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Optimization of operating parameters of earth air tunnel heat exchanger for space cooling: Taguchi method approach

Kamal Kumar Agrawal^{1*}, Mayank Bhardwaj², Rohit Misra³, Ghanshyam Das Agrawal¹ and Vikas Bansal³

*Correspondence:

kamal.rightway@gmail.com

¹ Mechanical Engineering
Department, Malaviya
National Institute
of Technology, Jaipur 302017,
India

Full list of author information
is available at the end of the
article

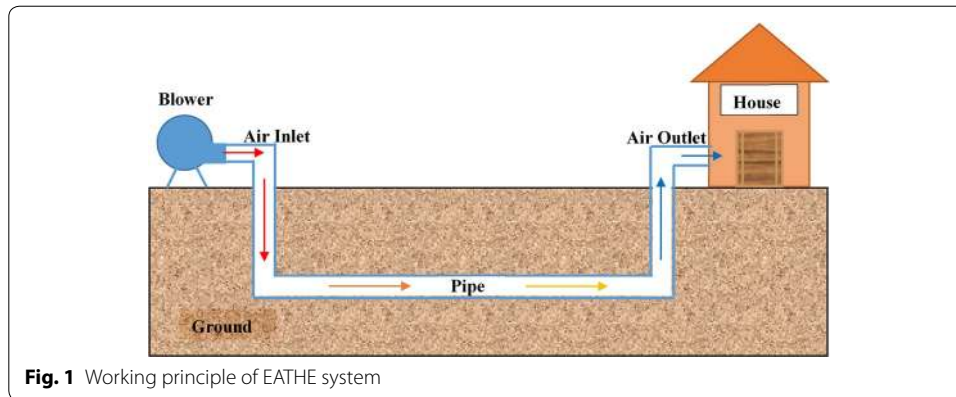
Abstract

In the present study, CFD-based parametric analysis is carried out to optimise the parameters affecting the temperature drop and heat transfer rate achieved from earth air tunnel heat exchanger (EATHE) system. ANSYS FLUENT 15.0 is used for CFD analysis, and k - ϵ model and energy equation were considered to define the turbulence and heat transfer phenomena. For a straight EATHE system configuration, four design and operating parameters, i.e., diameter of the pipe (A), length of pipe (B), inlet air velocity (C), and inlet air temperature (D), are considered at four different levels in Taguchi method. The Taguchi method is used to obtain maximum air temperature drop and heat transfer rate. The best combination of parameters for achieving a maximum drop in air temperature is $A_1B_4C_1D_4$ and that for obtaining maximum total heat transfer rate is $A_4B_4C_4D_4$. Statistical analysis reveals the percentage contribution of different factors for air temperature drop in the following order: inlet air temperature (57.80%), diameter of pipe (20.66%), length of pipe (12.03%), and air velocity (9.51%), while, for heat transfer rate, pipe diameter (53.28%), inlet air temperature (30.87%), air velocity (9.40%), and length of pipe (6.45%).

Keywords: Earth air tunnel heat exchanger, Design and operating parameters, Taguchi optimization, ANOVA, Air temperature drop, Heat transfer rate

Background

The significance of renewable energy is increasing due to depletion of fossil fuels and rise in fossil fuels prices. In last 2 decades, the energy demands in buildings have raised significantly due to increasing living standards and population. Space cooling and heating utilized about 33% of total energy consumption world over (Nejat et al. 2015; Omer 2008). The conventional cooling and heating systems are energy intensive. Therefore, many countries are adopting passive and low-grade energy systems for cooling and heating of buildings. Earth air tunnel heat exchanger (EATHE) system uses earth as a heat source/sink to transfer heat to/from fluid flowing through the buried pipes. At a depth of 3–4 m, soil temperature remains constant round the year, and when the air is passed through buried EATHE pipe, it produces a heating effect in winter and cooling effect in summer (Bansal et al. 1983; Bansal and Sodha 1986; Bharadwaj and Bansal 1981; Wang et al. 2009). The working principle of EATHE system is shown in Fig. 1.



For the efficient working of the EATHE system during the summer, the estimation of maximum air temperature drop and heat transfer rate that can be produced by EATHE system are two key performance indicators. Large temperature drops and heat transfer rate also improve the economic viability of the EATHE system. Hence, there should be a methodology to investigate the maximum air temperature drop obtainable from EATHE system for space cooling applications.

Mihalakakou (2003) calculated the heating potential of EATHE using a dynamic and deterministic numerical model. The estimated values of soil temperature were compared with measured soil temperature values and observed that the neural network could efficiently simulate the outlet air temperature of EATHE system. It was found that the ground temperature is the most critical parameter to estimate the outlet air temperature. Kumar et al. (2006) developed a deterministic model and an intelligent model by using the artificial neural network (ANN). The intelligent model calculates outlet air temperature of EAHE with an accuracy of $\pm 2.6\%$, whereas the accuracy of the deterministic model was $\pm 5.3\%$. It was found that the cooling/heating potential of the 80 m-long EAHE was 7.49 kW in winter and 12.25 kW in summer. Zhang and Haghghat (2009, 2010) developed a method to estimate the convective heat transfer in an EAHE system of the large rectangular cross-sectional area. Parametric studies were carried out using CFD simulations, and ANN models were trained using simulation results. A mathematical relationship was developed between six design parameters and area-weighted local average Nusselt numbers. It was observed that average Nusselt number was not affected by the turbulence intensity of air at the inlet, the surface temperature variation, nor the size of the outlet section of the duct. However, the heat convection was influenced by the duct length, width, and height; the size of the inlet; the temperature difference between inlet air and surface; air velocity; mode of operation. Diaz et al. (2013) applied a fuzzy logic controller to optimise the power consumption in an EATHE system. It was observed that an EATHE consumes less energy when the fuzzy logic controller is implemented instead of an on-off controller.

Kumar et al. (2008) used the concept of the goal-oriented genetic algorithm (GA) for evaluation and optimisation of different aspects of EAHE system. Four parameters, viz., air humidity, ambient air temperature, ground temperature at burial depth, and ground surface temperature, were considered, and through sensitivity analysis, it was found that outlet air temperature was significantly affected by the ground temperature

at burial depth and ambient air temperature. Kaushal et al. (2015) predicted the thermal performance of an EATHE-coupled solar air heater by applying finite-volume method. Response surface methodology (RSM) was used to optimise the process parameters. Five independent parameters were considered, viz., soil thermal conductivity, inlet air velocity, inlet air temperature, depth of solar air heater channel, and solar radiation intensity, and two output responses, viz., temperatures difference between outlet to inlet air for simple EATHE and hybrid EATHE, were taken. It was observed that the soil thermal conductivity is the most important factor followed by the depth of the solar air heater channel and the intensity of solar radiation.

It has been seen that, with an increase in pipe diameter, total temperature drop/rise in summer/winter falls and overall heating/cooling capacity enhances (Ahmed et al. 2016; Ghosal and Tiwari 2006; Krarti and Kreider 1996; Santamouris et al. 1995). Sodha et al. (1994) compared the single air-pipe EATHE system with the multi-air-pipe EATHE system at the same air mass flow rate. It was observed that, for a given mass flow rate, the heating potential (HP) and cooling potential (CP) increase with increasing the number of pipes of smaller diameter, because effective heat transfer area increases with increase in number of pipes. Mihalakakou et al. (1994a) found that, by reducing pipe diameter from 0.5 to 0.25 m, air temperature drop increases by 1.5–2.5 °C at the pipe's outlet in summer cooling operation. Mihalakakou et al. (1996a) observed that the convective heat transfer coefficient reduces with increase in the radius of the buried pipe; this leads to lower air temperature at the outlet of pipe in winter and thus reduces the heating capacity of the system. Typical diameters of pipe are 10–30 cm but may be as large as 1 m for commercial applications.

By increasing the pipe length of EATHE, the temperature difference between inlet and outlet air increases, but the rate of change of temperature decreases (Derbel and Kanoun 2010; Kabashnikov et al. 2002). It was observed that, after a certain length, heat transfer does not increase by increasing the pipe length (Benhammou and Draoui 2015), and it is termed as saturation length (L_{sat}). The saturation length increases with increase in the air flow rate. According to Lee and Strand (2008), there are no significant advantages in using pipes over 70 m length. In a parametric study, Ahmed et al. (2016) found that the pipe length is a dominating parameter over other parameters (air velocity, pipe diameter, pipe material, and pipe depth) which affects thermal performance of EATHE system. In an EATHE system, pipe length is the critical factor which affects the performance of EATHE. In many studies, it was identified that, by increasing pipe length, the drop/rise in air temperature is increased (Ghosal and Tiwari 2006; Mihalakakou et al. 1994c; Santamouris et al. 1995), but, after a certain extent, the effect of pipe length on temperature drop/rise decreases.

The velocity of flowing air in the buried pipe also significantly influences the performance of EATHE system. It was observed that, by increasing air velocity, the total temperature difference between inlet and outlet air temperature decreases (Kabashnikov et al. 2002; Mihalakakou et al. 1994a, b, 1996a, b). Niu et al. (2015) considered five flow velocities, viz., 0.5, 1.0, 1.5, 2, and 2.5 m/s, for cooling operation, and found that the air temperature drop rate was the highest at 0.5 m/s, because low velocity provides more contact time between air and pipe. Bansal et al. (2009) considered four flow velocities (2, 3, 4, and 5 m/s) for winter heating application, and observed that maximum air

temperature rise was obtained at 2 m/s, while the maximum hourly heat gain was found at air velocity 5 m/s. In another study for summer cooling, it was noted that maximum air temperature drop was observed at 2 m/s and maximum hourly cooling was observed at air velocity 5 m/s (Bansal et al. 2010). Similar results were also obtained by Wu et al. (2007) for cooling operation, by increasing air velocity (from 1 to 4 m/s); the outlet air temperature jumps to higher values, but the heat transfer rate increases because of increase in mass flow rate. Dubey et al. (2013) observed that, by increasing air velocity from 4.1 to 11.6 m/s, the air temperature drop reduced from 8.6 to 4.18 °C, and COP also decreased from 6.4 to 3.6. In an experimental study, Bisioniya et al. (2014) considered three different velocities (2, 3.5, and 5 m/s) for an EATHE pipe of 0.1 m diameter and 19.2 m length. The observed maximum and minimum drops in air temperature were 12.9 and 11.3 °C, at air flow velocities of 2 and 5 m/s, respectively.

Yusof et al. (2018) simulated different input parameters (inlet air temperature varied between 31 and 35 °C, ground temperature from 23 to 25 °C, and air flow rate between 0.03 and 0.07 kg/s) of an EAHE system under laboratory conditions. The highest temperature drop (9.62 °C) was obtained at the air flow rate of 0.03 kg/s and ground temperature of 23 °C, while the maximum heat transfer rate (558.3 W) was achieved at air flow rate of 0.07 kg/s and ground temperature of 23 °C.

Air temperature at the inlet of EATHE pipe plays a significant role, because the rate of heat transfer between air and soil is governed by the temperature difference between air and ground. Kumar et al. (2006) studied the impact of ambient air temperature on outlet air temperature. It was noticed that, with the increase in inlet air temperature, the outlet temperature of air also increases, but the amplitude decreases significantly. When the inlet temperature varied from 27 to 45.9 °C, outlet air temperature varied from 23.8 to 27.9 °C for an 80 m-long earth air tunnel. Elminshawy et al. (2017) used a small laboratory scale EAPHE experimental set-up under controlled conditions of operating parameters such as soil bulk temperature, air flow rate, and induced air temperature at three different compaction levels. It was noticed that, for a particular compaction level (at highest density), the cooling capacity of EAPHE system increases by 227% when the induced air inlet temperature is increased from 40 to 55 °C. Niu et al. (2015) established a 1-D steady-state control volume model and observed the impact of inlet air temperature on the performance of EAHE. It was found that, when the inlet air temperature was high, the decline rate of air temperature in EAHE pipe was higher. For the inlet air temperatures of 34, 32, 30, 28, and 26 °C, the highest and lowest decline rate of air temperature was found for 34 and 26 °C, respectively.

Vidhi et al. (2014a, b) presented an application of EAHE system for condenser cooling of a supercritical Rankine cycle (SRC) power generation. A 2-D model was developed in MATLAB to analyze the effect of various parameters on cooling of air in the EAHE and the efficiency of thermodynamic cycle. For the parametric study, pipe length, diameter, and installation depth were kept as 25–75 m, 25–50 cm, and 1–4 m, respectively. It was noticed that, by increasing the depth and length of pipe, the efficiency of the SRC increases; however, after a certain limit, the rate of improvement in SRC efficiency is very small.

Constructural Design has been widely used to seek for the optimal geometries, i.e., which leads to the best performances. Rodrigues et al. (2015) performed a numerical

investigation on different geometrical configurations of an EAHE based on Constructal Design for achieving the highest thermal potential. The results revealed that the thermal performance was improved up to 115 and 73% for heating and cooling, respectively, by increasing the number of buried pipes for the same occupied area and fixed mass flow rate of air.

A detailed literature survey indicates that the performance of EATHE system depends on various parameters such as inlet air temperature and humidity ratio, soil temperature, pipe diameter and length, burial pipe depth, soil thermal conductivity, air flow velocity, etc. These parameters have been optimised using different techniques by various researchers, but limited research outcomes have been reported in which the key parameters affecting the performance of EATHE were simultaneously optimised and the contribution of each parameter has been discussed. Therefore, in the present study, four performance-affecting parameters, i.e., pipe diameter, pipe length, air velocity, and inlet air temperature, have been considered to determine the contribution of each parameter and the best combination of these parameters for achieving maximum temperature drop and heat transfer rate for space cooling application. CFD simulations are performed for all 16 cases which are obtained by the Taguchi method for the considered parameters at different levels as CFD analysis proved as an efficient method of calculation with reduced operating time.

Simulation model description

A three-dimensional simulation model of the EATHE system has been prepared in ANSYS FLUENT package (15.0) for analysis. This CFD software package uses finite-volume method to change the complex governing equations into the numerically solvable algebraic equations. The control volume of EATHE system was defined by creating a cylindrical volume of soil around the pipe, as shown in Fig. 2a. The developed physical model of EATHE system was discretised using 3D hybrid (hexahedral and tetrahedral) meshing (Fig. 2b) with minimum and maximum element size of 0.0015 and 2.99 m, respectively, with a growth rate of 1.2 in ANSYS Workbench Meshing.

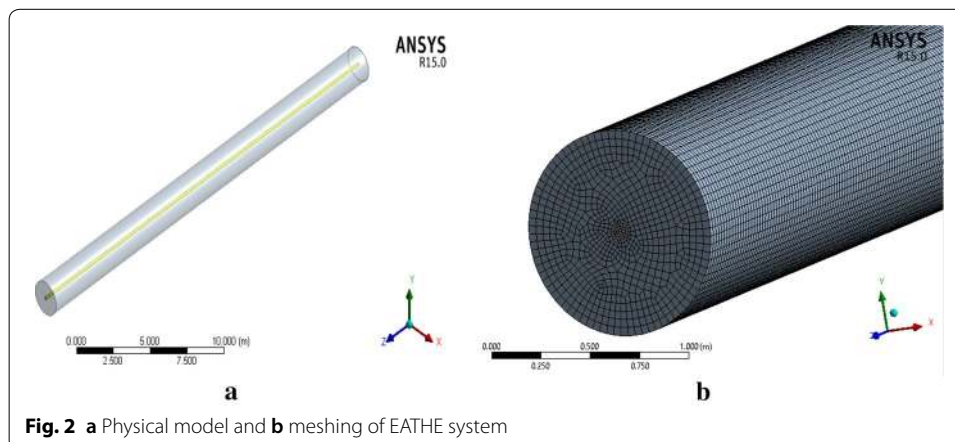


Fig. 2 a Physical model and b meshing of EATHE system

Governing equations

The following set of governing equations is used to perform simulation in FLUENT software to describe the heat and mass transfer and flow of fluid within any systems (ANSYS Inc. 2013).

- Law of mass conservation: The equation for mass conservation law or continuity equation is written as

$$u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial w}{\partial z} = 0 \quad (1)$$

- Law of energy conservation: the first law of thermodynamics or law of energy conservation stated as neither the energy can be created nor destroyed, it only changes its form in nature. The equation can be written as follows:

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \alpha \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] \quad (2)$$

- Law of momentum conservation (Navier–Stokes equation, also known as Newton's second law): the equation for momentum conservation is as follows:

X-momentum equation:

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right] \quad (3a)$$

Y-momentum equation:

$$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right] \quad (3b)$$

Z-momentum equation:

$$u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right] \quad (3c)$$

In the above Eqs. (1–3), u , v , and w are the velocity components in x -, y -, and z -directions, and T and p are the temperature and pressure of the flowing air, respectively.

Material properties

Different thermo-physical properties of air, soil, and PVC pipe used in CFD simulation are presented in Table 1.

Boundary conditions

The following conditions are taken at different sections during the simulation in CFD software.

Table 1 Material properties used in simulation

| Material | Density (kg/m ³) | Specific heat (J/kg-K) | Thermal conductivity (W/m-K) |
|----------|------------------------------|------------------------|------------------------------|
| Air | 1.22 | 1006 | 0.02 |
| Soil | 2050 | 1840 | 0.52 |
| PVC pipe | 1380 | 900 | 0.16 |

- At pipe inlet: uniform velocity is provided as input in the normal direction to the pipe; heat flux is taken as zero.
- At soil-pipe interface: no-slip condition is considered at pipe wall and soil interface.
- At pipe outlet: pressure outlet; heat flux is zero.

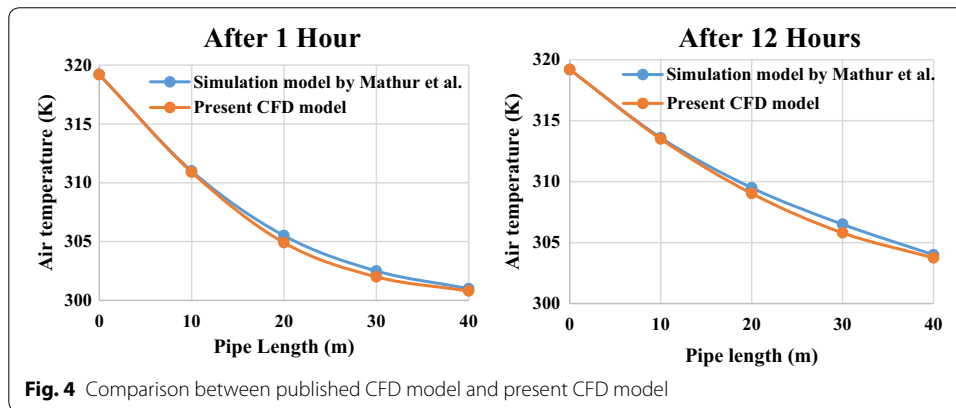
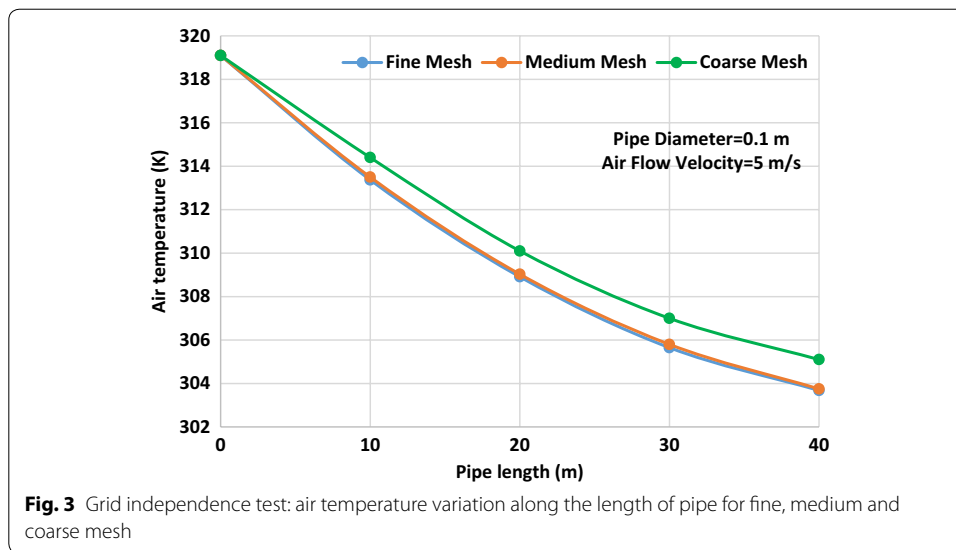
Turbulence model description

In the simulation, the pressure-based Navier–Stokes algorithm has been adopted and SIMPLE scheme was selected for solving pressure–velocity coupling. The pressure gradients are solved by second order and LSCB (least square cell-based), respectively. Second-order upwind for the kinetic energy of turbulence and second-order upwind for turbulent momentum were taken. The step size of 60 s is used for calculation. During simulation, the far-field boundaries were treated as an adiabatic wall, and EATHE pipe wall and surrounding soil temperatures were initialised at 27 °C as the average sub-soil temperature (at 3–4 m depth) remains 27 °C throughout the year in Ajmer, India. Air is treated as an incompressible ideal gas and the viscous k -epsilon (k - ϵ) realizable turbulence model with standard wall function is applied. The constants in the viscous model are as follows: $C_{1\epsilon} = 1.44$; $C_2 = 1.9$; $\sigma_k = 1.0$; $\sigma_\epsilon = 1.2$, and Pr_{wall} and Pr_{energy} are 0.85. The viscosity of air was kept constant as 1.78×10^{-5} kg/m-sec.

Grid independence test

Grid independence tests were conducted in FLUENT 15.0 to assess the quality of the developed CFD model. In the present analysis, CFD simulations have been performed using 3D hybrid (hexahedral and tetrahedral) meshing. A grid-independency test was carried out to check the effect of mesh size on the accuracy of the solution. Mesh size varies from 0.0015 and 2.99 m from pipe surface to soil outer layer. The independent grid size was determined by successive refinements, increasing the number of elements from 681,320 (Coarse mesh) to 948,231 (Fine mesh). A medium size mesh having 820,830 elements was also checked for suitability.

Figure 3 shows the simulated air temperatures along the length of EATHE pipe for coarse, medium, and fine mesh. Simulated air temperatures for medium and fine meshes have very close approximation with each other, and a maximum difference of 0.15 °C was observed between the temperatures for two. Hence, medium mesh used in the simulation meets the simulation requirement to produce mesh-independence results, and therefore, to save computation effort and time, medium mesh has been chosen for further parametric study.



Validation of simulation model

The developed CFD model has been validated against numerical results obtained by Mathur et al. (2015). It is observed from the Fig. 4 that the maximum deviation in the temperature profile achieved by present simulation model and numerical model of Mathur et al. (2015) is 0.7 °C along the pipe length. There is a good agreement between the previously published and present simulation model, and hence, the proposed CFD model is suitable for further analysis.

Methodology

Taguchi technique

The Taguchi method is a statistical technique of laying out the conditions of experiments involving multiple factors to optimise the parameters and improve the performance of the system. The method is popularly known as the factorial design of experiments. A full factorial design will identify all possible combinations for a given set of factors and results in a large number of experiments. To reduce the number of experiments, Taguchi proposed an orthogonal array-based method to study the entire parameter space (matrix

of experiments) with a smaller number of experiments. With the help of this matrix, one can get maximum information from a minimum number of trials and also the best level of each parameter can be obtained for an objective function. For the analysis of data, signal-to-noise (*S/N*) ratios are used to calculate the response of the experimental trials. There are three types of analysis of the response results: lower is better, nominal is better, higher is better, and these can be expressed by the following equations (Inc 2015, 2016).

The lower is better characteristics are expressed by the following equation:

$$SNR = -10 \log_{10} \left(\frac{1}{n} \sum h^2 \right) \tag{4}$$

The nominal is better characteristics are expressed by the following equations:

$$SNR = -10 \log_{10} (s^2) \tag{5}$$

or

$$SNR = 10 \log_{10} \left(\frac{\bar{Y}^2}{s^2} \right) \tag{6}$$

The higher is better characteristics which are expressed by the following equation:

$$SNR = -10 \log_{10} \left(\frac{1}{n} \sum \frac{1}{h^2} \right) \tag{7}$$

In the above equations, *n* = number of cases/test runs; *h*² = experimental results/data; where *Y* = mean of responses for a combination of selected factor level; *s* = standard deviation of the responses for given factor-level combination.

Taguchi design of experiments

For performing the Taguchi optimisation, four parameters at four levels have been considered, as shown in Table 2. The minimum number of experimental trials to be conducted can be preset using the following relation:

$$N_{\text{Taguchi}} = 1 + nv (L - 1) \tag{8}$$

where *N*_{Taguchi} is the minimum number of experiments or cases required to be conducted, *nv* is the number of variables or control parameters, and *L* is the number of levels selected. For the present study, *nv* = 4 and *L* = 4. Therefore, a minimum of thirteen computational trials have to be conducted, and the nearest orthogonal array is L16, and

Table 2 EATHE factors considered at different levels in Taguchi method

| Factor | Parameter | Level | | | |
|--------|---------------------------|--------|--------|--------|--------|
| | | L1 | L2 | L3 | L4 |
| A | Diameter of pipe (m) | 0.10 | 0.15 | 0.20 | 0.25 |
| B | Length of pipe (m) | 30 | 40 | 50 | 60 |
| C | Inlet air velocity (m/s) | 2 | 3 | 4 | 5 |
| D | Inlet air temperature (K) | 307.35 | 311.35 | 315.35 | 319.35 |

Table 3 Taguchi L16 orthogonal array

| Experiment no. | Factor A | Factor B | Factor C | Factor D |
|----------------|----------|----------|----------|----------|
| 1 | 0.10 | 30 | 2 | 307.35 |
| 2 | 0.10 | 40 | 3 | 311.35 |
| 3 | 0.10 | 50 | 4 | 315.35 |
| 4 | 0.10 | 60 | 5 | 319.35 |
| 5 | 0.15 | 30 | 3 | 315.35 |
| 6 | 0.15 | 40 | 2 | 319.35 |
| 7 | 0.15 | 50 | 5 | 307.35 |
| 8 | 0.15 | 60 | 4 | 311.35 |
| 9 | 0.20 | 30 | 4 | 319.35 |
| 10 | 0.20 | 40 | 5 | 315.35 |
| 11 | 0.20 | 50 | 2 | 311.35 |
| 12 | 0.20 | 60 | 3 | 307.35 |
| 13 | 0.25 | 30 | 5 | 311.35 |
| 14 | 0.25 | 40 | 4 | 307.35 |
| 15 | 0.25 | 50 | 3 | 319.35 |
| 16 | 0.25 | 60 | 2 | 315.35 |

hence, L16 is selected for the experimental trials (however, based on the factorial design, $4^4 = 256$ cases are required to be conducted). Each computational trial is carried out according to L16 array combinations, as shown in Table 3 in FLUENT. Higher is better concept has been applied for calculation of S/N ratios (SNR), because maximum air temperature drop and heat transfer rate are the objective of present study.

Results and discussion

The primary aim of this study is to find out the best combination of considered parameters to maximize the air temperature drop and heat transfer rate for achieving the maximum cooling effect from EATHE.

Taguchi method—analysis of S/N ratio

Table 4 shows the standard experimental design of L16 orthogonal array with computed temperature drop in air temperature and total heat transfer rate in EATHE system for cooling as per experimental trials. The S/N ratio values of the temperature difference and heat transfer rate are calculated using higher is better concept. The average responses for S/N ratios for each level of four parameters for temperature difference and heat transfer rate are presented in Tables 5 and 6.

To solve the orthogonal array (Table 3), the steps are given in the following :

- Calculate the higher is better response characteristic for every factor-level combination.
- For every factor, the average response characteristic at each level is calculated using Minitab software.
- For every factor, calculate the delta value.
- Finally, calculate the rank of the factor.

Table 4 Taguchi L16 experimental plan with corresponding temperature drop in air and *S/N* ratios

| Experimental no. | Factor A | Factor B | Factor C | Factor D | Outlet air temperature (K) | Temperature drop (response) | SNR | Heat transfer rate (Watt) (response) | SNR |
|------------------|----------|----------|----------|----------|----------------------------|-----------------------------|-------|--------------------------------------|-------|
| 1 | 0.10 | 30 | 2 | 307.35 | 300.53 | 6.82 | 16.67 | 129.13 | 42.22 |
| 2 | 0.10 | 40 | 3 | 311.35 | 300.70 | 10.65 | 20.54 | 302.47 | 49.61 |
| 3 | 0.10 | 50 | 4 | 315.35 | 301.08 | 14.27 | 23.08 | 540.38 | 54.65 |
| 4 | 0.10 | 60 | 5 | 319.35 | 301.15 | 18.20 | 25.20 | 861.51 | 58.70 |
| 5 | 0.15 | 30 | 3 | 315.35 | 304.84 | 10.51 | 20.43 | 671.62 | 56.54 |
| 6 | 0.15 | 40 | 2 | 319.35 | 302.90 | 16.45 | 24.32 | 700.80 | 56.91 |
| 7 | 0.15 | 50 | 5 | 307.35 | 301.91 | 5.43 | 14.69 | 579.39 | 55.25 |
| 8 | 0.15 | 60 | 4 | 311.35 | 301.58 | 9.77 | 19.79 | 832.44 | 58.40 |
| 9 | 0.20 | 30 | 4 | 319.35 | 310.72 | 8.62 | 18.71 | 1307.22 | 62.32 |
| 10 | 0.20 | 40 | 5 | 315.35 | 307.43 | 7.92 | 17.97 | 1505.27 | 63.55 |
| 11 | 0.20 | 50 | 2 | 311.35 | 301.98 | 9.37 | 19.43 | 715.71 | 57.09 |
| 12 | 0.20 | 60 | 3 | 307.35 | 301.52 | 5.83 | 15.31 | 664.59 | 56.45 |
| 13 | 0.25 | 30 | 5 | 311.35 | 307.60 | 3.75 | 11.48 | 1109.43 | 60.90 |
| 14 | 0.25 | 40 | 4 | 307.35 | 303.98 | 3.37 | 10.55 | 797.60 | 58.03 |
| 15 | 0.25 | 50 | 3 | 319.35 | 306.94 | 12.44 | 21.89 | 2202.88 | 66.86 |
| 16 | 0.25 | 60 | 2 | 315.35 | 302.87 | 12.48 | 21.92 | 1476.87 | 63.38 |

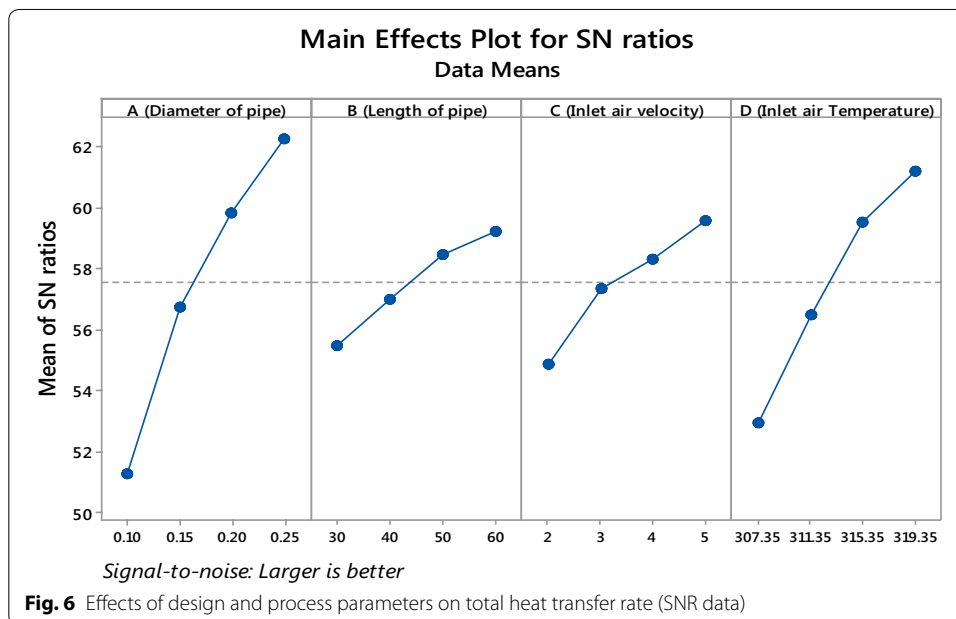
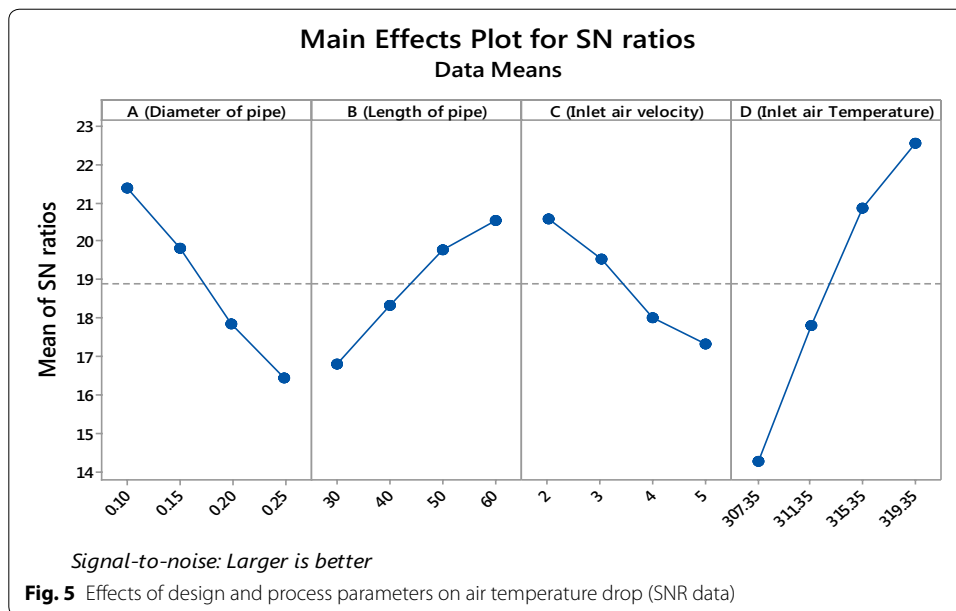
Table 5 Taguchi response table for air temperature drop in EATHE system

| Level | Factor A | Factor B | Factor C | Factor D |
|-------|----------|----------|----------|----------|
| 1 | 21.38 | 16.82 | 20.59 | 14.31 |
| 2 | 19.81 | 18.35 | 19.55 | 17.82 |
| 3 | 17.86 | 19.78 | 18.04 | 20.85 |
| 4 | 16.46 | 20.56 | 17.34 | 22.53 |
| Delta | 4.91 | 3.73 | 3.25 | 8.22 |
| Rank | 2 | 3 | 4 | 1 |

Table 6 Taguchi response table for heat transfer rate in EATHE system

| Level | Factor A | Factor B | Factor C | Factor D |
|-------|----------|----------|----------|----------|
| 1 | 51.30 | 55.50 | 54.90 | 52.99 |
| 2 | 56.78 | 57.03 | 57.37 | 56.50 |
| 3 | 59.86 | 58.47 | 58.36 | 59.53 |
| 4 | 62.30 | 59.24 | 59.60 | 61.20 |
| Delta | 11.00 | 3.74 | 4.70 | 8.21 |
| Rank | 1 | 4 | 3 | 2 |

Figures 5, 6 show the average *S/N* ratio values plots for all four levels of four parameters for the EATHE temperature drop and heat transfer rate, respectively. From Tables 5 and 6, the optimum set of parameters for obtaining maximum air temperature drop and heat transfer rate can be determined by selecting the highest value of *S/N* ratio for each factor. Hence, the optimum control parameter level is A_1 (factor A at level 1), B_4 (factor B at level 4), C_1 (factor C at level 1), and D_4 (factor D at level 4), for maximum air



temperature drop. However, optimum control parameter level for maximum heat transfer rate is A_4 (factor A at level 4), B_4 (factor B at level 4), C_4 (factor C at level 4), and D_4 (factor D at level 4).

ANOVA analysis

Analysis of variance (ANOVA) is used to estimate the relative importance of the control parameters by computing the percentage contribution of each parameter in overall response. The sum of squares (SS) and percentage of contribution are included in the ANOVA table (Tables 7 and 8). The parameter with the highest percentage of

Table 7 Contribution of each parameter for maximum air temperature drop in EATHE

| Parameter | Factor | $\overline{\text{SNR}}$ | SS_i | SS | Contribution, % |
|-----------------------|--------|-------------------------|--------|------|-----------------|
| Diameter of pipe | A | 18.87 | 14.01 | 7.83 | 20.66 |
| Length of pipe | B | | 8.15 | | 12.03 |
| Inlet air velocity | C | | 6.45 | | 9.51 |
| Inlet air temperature | D | | 39.21 | | 57.80 |

Table 8 Contribution of each parameter for maximum heat transfer rate in EATHE

| Parameter | Factor | $\overline{\text{SNR}}$ | SS_i | SS | Contribution, % |
|-----------------------|--------|-------------------------|--------|--------|-----------------|
| Diameter of pipe | A | 57.55 | 67.55 | 126.78 | 53.28 |
| Length of pipe | B | | 8.17 | | 6.45 |
| Inlet air velocity | C | | 11.91 | | 9.40 |
| Inlet air temperature | D | | 39.13 | | 30.87 |

contribution is ranked highest in terms of relative importance among all the control parameters and also has a major contribution to the overall response.

Percentage contribution of each parameter

ANOVA provides the contribution of the individual parameter. The following steps are being used for calculating the percentage contribution of each parameter on different SNR responses.

Step I Calculation for mean of signal-to-noise response $\overline{\text{SNR}}$ for all the 16 cases, i.e.,

$$\overline{\text{SNR}} = \frac{1}{16} \sum_{i=1}^{16} (\text{SNR})_i \tag{9}$$

Step II Calculating the sum of squares (SS_i) for each parameters based on their SNR response, i.e.,

$$SS_i = \sum_{i=1}^{16} ((\text{SNR})_i - \overline{\text{SNR}})^2 \tag{10}$$

Step III Calculating the sum of squares (SS) for each parameter, i.e.,

$$SS = \sum_{j=1}^4 ((\text{SNR})_i - \overline{\text{SNR}})^2 \tag{11}$$

Step IV At last, the contribution of each parameter in percentage is determined by the following equation:

$$\text{Contribution, \%} = \frac{\text{Sum of squares (SS) of each parameter}}{\sum_{i=1}^n \text{SS}_i} \times 100 \quad (12)$$

Here, i = for individual values of the sum of squares; n = num of experimental cases in the array.

Table 7 shows that the inlet air temperature has got the maximum influence on air temperature drop obtainable having a percentage contribution of 57.80%. The contribution of other parameters such as diameter of pipe, length of pipe, and inlet air velocity is found to be 20.66, 12.03, and 9.51%, respectively. The air temperature drop produced by EATHE system highly depends on inlet air temperature, because when the difference between inlet air temperature and soil temperature increases, more drop in temperature of air flowing through the buried pipes is achieved.

Table 8 shows the percentage contribution of each parameter for heat transfer rate in an EATHE system. It is seen that the diameter of pipe has a maximum contribution, i.e., 53.28% of the total. The contribution inlet air temperature, inlet air velocity, and length of pipe are found to be 30.87, 9.40, and 6.45%, respectively. The contribution of pipe diameter is found to be highest on heat transfer rate, because the heat transfer rate is directly proportional to the mass flow rate of air which is proportional to the square of the pipe diameter.

In the present study, the percentage contribution of the pipe length is least for heat transfer rate. It is noticed from the present study that the maximum heat transfer occurs in the initial 30 m length of pipe in EATHE system. Therefore, pipe length in the range of 30–60 m does not produce a significant effect on heat transfer rate in EATHE system. Similarly, the contribution of air flow velocity is least for air temperature drop in EATHE, because maximum air temperature drop is achieved at an air velocity of 2 m/s and by increasing air velocity from 2 to 5 m/s; the drop in air temperature is not significantly affected.

Confirmation test—Taguchi method

The optimum combination of parameters is investigated using CFD and compared with the 16 cases of Taguchi method for maximum temperature difference and heat transfer rate. It is found that the optimum case for achieving maximum temperature difference, i.e., $A_1B_4C_1D_4$ gave temperature difference of 19.05 and the optimum case for having maximum heat transfer rate, i.e., $A_4B_4C_4D_4$ provide heat transfer rate of 3085 W which are higher than all the previous experimental trials taken in Taguchi method.

Conclusions

In this study, a methodology is proposed to maximize the air temperature drop and heat transfer rate in EATHE system for cooling applications using the Taguchi method. For this purpose, four operating parameters at four levels of operation of the EATHE system were considered. A total of 16 trials were run using a validated simulation model in the ANSYS FLUENT software. ANOVA is employed to optimise the operating parameters. The major findings and observations of the study are the following:

- Taguchi optimisation analysis inferred that, for the EATHE system, inlet air temperature is the most influencing (57.80%) control parameter in cooling mode for achieving maximum air temperature drops and the diameter of pipe has a maximum contribution (53.28%) in maximizing the heat transfer rate in EATHE system.
- The least influencing parameter for a temperature drop of air is air velocity while that for the heat transfer rate is pipe length.
- The air temperature drop and heat transfer rate characteristics are very much influenced by the geometric and flow parameters (control factors), viz., diameter of the pipe, length of pipe, air flow velocity, and inlet air temperature. The contribution ratio of each of these parameters on air temperature drop is 20.66, 12.03, 9.51, and 57.80% respectively, and that of heat transfer rate is 53.28, 6.45, 9.40, and 30.87% respectively.
- The optimum combination of parameters for achieving a maximum drop in air temperature is $A_1B_4C_1D_4$ and that for obtaining maximum total heat transfer rate is $A_4B_4C_4D_4$.

Highlights

- Performance of earth-air-tunnel heat exchanger (EATHE) system has been investigated using CFD simulation.
- Effect of geometric and flow parameters on the performance of EATHE has been analysed.
- Taguchi method is applied for maximization of air temperature drop and heat transfer rate in EATHE system.
- Analysis of variance (ANOVA) and signal to noise (S/N) ratio is used for evaluation of simulation results.
- Contribution ratio of each control factor has been evaluated.

Abbreviations

C_p : specific heat of air (J/kg K); \dot{m} : mass flow rate of air (kg/s); Q : heat transfer rate (W); T_i : inlet air temperature (K); T_o : outlet air temperature (K); ΔT : temperature difference ($T_i - T_o$); ANN: artificial neural network; ANOVA: analysis of variance; CFD: computational fluid dynamics; EAPHE: earth air-pipe heat exchanger; EATHE: earth air tunnel heat exchanger; HEAHE: hybrid earth to air heat exchanger; GA: genetic algorithm; PVC: poly-vinyl chloride; RSM: response surface methodology; SNR: signal-to-noise (S/N) ratios.

Authors' contributions

All authors contributed equally towards preparing this manuscript. All authors read and approved the final manuscript.

Author details

¹ Mechanical Engineering Department, Malaviya National Institute of Technology, Jaipur 302017, India. ² Department of Renewable Energy, Rajasthan Technical University, Kota 304010, India. ³ Mechanical Engineering Department, Government Engineering College, Ajmer, Ajmer 305001, India.

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