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Performance analysis of earth–pipe–air heat exchanger for summer cooling

Vikas Bansal *, Rohit Misra, Ghanshyam Das Agrawal, Jyotirmay Mathur

Mechanical Engineering Department, Malviya National Institute of Technology, Jaipur 302017, India

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ABSTRACT

Earth–pipe–air heat exchanger (EPAHE) systems can be used to reduce the cooling load of buildings in summer. A transient and implicit model based on computational fluid dynamics was developed to predict the thermal performance and cooling capacity of earth–air–pipe heat exchanger systems. The model was developed inside the FLUENT simulation program. The model developed is validated against experimental investigations on an experimental set-up in Ajmer (Western India). Good agreement between simulated results and experimental data is obtained. Effects of the operating parameters (i.e. the pipe material, air velocity) on the thermal performance of earth–air–pipe heat exchanger systems are studied. The 23.42 m long EPAHE system discussed in this paper gives cooling in the range of 8.0–12.7 °C for the flow velocities 2–5 m/s. Investigations on steel and PVC pipes have shown that the performance of the EPAHE system is not significantly affected by the material of the buried pipe (pipe). Velocity of air through the pipe is found to greatly affect the performance of EPAHE system. The COP of the EPAHE system discussed in this paper varies from 1.9 to 2.9 for increase in velocity from 2.0 to 5.0 m/s.

1. Introduction

In recent times, air conditioning is widely employed not only for industrial productions but also for the comfort of occupants. It can be achieved efficiently by vapor compression machines, but due to the depletion of the ozone layer and global warming by chlorofluorocarbons (CFCs) and the need to reduce high grade energy consumption; numerous alternative techniques are currently being explored. One such method is the earth–pipe–air heat exchanger system, in which hot outdoor air is sent into the pipes that are buried in the ground. When air flows in the earth–air–pipes, heat is transferred from the air to the earth. As a result, the air temperature at the outlet of the earth–air–pipes is much lower than that of the ambient. The outlet air from the earth–air–pipes can be directly used for space cooling if its temperature is low enough. Alternatively, the outlet air may be cooled further by associated air conditioning machines. Both of the above uses of earth–air–pipes can contribute to the reduction in energy consumption.

Several researchers have studied the use of the ground as heat source and sink such as Bansal et al. [1]. They evaluated a large earth–air–pipe system meant to provide thermal comfort inside the whole building complex at one of the hospitals in India. Mihalakakou et al. [2] presented a parametrical model in which varying parameters were pipe length, pipe radius, velocity of the air inside the tube and depth of the buried pipe below earth surface. Santamouris et al. [3] investigated the impact of different ground surface boundary conditions on the efficiency of a single and a multiple parallel earth-to-air heat exchanger system. Kumar et al. [4] evaluated the conservation potential of an earth–air–pipe system coupled with a building with no air conditioning. Ghosal et al. [5] developed a thermal model to investigate the performance of earth–air heat exchanger (EAHE) integrated with green house. Ajmi et al. [6] studied the cooling capacity of earth–air heat exchangers for domestic buildings in a desert climate. Badescu et al. [11] developed a ground heat exchanger model based on numerical transient bi-dimensional approach. Wu et al. [7] developed a transient and implicit model based on numerical heat transfer and computational fluid dynamics and then implemented it on the CFD (computational fluid dynamics) platform, PHOENICS, to evaluate the effects of the operating parameters (i.e. the pipe length, radius, depth and air flow rate) on the thermal performance and cooling capacity of earth–air–pipe systems. Cucumo et al. [8] proposed a one-dimensional transient analytical model to estimate the performance of earth-to-air heat exchangers, installed at different depths, used for building cooling/heating. Cui et al. [9] developed a finite element numerical model for the simulation of the ground heat exchangers in alternative operation modes over a short time period for ground-coupled heat pump applications.

* Corresponding author. Tel.: +91 9982378283.
E-mail address: bansal_vikas1@yahoo.com (V. Bansal).

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Nomenclature

$\dot{m}$	mass flow rate of air through the pipe
c_p	specific heat capacity of air
C_d	coefficient of discharge of the pipe = 0.6
d	diameter of the pipe
v	mean velocity of air through the pipe
Q_c	total hourly cooling from the EPAHE system
Q_i	work done per second for running the blower
T_{inlet}	temperature at the inlet of earth–pipe–air heat exchanger
T_{exit}	temperature at the exit of earth–pipe–air heat exchanger
EPAHE	earth–pipe–air heat exchanger
PVC	polyvinyl chloride
COP	coefficient of performance

In present study, transient analysis of Earth–pipe–air heat exchanger (EPAHE) has been done using FLUENT. EPAHE is simulated for studying the performance during summer for cooling. The model developed is validated with experimental results obtained on an experimental set-up installed in Ajmer (Western India). Effect of pipe material and flow velocity of air on the performance of the EPAHE is studied.

2. Description of the earth–pipe–air heat exchanger system

The EPAHE as shown in Fig. 1 comprises of two horizontal cylindrical pipes of 0.15 m inner diameter with buried length of 23.42 m, made up of PVC and mild steel pipes and buried at a depth of 2.7 m in a flat land with dry soil. The two pipes viz. PVC and steel are connected to common intake and outlet manifold for air passage. Globe valves are fitted for each pipe assembly for flow control of air. At the inlet, the open end of this single pipe is connected through a vertical pipe to a 1 HP, single phase motorized, 2800 RPM, 0.033 m^3/s blower. The air from the ambient is forced through the earth–air–pipe system with the help of blower. Velocity of the air through the pipe can be varied by changing the RPM of the blower with the help of an autotransformer whose range is 0–270 V, 2 A max., type: 2D-1PHASE with a least count of 1 V. Six thermocouples are inserted at fixed distance along the length of each pipe at T_1, T_2, T_3, T_4, T_5 and T_6, to measure temperature of the air along the length of each pipe. Thermocouples are of K-type with temperature indicator having a least count of 0.1 °C. Flow of air through the individual pipe can be controlled with the help of valves. For flow of air through one pipe only one valve is kept open at a time. Observations were taken for different velocities and flow of air through both the pipes separately. Air flow velocities are measured with the help of a vane probe type anemometer having range of 0.4–30.0 m/s with a least count of 0.1 m/s.

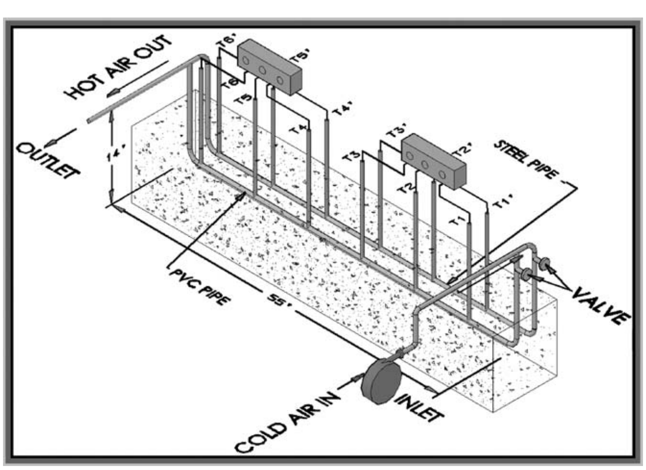

Fig. 1. Experimental set-up of EPAHE.

3. Description of CFD model

Computational fluid dynamic (CFD), well known as a powerful method to study heat and mass transfer for many years. CFD codes are structured around the numerical algorithms that can tackle fluid flow problems. It provides numerical solutions of partial differential equations governing airflow and heat transfer in a discretised form. Complicated fluid flow and heat transfer processes involved in any heat exchanger can be examined by CFD software, FLUENT 6.3. FLUENT 6.3 packages include sophisticated user interfaces to input problem parameters and to examine the results. CFD codes in FLUENT contain three main elements: (i) a pre-processor, (ii) a solver and (iii) a post-processor. Pre-processing consists of the input of a flow problem to a CFD program by means of definition of the geometry of the region of interest: the computational domain, grid generation—the subdivision of the domain into a number of smaller, non-overlapping sub-domains: a grid (or mesh) of cells (or control volumes or elements), selection of the physical and chemical phenomena that need to be modelled, definition of fluid properties, specification of appropriate boundary conditions at cells which coincide with or touch the domain boundary. Solver uses the finite control volume method for solving the governing equations of fluid flow and heat transfer. Post-processor shows the results of the simulations using vector plots, contour plots, graphs, animations, etc.

Thermal modelling of the Earth–pipe–air heat exchanger (EPAHE) system shown in Fig. 1 is done using FLUENT 6.3. The model was developed inside the FLUENT simulation program using GAMBIT.

The CFD simulations were performed considering 3D transient turbulent flow (standard k–ε model) with heat transfer enabled. In this transient analysis time step is taken as 100 s with 20 iterations in each step. Total numbers of the control volume used for the CFD analysis were about 3.8 million. CFD analysis is carried out for two different pipe materials viz. mild steel and PVC.

The main objective of the CFD study was to investigate the effect of buried pipe material on the performance of the EPAHE system (for this two materials, mild steel and PVC were considered) and also to study the effect of air velocity on the performance of the EPAHE system.

In the study it was assumed that air is incompressible and subsoil temperature remains constant since the penetration of the heat from the surface of the soil is very slow. It was also assumed that engineering materials used are isotropic and homogeneous.

The physical and thermal parameters of different engineering materials used in the present simulation are listed in Table 1.

4. Experimental validation and performance analysis

CFD based EPAHE modelling is validated by taking observations on an actual EPAHE fabricated at Ajmer (Western India) as shown in Fig. 1. Observations were taken on March 12, 2009 and repeated on April 08, 2009 at Ajmer. Both in experiments and simulations, flow of air is made through PVC and steel pipes separately. Observations were taken for flow velocities 2.0, 3.0, 4.0 and 5.0 m/s. Total hourly cooling has been calculated for flow velocities 2.0,

Table 1
Physical and thermal parameters used in simulation.

Material	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)
Air	1.225	1006	0.0242
Soil	2050	1840	0.52
Steel	7833	465	54
PVC	1380	900	0.16

3.0, 4.0 and 5.0 m/s by the following equation:

$$Q_c = 3600\dot{m}C_d c_p(T_{\text{inlet}} - T_{\text{exit}}) \tag{1}$$

where $\dot{m} = (\pi/4)d^2\rho v$; $\dot{m}$, mass flow rate of air through the pipe; c_p, specific heat capacity of air; C_d, coefficient of discharge of the pipe = 0.6; d, diameter of the pipe; v, mean velocity of air through the pipe; ρ, density of air.

Coefficient of performance (COP) of the system can be evaluated from the following expression:

$$\text{COP} = \frac{\dot{m}C_d c_p(T_{\text{inlet}} - T_{\text{exit}})}{Q_i} \tag{2}$$

In Figs. 2 and 3, points T_{inlet} and T_{exit} represent the inlet and outlet of the buried pipe of the earth–pipe–air heat exchanger system respectively. Fig. 2 represents the comparison of the results of the simulation and experiments for air velocities of 2.0, 3.2, 4.0 and 5.0 m/s at the outlet of the steel and PVC pipes respectively. Tables 2 and 3 show the validation of simulated temperatures with experimental results. This is apparent that variation in simulated and experimental results ranges from 0 to 11.4% of experimental results. This variation may occur due to the variation in coefficient of friction of engineering material used in simulation and experiment, irregularities such as joints in experimental set-up and improper insulation at the risers of experimental set-up. Tables 2 and 3 also depict that as the velocity of air is increased, the temperature of the air at the outlet of the pipe gets enhanced. The increase in temperature of the air at the exit of pipe due to the increment in air velocity occurs because when the air velocity is increased from 2.0 to 5.0 m/s, the convective heat transfer coefficient is increased by 2.3 times while the time to which the air remains in contact with the ground is reduced by 2.5 times. Thus the later effect is dominant and therefore, less drop in temperature is obtained at air velocity 5.0 m/s than the 2.0 m/s. At higher velocities though the drop in temperature of air is less yet the total cooling effect achieved per unit time is much more. It can be seen that the maximum drop in the temperature occurs at air velocity 2 m/s. It can be seen that the maximum rise in the temperature occurs at air velocity 2 m/s for both PVC and steel pipes. The maximum rises in temperature for PVC and steel pipes are 10.3 and 12.7 °C respectively.

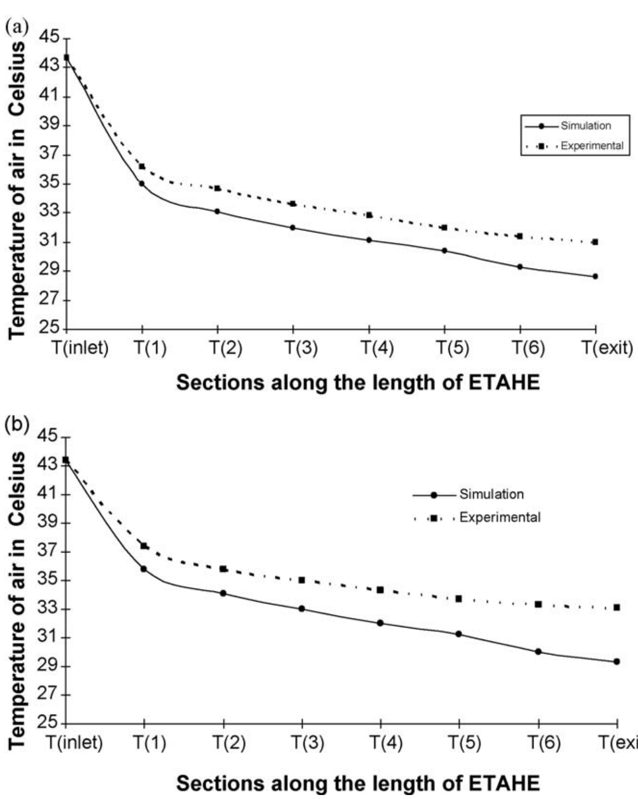

Fig. 2. Temperature distribution along the length of the pipe for exit velocity 2.0 m/s for (a) steel pipe and (b) PVC pipe.

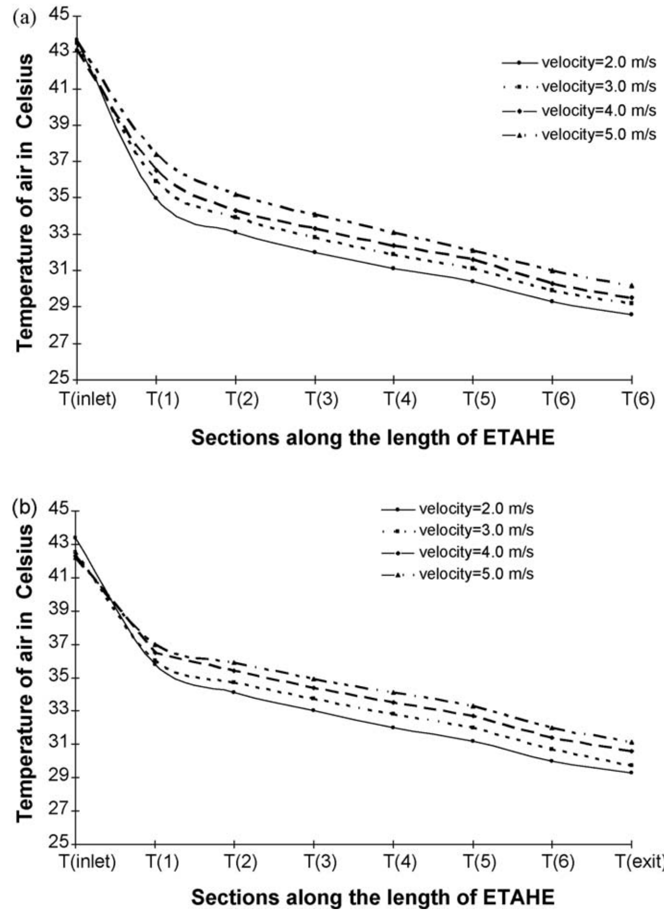

Fig. 3. Simulated temperature along the length of the pipe for various exit velocities for (a) steel pipe and (b) PVC pipe.

This can be concluded from Fig. 3 that there is very small difference in temperature of the air at the outlet of pipe between PVC and steel pipe if all other input conditions are same. This variation occurs because the material with higher coefficient of friction marginally improves the performance of earth–pipe–air heat exchanger system due to the reduction in thickness of laminar sub-layer which results in variation in Nusselt number but the variation in Nusselt number is only 4–5%. Though the steel has higher thermal conductivity than PVC, yet the variation in temperature of the air at the outlet of pipe between steel and PVC is very small. Therefore, this can be concluded that in EPAHE system, convective heat transfer plays more important role than

Table 2
Comparison of experimental and simulated temperature at different sections along the length of steel pipe.

Section	Air velocity = 2 m/s			Air velocity = 3 m/s			Air velocity = 4 m/s			Air velocity = 5 m/s		
	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.
T_{inlet}	43.7	43.7	0.00	43.5	43.5	0.00	43.1	43.1	0.00	43.6	43.6	0.00
T_1	36.2	35	3.31	37.1	35.9	3.23	38.2	36.5	4.45	38.8	37.4	3.61
T_2	34.7	33.1	4.61	35.5	33.9	4.51	36.7	34.3	6.54	37.3	35.2	5.63
T_3	33.6	32	4.76	34.5	32.8	4.93	35.5	33.3	6.20	36.5	34.1	6.58
T_4	32.8	31.1	5.18	33.7	31.9	5.34	34.4	32.4	5.81	35.5	33.1	6.76
T_5	32	30.4	5.00	33	31.1	5.76	33.7	31.6	6.23	34.6	32.1	7.23
T_6	31.4	29.3	6.69	32.4	29.9	7.72	33	30.3	8.18	34.1	31	9.09
T_{exit}	31	28.6	7.74	32	29.2	8.75	32.5	29.5	9.23	33.7	30.2	10.3

Table 3
Comparison of experimental and simulated temperature at different sections along the length of PVC pipe.

Section	Air velocity = 2 m/s			Air velocity = 3.0 m/s			Air velocity = 4 m/s			Air velocity = 5 m/s		
	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.	Exp. temp.	Sim. temp.	% diff.
T_{inlet}	43.4	43.4	0.00	42.5	42.5	0.00	42.3	42.3	0.00	42.2	42.2	0.00
T_1	37.4	35.8	4.28	38	36	5.26	38.2	36.5	4.45	39.3	37	5.85
T_2	35.8	34.1	4.75	36.5	34.7	4.93	36.8	35.4	3.80	37.9	35.9	5.28
T_3	35	33	5.71	35.7	33.7	5.60	35.8	34.4	3.91	37	34.9	5.68
T_4	34.3	32	6.71	34.8	32.8	5.75	34.9	33.5	4.01	36.1	34.1	5.54
T_5	33.7	31.2	7.42	33.7	32	5.04	34	32.7	3.82	35.3	33.3	5.67
T_6	33.3	30	9.91	33.3	30.7	7.81	33.7	31.4	6.82	34.8	32	8.05
T_{exit}	33.1	29.3	11.4	33.1	29.7	10.2	33.5	30.6	8.66	34.2	31.1	9.06

conductive heat transfer. This indicates that the performance of the EPAHE system does not depend upon the material of the pipe. Total hourly cooling obtained from this EPAHE system varies from 1.2 to 3.1 MWh. Maximum hourly cooling is observed at air velocity 5 m/s. The COP of the EPAHE system discussed in this paper varies from 1.9 to 2.9 for increase in velocity from 2.0 to 5.0 m/s.

Many researchers had demonstrated the results of experiments on EPAHE for summer cooling. Boulard et al. [10] presented results of a greenhouse with an underground heat storage system consisting of two layers of 0.125-m diameter PVC drain pipes buried 0.8 and 0.5 m deep, and a centrifugal fan circulating the greenhouse air in the south of France to maintain an average night inside–outside temperature difference of 7–9 °C in March–April. Goswami et al. [12] developed an EPAHE system consisted of a 12-in. diameter; 100-foot-long corrugated plastic pipe buried 9 ft deep, a 1/4-hp blower fan to move air through the pipe at the Energy Research and Education Park at the University of Florida. They found that the system can reduce the ambient air temperature from 90 °F to one in the range of 80–83 °F. The EPAHE system discussed in this paper shows the performance of the system in dry climate of the Western India for pipe diameter, velocities and materials different than the previous researchers had done. The performance of the EPAHE system was also validated by the simulations performed on CFD simulation platform FLUENT, which was less covered by the researchers. The simulations can be used to estimate the performance of the EPAHE system for different operating parameters.

5. Conclusion

There is a fair agreement between the experimental and simulation results for modelling of EPAHE system with maximum deviation of 11.4%. Drop in air temperature is found to decrease with increase in flow velocity. This can be concluded from this analysis that the performance of the EPAHE system is not affected by the material of the buried pipe, therefore a cheaper material pipe can be used for making the pipe. For the pipe of 23.42 m length and 0.15 m diameter, temperature rise of 8.0–12.7 °C has been observed for the flow velocity ranging from 2 to 5 m/s. The hourly cooling obtained through the system is found to be in the range of 1.2–3.1 MW h. The COP of the EPAHE system discussed in this paper varies from 1.9 to 2.9 for increase in velocity from 2.0 to 5.0 m/s.

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