of SAHE system in tropical parts of India have been addressed in the literatures. Many researchers use numerical studies to validate the developed model and also the validation of developed mathematical model with experimental investigation is also very limited. This paper focuses on the use of SAHE system on Salem located in a southern state of India.

Soil-to-air heat exchanger

The methodology of SAHE system is based on combination of pipes buried on ground, with two ends of pipe acts as suction end and delivery end. The draught fan is used for supplying air to inlet and the air travels through pipe arrangement buried in to the cool soil. The heat absorption/rejection is takes place among the hot air to the pipe, and similar way among pipeline to surrounding soil. For economical aspect, it is advised not to dig deeper in to ground and it's far better to extend no of tubes as well as tube length [10]. The amount of acidity level in the selected soil has been tested by titration process with a strong base. The pH value of 7.61 corresponds to neutralization capacity and the base property of pH soil is of non-corrosive nature to aluminum pipes.

Sub-soil temperature model

Two modes of heat transfer occur in the SAHE system *viz.*, conduction between soil and pipe material, convection between pipe and air flowing inside the pipe. Ajmi *et al.* [7], and Bisoniya *et al.* [13] have developed a mathematical model given in eq. (1) to simulate the annual sub-soil temperature considering a semi-infinite homogenous solid.

Equation (1) is used to predict the soil temperature at a location in the town Salem which is located in the state of Tamilnadu in India. The soil temperature is predicted for a depth of 2 m in the presented location. The other parameters in eq. (1) considered for the study are $T_m = 24$ °C. Soil temperature varies according to the climatological conditions prevailing in the test location and the temperature variations deeper in the soil can be predicted using the labs model [16] given in eq. (1):

$$T_{(z,t)} = T_{\mathrm{m}} - A_{\mathrm{S}} \mathrm{e}^{\left(-z\sqrt{\frac{\pi}{8760\alpha}}\right)} \cos\left[\frac{2\pi}{8760}\left(t - t_0 - \frac{z}{2}\sqrt{\frac{8760}{\pi\alpha}}\right)\right] \tag{1}$$

According to the previous model, the selected soil temperature varies sinusoidally relative to the solar surface heat flow [16].

Soil temperature (thermal characteristics) is one of the factors which adversely affect the rate of cooling and heating. To evaluate the achievable performance of geo cooling system, primarily focused on soil temperature has to be measured at different depths. Thus the observed data also helps to identify the optimum deep for geo cooling systems and to predetermine the sizing of the device based on the sum of rate involved for cooling. Initially measured temperature at various depths like 0.91, 1.21, 1.52, 1.82, 2.133, and 2.438 m are 19.21, 20.48, 21.63, 22.68, 23.61, and 24.43 °C, respectively. The measured temperature does not have much variations below 2.0 m depth. The temperature of the ground at a depth of 2-3 m is constant throughout the year [8, 13]. Based on the observed temperature results, the authors considered the ground depth of 2.4 m as economically fit. Also, from the economic design point of view, the SAHE set-up might be fixed below the basement of the water tank of a residential building which is approximately 2-3 m deep and through this approach effective space utilization and heat transfer rate could be achieved.

The SAHE model set-up

The set-up was built in the region of south India, Salem (latitude 11.69°N, longitude 78.14°E) at an altitude of 278 m (912 ft) from mean sea level. The selected city's climate is dry in general expect monsoon season in the month of September to November. The highest temperature was observed in the period of March to May. The average maximum ambient temperature was recorded in May 38.6 °C and minimum in January 19.7 °C (Indian Meteorological Department).

Thus the selected room is north facing with size of 4.75 m × 4.85 m × 3.9 m and the layout of the room is shown in fig. 1. The wall thickness is 0.275 m and painted in both inner and outer surface of the room, from north facing wall a door is situated apart from that window is placed parallel wall of door.

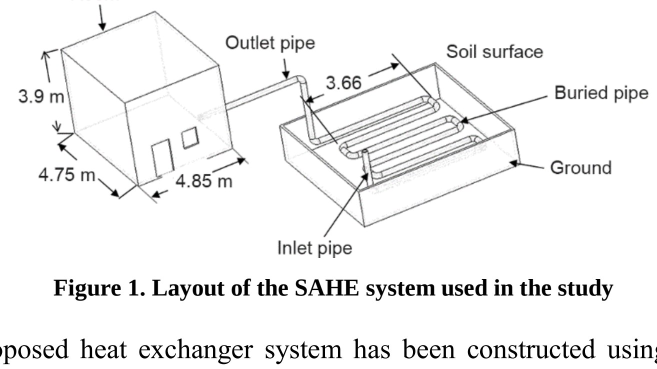

Figure 1. Layout of the SAHE system used in the study

The proposed heat exchanger system has been constructed using aluminum pipes while PVC couplings are used to connect the five lengths of pipes each 100 mm diameter and 3.66 m length. The SAHE set-up before burying into soil is shown in fig. 2. Air draught fan is used to made air-flow through pipe which is constructed in a horizontal loop. The circular cross section pipe is buried 2.4 m deeper from the subsoil surface is made to contact the soil around the circumference of pipe with closed packing structure it enables heat convection from pipe to soil as well as *vice versa*.

Figure 2. Underground pipe in SAHE system

The SAHE system analysis

Once the soil steady temperature is known, heat transfer in SAHE could be found using the following two methods: logarithmic mean temperature difference method (LMTD) and number of transfer units (NTU). For the present SAHE system the pipe diameter is 0.101 m for a total length of 24 m with five parallel tubes.

The Nusselt number depends on the surface thermal condition of the pipe; it indicates that the flow is laminar or turbulent, related to the Reynolds number [11, 12].

Heat transfer coefficient:

$$h_c = \frac{\mathrm{Nu}\,K_{\mathrm{air}}}{D} \tag{2}$$

$$h_c = \left[\frac{\dfrac{f}{8(\mathrm{Re}-1000)\,\mathrm{Pr}}}{1+12.7\sqrt{\dfrac{f}{8}}(\mathrm{Pr}^{2/3}-1)} \right] \frac{K_{\mathrm{air}}}{D} \tag{3}$$

The air outlet temperature of buried pipe can be obtained by the exponential form of relation given [5, 10]:

$$T_{\mathrm{out}} = T_{(z,t)} + [T_{\mathrm{in}} - T_{(z,t)}]\mathrm{e}^{-\mathrm{NTU}} \tag{4}$$

The CFD analysis of the proposed heat exchanger system

The CFD package is employed for performing complicated heat transfer rate, and fluid flow analysis in applications like heat exchangers, *etc*. In this research work, ANSYS CFX software has been used for performing CFD analysis on the proposed heat exchanger system. The CAD model of the proposed SAHE system has been modeled as per the dimensions. The boundary conditions such as soil temperature, inlet air temperature, mass-flow rate of inlet air has been defined in the model. The CFD analysis provides solutions such as pressure, temperature, and flow velocity for SAHE system and thus it is verified with experimental data's interfaced through LabVIEW software interfaced with temperature sensors (LM35).

The hourly temperature variations of SAHE for suction and delivery are measured continuously during daytime using sensors placed at two ends. The underground soil temperature variation was measured using thermocouple at different depth also it verified with mathematical calculation of subsoil temperature prediction [7]. Figure 3 shows the predicted sub soil temperature all around year showing slight deviations against mathematical modeling.

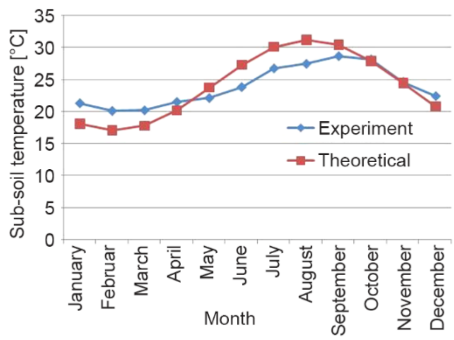

Figure 3. Variation of sub-soil temperature during different period

The mass-flow rate assumed as constant throughout the period of study as well as initially the velocity as kept constant at 1 m/s to conduct the test. The temperature differences exists from inlet to outlet around 3-5 ºC in summer and 2-3 ºC in winter were the air travelling through the pipe length of 24 m.

The CFD analysis has been carried out to predict the effectiveness of SAHE system during different environment conditions. Figure 4 shows the temperature transportation along the air passing through the pipe with the inlet air temperatures of 30 ºC. The analysis shows that a maximum temperature difference of 7-10 ºC can be achieved using SAHE system.

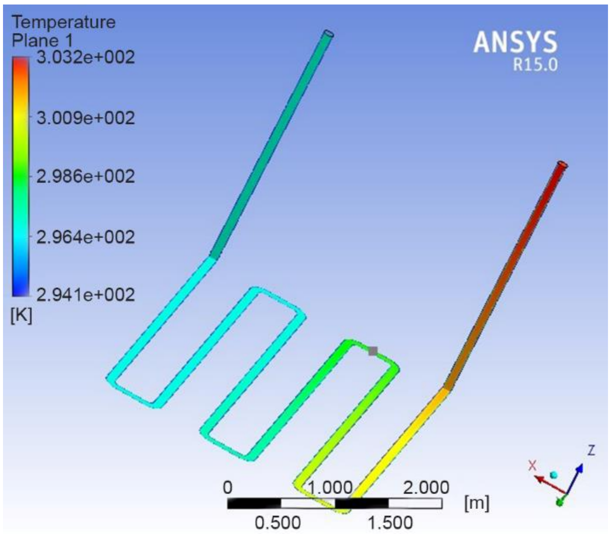

Figure 4. Temperature distribution of air inside pipe with inlet air temperature of 30 ºC

Conclusions

The main purpose of this study is to demonstrate the methodology of analysis the SAHE system. Computational modeling provides a greater advantage of performing several iterations with different environment conditions and can also be used to extend the study for varying pipe layout configuration, pipe geometry, depth, and mass-flow rates. The experimental study of developed SAHE model shows that maximum temperature difference exists during summer season compared to winter season. The SAHE method is an effective method for both cooling and heating for commercial applications. This study has a further scope to test the different packaging materials instead of soil, finned pipe, different pipe material and layout, and to analyze the temperature variations during setback period.

Nomenclature

A_s – annual surface temperature amplitude, [°C]
D – diameter of the circular pipe, [m]
f – pipe friction factor
h_c – heat transfer coefficient
K – thermal conductivity
Pr – Prandtl number
Re – Reynold's number
$T_{(z,t)}$ – subsoil temperature at a depth of 'z' meters at a time of 't' hours
T_{in} – inlet pipe air temperature, [°C]
T_m – average annual ground temperature, [°C]
T_{out} – outlet pipe air temperature, [°C]
t – time, [hours]
z – ground depth, [m]

Greek symbol

α – thermal diffusivity of the selected soil, [m^{2}h^{-1}]

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