Experimental and numerical study on the cooling performance of a new earth-air heat exchanger (EAHE) system with a supply air static pressure chamber

Qizhi Yang¹, Zhiru Hu¹, Zhuo Zhou¹, Yuxin Zhang¹, Bin Wang¹, and Yong Wang¹*

¹College of Civil Engineering, Chongqing University, Chongqing 400045, China

Abstract. Earth-air heat exchanger (EAHE) is a low-carbon device that uses renewable energy to improve the thermal environment of buildings by heating/cooling the air with the help of the thermal inertia of the soil. However, the traditional earth-air heat exchanger has the problem of large fluctuations in air temperature with the outdoor air temperature fluctuations. A system that combines an air supply chamber with an EAHE is proposed to address this problem. The outdoor air first enters the underground air supply static pressure chamber for initial cooling, and then enters the EAHE treatment. To investigate the effect of this air supply static pressure chamber on the cooling performance of EAHE, a three-dimensional numerical model was developed in ANSYS Fluent and validated with field measurement data. Then comparative studies of the EAHE system with a supply air static pressure chamber and the traditional EAHE system were conducted under summer conditions in Chongqing (China). The results show that the air supply static pressure chamber can reduce the EAHE outlet air temperature fluctuation by 31.98% at the maximum under the continuous operation of different air volume systems for 7 days. At the same time, the cooling capacity can be increased by 19.89% at maximum compared with the conventional EAHE cooling capacity.

1 Introduction

In response to global climate change, China has proposed carbon peaking and carbon neutrality goals. An important way to achieve this goal is to increase the utilization of renewable energy in buildings. Among the various types of renewable energy, geothermal energy is widely used as a heat source for heating/cooling of buildings because it is widely distributed, easy to obtain, and the temperature fluctuation at a certain depth is approximately zero throughout the year[1,2]. Earth-air heat exchanger (EAHE) is one of the main forms of using geothermal energy in buildings[3,4]. An EAHE consists of one or several ducts buried underground. It is connected to the outdoor air at one end and to the ventilation...
system of the building at the other end. With the help of the soil temperature stability, the EAHE can be used for heating and cooling in winter and summer.

Although EAHE has been reported to have great potential for energy saving and application[5,6], there are still some important issues that need to be solved in practical applications. Because most of the existing EAHE pipes are buried at a depth of 2-4m[7], the soil temperature at this depth is easily affected by weather and other factors, resulting in large temperature variations. Therefore, the EAHE outlet temperature will increase and fluctuate more in summer due to the increase of soil temperature and the fluctuation of outdoor temperature[8]. This reduces the potential for direct use of the EAHE and often requires the coupling of other supplementary cooling/heating systems to meet indoor environmental control requirements.

To address the above issues, this study proposes a new EAHE system(SASPC-EAHE), which is characterized by two parts: an air supply static pressure chamber buried underground and connected EAHE pipes. Before the outdoor air enters the heat exchanger pipe, it is initially cooled down by a supply air static pressure chamber in order to reduce the temperature and fluctuation of the EAHE outlet air. To evaluate the cooling performance of this new system, an experimental setup was built and tested in Chongqing, China. In addition, a three-dimensional numerical model was built using ANSYS Fluent, and a comparative study between SASPC-EAHE and traditional EAHE was carried out by numerical simulation under summer conditions in Chongqing.

2 Experimental set-up and numerical model

2.1 Experimental set-up

The experimental setup is designed and illustrated in Fig.1(a). The part in the dashed box is the focus of this paper's research and shown in Fig.1(b). The air supply static pressure chamber consists of two parts, above and below ground. The above-ground part has an outdoor air inlet with dimensions of 2.8m(length)×0.8m(height). The dimensions of the part below the ground are 2.8m(length)×2m(width)×2m(width). The earth-air heat exchanger is a 3 m long PVC pipe with a nominal diameter of 200. The bottom of this PVC pipe is buried at a depth of 2m and connected to the air supply static pressure chamber. In summer, the hot outdoor air first enters the air supply static pressure type for preliminary cooling, and then later enters the earth-air heat exchanger for further cooling.
having range of 0-20m/s with an accuracy of ±0.03m/s +5% reading.

2.2 Numerical model

In this study, the air supply static pressure chamber and EAHE were divided into two parts to model, and commercial computational fluid dynamics software (CFD), ANSYS Fluent, was used to simulate transient air flow and heat transfer phenomena. For air, the two computational domains of the air supply static pressure chamber and EAHE use the realizable k-e turbulence model and the standard k-e turbulence model, respectively. In the calculation process, the simulation results of the supply air static pressure chamber are first obtained and then imported into the EAHE simulation by user-defined function (UDF) as the inlet condition.

2.2.1 Governing equations

The basic governing equation in CFD can be represented by a general equation[9]:

\[
\frac{\partial (\rho \Phi)}{\partial t} + \frac{\partial (\rho \Phi u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma_\Phi \frac{\partial \Phi}{\partial x_j} \right) + S_\Phi \tag{1}
\]

Where \( \rho \) is density; \( u_j \) is the velocity component in \( j \) direction; \( \Phi \) represents the common variables of interest, i.e., three velocity components, temperature, species, turbulent kinetic energy, and its dissipation rate; \( \Gamma_\Phi \) is the transport coefficient dependent on \( \Phi \); and \( S_\Phi \) is the source term dependent on \( \Phi \).

2.2.2 Boundary conditions and initial condition

For the air supply static pressure chamber calculation model:

The airflow inlet and outlet are adopted as the pressure outlet and velocity inlet boundary conditions respectively; the air inlet temperature is introduced on an hourly rate using the UDF; because the roof material is insulation material, it is set as adiabatic boundary; for the rest of the enclosure above the ground, the first type of boundary conditions is used.

For the EAHE calculation model:

Velocity inlet and pressure outlet boundary conditions are used for the air inlet and outlet, respectively; the inlet temperature is likewise introduced by hour using the UDF.

The bottom soil boundary of both models is a constant temperature boundary. At ground surface, neglecting the evaporation/condensation heat transfer process, its heat transfer process under the combined influence of solar radiation, air convection and ground conditions can be expressed by the following equation[1]:

\[
-\lambda_s \left( \frac{\partial T}{\partial y} \right)_{y=0} = h_{gs} (T_{\text{sol-air}} - T_{gs}) \tag{2}
\]

Where

\[
T_{\text{sol-air}} = T_a + \frac{a_o I}{h_{gs}} - \frac{\varepsilon_s \Delta R}{h_{gs}} \tag{3}
\]

In the above equations, \( \lambda_s \) is the thermal conductivity of the soil; \( h_{gs} \) is the convective heat transfer coefficient of the ground, taking the value of 1 \((W/m^2\cdot K)\); \( y \) is the soil depth; \( T_{\text{sol-air}} \) is the integrated outdoor air temperature; \( T_{gs} \) and \( T_a \) are the ground temperature and air temperature respectively; \( a_o \) is the absorption rate of solar radiation by the ground surface, \( I \) is the total solar radiation incident to the surface; \( \varepsilon_s \) is the long-wave emissivity of the ground; \( \Delta R \) is a term that depends on the relative humidity of the air above the ground and surface, the effective sky temperature and the radiation properties of the soil. \( \Delta R = 63 W/m^2 \) can be taken as a good first approximation[10].

The rest of the soil boundary conditions are set to 0 heat flux. The physical and thermal properties of the soil and pipe are listed in Table. 1.

https://doi.org/10.1051/e3sconf/202235601019

E3S Web of Conferences 356, 01019 (2022)
Table 1. Physical and thermal parameters of soil and PVC pipe.

| Item                                | Value  |
|-------------------------------------|--------|
| Soil thermal conductivity (W m⁻¹ K⁻¹) | 1.1    |
| Soil thermal capacity (J kg⁻¹ K⁻¹)   | 860    |
| Soil density (kg m⁻³)                | 1800   |
| Pipe thermal conductivity (W m⁻¹ K⁻¹) | 0.15   |
| Pipe thermal capacity (J kg⁻¹ K⁻¹)   | 1250   |
| Pipe density (kg m⁻³)                | 1350   |

Initial conditions:

The initial conditions of soil temperature are related to the depth $y$:

$$T(y,0) = \bar{T}_{gs} + A_{gs}e^{\left(-\frac{\pi}{\sqrt{\alpha_{gs}T}}\right)} \times \cos\left(\omega_{y}t - \frac{\pi}{\sqrt{\alpha_{s}T}} - \varphi_{y0}\right) \quad (4)$$

where $y$ is the depth of the subsoil; $\bar{T}_{gs}$ is the annual average temperature of the ground surface; $A_{gs}$ is the annual amplitude of the surface temperature variation; $\alpha_{s}$ is the thermal diffusion coefficient of the soil; $T_y$ is the annual period of the surface temperature wave; $\omega_{y} = 2\pi/T_y$ is the annual fluctuating frequency; $y$ is the annual period; and $\varphi_{y0}$ is the annual phase constant of the ground surface.

2.3 Mesh independence test

The two physical models were meshed using structured meshing in ICEM_CFD software. Three different grid sizes and three time steps were studied for each physical model to ensure computational accuracy and reduce computational time. The simulation results show that 2.44 million grid size corresponding to 10s time step is chosen for the air supply static pressure chamber model, and 1.15 million grid size and 30s time step is chosen as the optimal solution for the EAHE model.

2.4 Model validation

The numerical model proposed in this study and the computational model used were validated by the results of field experiments. A 24-hour system operation at an airflow rate of 380 m³/h was conducted from May 30 to May 31, 2020. The simulated data of the experimentally monitored temperature and EAHE outlet temperature during the system operation are shown in Fig. 2. It can be seen that the simulation results were in good agreement with the experimental measurements for the vast majority of the time. However, there is a relatively large error within the first hour of the start of system operation, with a maximum relative error of 6.81%. The relative errors observed after one hour of system operation are less than 5%. Therefore, the results indicate that the developed numerical model and computational model are applicable to the further research of SASPC-EAHE system.

![Fig. 2. Comparison of the EAHE outlet air temperatures for the experiment data and the simulation data.](image)

3 Results and discussion

3.1 Experimental result

A continuous 24h field test was conducted on the supply air static pressure chamber at an air flow rate of 380m³/h from 13:00 on May 30 to 13:00 on May 31, 2020. The air temperature of the air inlet and outlet of the air supply static pressure chamber was monitored separately, where the air
outlet of the air supply static pressure chamber is the EAH air inlet, and the test results are shown in Fig. 3. It can be found that the maximum cooling of the air supply static pressure room is about 7.3°C when the outdoor temperature is higher, which can indicate that the air supply static pressure room has a strong precooling ability for the outdoor air before entering EAH.

### 3.2 Cooling performance of SASPC-EAHE

The SASPC-EAHE system and the traditional EAHE system were simulated by the validated CFD numerical model under the same operating conditions for 7 days of continuous operation, respectively. In addition, the SASPC-EAHE model was simulated for three cases of air supply static pressure chamber connected to one, two and three DN200 PVC pipes. In order simplify the calculation model, the SASPC-EAHE models connected to different numbers of PVC pipes are replaced by a physical model connected to only one PVC pipe. In other words, the connections to different numbers of PVC pipes are represented only by changing the air volume entering the air supply static pressure chamber. The air volumes corresponding to the three cases are 339.29 m³/h (SASPC-EAHE1), 678.58 m³/h (SASPC-EAHE2) and 1017.87 m³/h (SASPC-EAHE3), respectively. The meteorological conditions in all simulations are selected from the typical meteorological year data of Chongqing from August 1 to August 7.

Fig. 3. Temperature variation of air inlet and outlet of the air supply static pressure chamber.

**Fig. 4.** Hourly outlet air temperature of different EAHES.

Fig. 4 shows the EAHE outlet air temperature for the different cases. As seen, the maximum fluctuation of outlet air temperature of traditional EAHE is 4.1°C, while the maximum fluctuation of outlet air temperature of SASPC-EAHE1 is 2.8°C, which indicates that the supply air static pressure chamber reduces the fluctuation of outlet air temperature by 31.98% under this condition. In the cases of SASPC-EAHE2 and SASPC-EAHE3 the outlet air temperature fluctuations were reduced by 18.68% and 8.57%, respectively, compared to that of the traditional EAHE. These results suggest that the initial treatment of the outdoor air using the supply air static pressure chamber is beneficial in improving the EAHE’s outlet air temperature stability and the possibility of continuous operation. And, the more stable air outlet temperature can expand the application place of EAHE. In addition, it can be calculated that the cooling capacity of SASPC-EAHE1, 2 and 3 is improved by 19.89%, 11.88% and 8.57%, respectively, compared to the traditional EAHE. This indicates that the SASPC-EAHE system has a good energy saving potential. However, it should also be noted that its performance will be worse at higher air volumes of treated outdoor air. Therefore, subsequent studies will investigate the maximum handling capacity of the air supply static pressure chamber and the optimal matching with EAHE. However, it should also be noticed that the performance decreases at higher air volumes of treated outdoor air. Therefore, the
maximum handling capacity of the air supply static pressure chamber and the optimal matching with EAHE will be investigated in the subsequent study.

4 Conclusions

In this study, a new EAHE system called SASPC-EAHE is proposed, which works on the principle that the outdoor air enters the buried air supply static pressure chamber for initial cooling and then enters the EAHE for heat exchange. To evaluate the performance of the system, a field test bench was built and CFD numerical simulations were performed for different operating conditions.

The experimental results show that the air supply static pressure chamber in the new EAHE system can significantly reduce the outdoor air temperature during daytime. In addition, the simulation results show that compared to the traditional EAHE system, the SASPC-EAHE can reduce the outlet air temperature fluctuation by a maximum of 31.98% and increase the cooling capacity by a maximum of 19.89% in the simulated conditions. However, it should also be noted that the performance of the supply air static pressure chamber deteriorates at higher air volumes of treated outdoor air. Therefore, subsequent studies will investigate the maximum handling capacity of the supply air static pressure chamber and the optimal matching solution with EAHE.

References

1. A. K. Khatry, M. S. Sodha, and M. A. S. Malik, Sol. Energy 20, 425 (1978)
2. S. S. Bharadwaj and N. K. Bansal, Build. Environ. 16, 183 (1981)
3. D. Yang, Y. Guo, and J. Zhang, Energy Convers. Manag. 109, 184 (2016)
4. T. S. Bisoniya, A. Kumar, and P. Baredar, Renew. Sustain. Energy Rev. 19, 238 (2013)
5. D. Yang and J. Zhang, Build. Environ. 85, 29 (2015)
6. T. Zhou, Y. Xiao, Y. Liu, J. Lin, and H. Huang, Energy Convers. Manag. 177, 210 (2018)
7. S. Zhou, W. Cui, J. Tao, and Q. Peng, Appl. Therm. Eng. 101, 173 (2016)
8. R. Singh, R. L. Sawhney, I. J. Lazarus, and V. V. N. Kishore, Renew. Sustain. Energy Rev. 82, 2162 (2018)
9. S. Patankar, Numerical Heat Transfer and Fluid Flow (Hemisphere Publishing Corp, Washington, D.C., n.d.)
10. V. Badescu, Renew. Energy 32, 845 (2007)