NUMERICAL STUDY ON THE THERMAL PERFORMANCE OF EARTH-TUBE SYSTEM IN NINGBO, CHINA

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ABSTRACT

Earth tube system (ETS), which capitalizes on the high soil thermal inertia, is gaining popularity in recent years as an alternative to conserve energy for space cooling/heating in buildings. This paper presents a numerical study of the thermal performance of the basic ETS in Ningbo, China, through Computational Fluid Dynamic (CFD) modeling and then assesses its corresponding energy saving potential in the local climate. The primary impact parameters, i.e. pipe diameter and inlet air velocity, are discussed in terms of their influences on the ETS thermal performance. It is found that (1) the outlet temperature increased as the inlet velocity was higher as a result of reduced contact time between soil and airflow; (2) the outlet temperature increased when the diameter of the pipe was larger due to more airflow was passed through in a unit time; (3) a balance between outlet temperature required and volumetric airflow rate stipulated by regulations needed to be established provincially; (4) the ETS was estimated being able to provide cooling of 1185kWh in summer period (i.e. 86% of the projected energy demand) in Ningbo and attained a COP of 3.3. The overall research indicated the ETS has the potential to become the effective energy saving technology in Ningbo buildings and thus could contribute to the related carbon emission reduction in China.

INTRODUCTION

Nowadays, China is experiencing the inexorable development of urbanization and industrial growth. During such period, it would account for 19% of total worldwide emissions and nearly 40% of the emissions shall be contributed by the building sector. This percentage would be much higher in hot summer and cold winter (HSCW) regions owing to the weather extremity and insufficiency in energy conservation. So there is a really high demand in finding an alternate way to mitigate the rapidly increasing energy consumption and carbon emissions.

The earth-tube system (ETS), as shown in Fig. 1, is a kind of efficient cooling and heating technology by using underground thermal mass of soil at a sufficient depth since the soil temperature is lower than the outside air temperature in summer but higher in winter. The air drawn through the ETS is therefore cooled in summer and heated in winter. Such system can be used in several different buildings and is applicable to different climates.

A wide range of research studies have been performed with respect to the performance of ETS in order to investigate its potential as an alternative in reducing energy consumption. Kumar et al. (2003) predicted energy conservation potential of ETS by developing a numerical model using finite difference method and software MATLAB where the effects of ground temperature gradient, surface conditions, moisture content and various design aspects of ETS was incorporated.

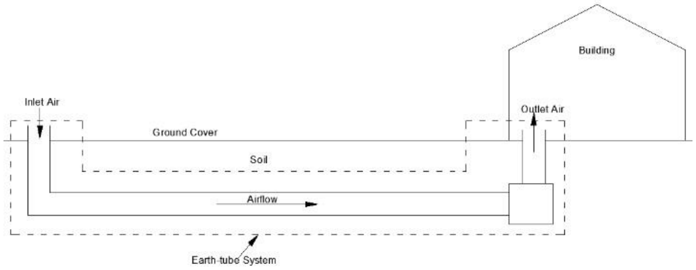

Fig. 1 Schematic arrangement of earth-tube system

Svec et al. (1983) also presented a numerical model for steady-state, transient and cyclic behavior of ETS of several configurations and found a substantial reduction in heat flow when pipe radius was small. Sensitivity analysis based on system parameters such as inlet air temperature, pipe radius, air velocity, pipe length, depth for evaluating the performance of ETS was carried out by Tzaferis et al. (1992) using eight different algorithms and Agas et al. (1991) alike in evaluating the performance of various cooling techniques. Deglin et al. (1999) studied the effects of various parameters on the efficiency of ETS through a three-dimensional transient heat flow model. Based on the representation of temperature in the form of the Fourier integral, Kabashnikov et al. (2002) developed a mathematical model calculating the temperature of soil along ETS. Isvoranu (2011) carried out a time-dependent simulation of ETS operation by proposing an analytical pneumatic a thermal design procedure and observed that the energy delivered by the ETS considerably depended upon the geometrical configuration. Maerefat and Haghighi (2010) undertook a theoretical analysis in an investigation on potential of use of solar chimney together with earth-to-air ventilation system and concluded that they were a perfect combination where the earth-to-air heat pipe was powered by solar chimney exceptionally. Hakan et al. (2009) developed a one-dimensional transient analytical model to estimate the performance of ETS at several depths used for building cooling/heating.

As the performance of ETS is affected by various factors, such as pipe radius, length, burial depth, soil conditions, moisture and ambient temperature, solar radiation, ground cover variations etc., a detailed investigation needs to be conducted when the ETS is applied in different climates and regions. Therefore, it is important to explore the characteristics of ETS in the local soil condition of Ningbo city that locates in HSCW region of China. In this paper, several parameters on the thermal performance of the ETS application in local conditions will be numerically studied through a three-dimensional CFD model. The simulation model will be then validated in regard with its effectiveness, and further used in assessing the energy-saving potential of the ETS application in the local city.

NOMENCLATURE

u	[m/s]	Velocity components in x direction
v	[m/s]	Velocity components in y direction
w	[m/s]	Velocity components in z direction
k	[-]	Turbulence
ρ	[kg/m^3]	Density
p	[pas]	Pressure
D	[m]	Diameter
T	[K]	Temperature
t	[s]	Time
COP	[-]	Coefficient of Performance
T_o	[K]	Temperature at outlet
α	[m^2/s]	Thermal diffusivity
μ_t	[kg/ms^2]	Eddy viscosity
S_ε	[m]	User-defined source term
S_k	[m]	User-defined source term
ε	[-]	Dissipation rate
$\dot{Q}$	[J/s]	Energy flow rate
$\dot{m}$	[m/s]	Mass flow rate
T_i	[K]	Temperature at inlet
Q	[J]	Energy
C_p	[J/kgK]	Specific heat
σ_ε		Turbulent Prandtl numbers for ε
σ_k		Turbulent Prandtl numbers for k
Y_M		Fluctuating dilatation to the overall dissipation rate
G_b		Turbulence kinetic energy generated due to buoyancy
G_k		Turbulence kinetic energy generated due to velocity gradients

PHYSICAL MODEL

The ETS described in this study (see Fig. 2) is simplified that comprises only one horizontal cylindrical pipe with a length of 40m as a compromise between increasing excavation costs and lower outlet temperature. The pipe diameter and inlet velocity will be varied for study. ETS is normally preferred to be buried at a depth of 3m for economic reasons, however, considering the temperature of soil at a depth of 4m is much more stable in Ningbo (informed from local weather data), 4m burial depth was used (to justify the assumptions made for the soil with constant temperature). Because the soil type varies among different regions (e.g. dry soil, clay, wet soil with sand) in Ningbo, its properties were taken as an average from Yang's (2013) research where soil conditions in Ningbo were thoroughly studied (see soil properties listed in Table 1). The general working principle is: airflow enters from the inlet (left side) and is then sent out towards the outlet (right side), exchanging heat with adjacent soil in between for cooling.

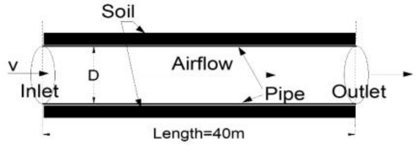

Fig. 2 Physical model of the earth tube

Governing Equations

The governing transport equations in Cartesian coordinates for the fluid flow, heat and mass transfer are provided as follows (ANSYS Theory Guide, 2011):

Continuity equation (for solving mass continuity):

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

x -Momentum equation (for solving x -velocity residual):

$$[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}]=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\vartheta[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}] \tag{2}$$

y -Momentum equation (for solving y -velocity residual):

$$[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}]=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\vartheta[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}] \tag{3}$$

z -Momentum equation (for solving z -velocity residual):

$$[u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}]=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\vartheta[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}] \tag{4}$$

Energy equation (for solving energy residual):

$$[u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}]=\alpha[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}] \tag{5}$$

In the Eqns. (1-5), u , v and w are the velocity components in x , y and z directions, p and T is the pressure and temperature of the flowing air respectively.

The initial conditions are:

$$T(r,x,0)=T_0(r) \tag{6}$$

By assuming the temperature at r=0.1m is equal to that of the soil temperature the initial condition may be expressed as:

$$T(0.1,x,t)=T(0.1) \tag{7}$$

Transport equations for the realizable $k-\varepsilon$ model (ANSYS Theory Guide, 2011) are:

$$\frac{\partial}{\partial t}(\rho \mathrm{k})+\frac{\partial}{\partial x_j}(\rho \mathrm{ku}_j)=\frac{\partial}{\partial x_j}[(\mu\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}]+\mathrm{G}_k+\mathrm{G}_b-\rho\varepsilon-Y_M+S_k \tag{8}$$

Which is used for solving turbulence, k. And

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon \mathrm{u}_j)=\frac{\partial}{\partial x_j}[(\mu\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}]+\rho C_1 S\varepsilon-\rho C_2\times\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}$$

$$+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{9}$$

Which is used for solving dissipation rate, ε. Where

$$C_1=\max[0.43\frac{\eta}{\eta+5}],\ \eta=S\frac{k}{\varepsilon},\ S=\sqrt{2S_{ij}S_{ij}} \tag{10}$$

The eddy viscosity is calculated from equation:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{11}$$

The model constants are:

$$C_{1\varepsilon}=1.44,\ C_2=1.9,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.2$$

The total heat transfer through air to soil can be calculated using the temperature difference between inlet temperature and outlet temperature, as is shown below:

$$\dot{Q}=\dot{m}C_p(T_i-T_o) \tag{12}$$

$$Q=t\dot{Q} \tag{13}$$

In this practice $C_p = 1.005(J/kgK)$. Eqn. (13) is used to calculate the heat transfer rate between soil and passing airflow and Eqn. (12) is used to calculate the amount of cumulative energy through time of operation. Additionally, the performance of such system is commonly expressed in terms of the coefficient of performance (COP), defined as:

$$COP = \frac{System.Output}{Work.Input} \tag{14}$$

The system output in this practice is the heat transfer from the air to the surrounding soil and the work input is the mechanical fan power ($W_{fan} = 0.4kW$). In theory, a system with higher value of COP is more efficient.

SIMULATION METHODS

Description of geometrical configuration of the ETS and average soil properties are presented in **Table 1**. The physical geometry of the system was created using structured hexahedral meshing with a 10-layer smooth inflation. This meshing enabled higher accuracy for the results and ensured the temperature field near the pipe-soil interface was explicitly simulated as the temperature varies faster near the pipe than in the centre of airflow due to ‘no-slip condition’ of the wall. The control volume was defined by creating a cylinder volume of pipe. The details of the meshing are displayed in **Fig.3** and **Table 2.** It is common practice that y+ values are to be studied for turbulent models thereby further validating the use of mesh employed in the simulation where y+ values are ranging from 20 to 34 indicating the mesh near wall is acceptable.

ANSYS v. 15 FLUENT was used in this study using finite volume method enabling numerical calculation of governing equations to be solved iteratively. Pressure-based solver and Transient Time were initiated with in the simulation where gravitational acceleration was also taken into account. Realizable $k-\varepsilon$ model with enhanced wall treatment was selected as it contains an alternative formulation for the turbulent viscosity and a modified transport equation for the dissipation rate, ε, giving more accurate results than the simple standard model while not so complicated that would considerably increase the computing time as the Reynolds Stress Model. The k-epsilon model is commonly used for analyzing turbulence model, in particular, giving good results for wall-bounded and internal flows. The energy option was turned on to investigate the heat transfer process in the system. As to the pressure-velocity coupling method, SIMPLEC scheme was adopted as it works better for relatively uncomplicated flow in which convergence is limited by the pressure-velocity coupling and this in turn lower the computing time for the converged solution. Also, SIMPLEC can even improve the convergence provided that it is being limited by the pressure-velocity coupling. To reduce the inaccuracy of the simulation, the settings in Spatial Discretization for all criteria were Second Order Upwind and the model was solved implicitly. The convergence criteria for all variables except for energy were set to be 10^{-3} and the energy was set to be 10^{-6} for higher accuracy.

Table 1 Input data for the ETS model

Parameter	Unit	Value
Pipe Length	m	40
Pipe depth	m	4
Soil temperature	K	295
Soil thermal conductivity	W/mK	1.52
Soil thermal diffusivity	m^2/s	0.00232
Diameter	m	varied
Inlet velocity	m/s	varied
Inlet air temperature	K	305

Table 2 Meshing information

Sizing	Use Advanced Size Function	On: Curvature
	Relevance Centre	Medium
	Smoothing	Medium
	Transition	Slow
	Max Face Size (m)	1.9938
	Min Face Size (m)	0.01994
Inflation	Maximum layers	10
	Growth Rate	1.2
	Transition Ration	0.272

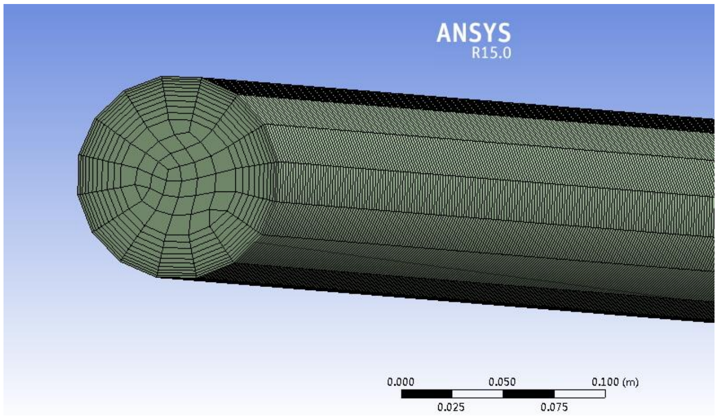

Fig. 3 Defined cylindrical control volume for simulation

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EVALUATION OF FLOW PERFORMANCE

By considering the specific flow condition, one simulation of D=0.2m, v=2m/s was taken as an example for demonstration. The static temperature profile (see **Fig. 4**) and contours of static temperature (see **Fig. 5**) along the pipe during cooling mode were displayed using ANSYS Fluent v. 15. It was expected that the heat transfer process started from the inlet towards the outlet of the pipe but a drastic temperature gradient was found near the walls because of the better surface contact through which heat was exchanged by both convection and conduction. t was also observed that the viscous boundary layer grew along the tube originating from the inlet till the tube was completely full. This phenomenon is also corroborated by **Fig. 6** where a certain degree of turbulence at the initial stage is shown but a constant velocity is reached thereafter.

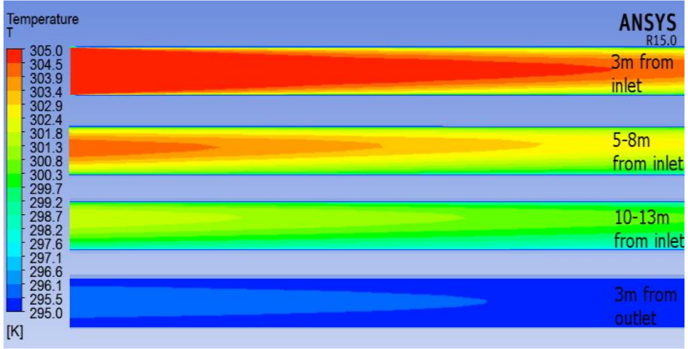

Fig. 4 Contours of air temperature along pipe in cooling mode

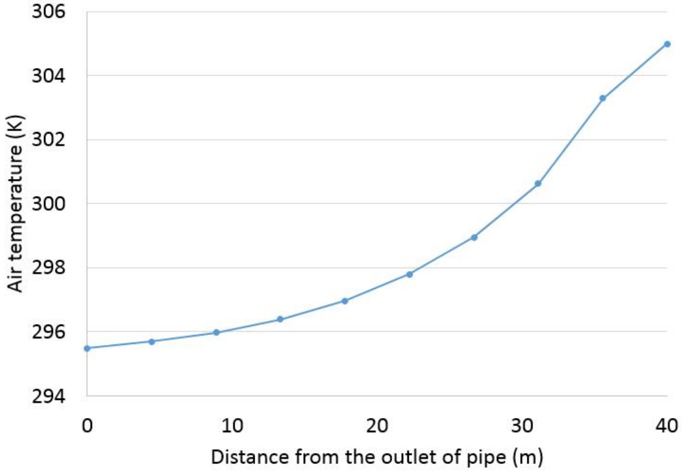

Fig. 5 Temperature profile along the pipe in cooling mode

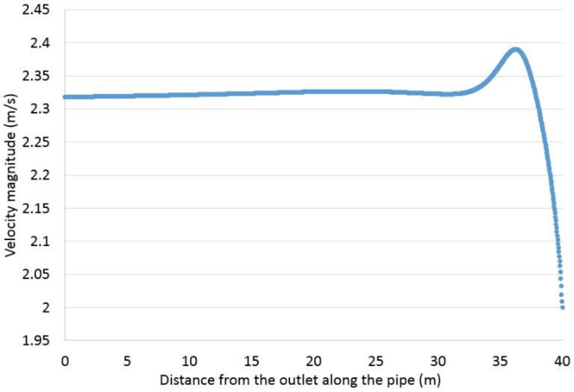

Fig. 6 Velocity as a function of the distance from the outlet of the pipe along the centerline (cooling mode)

Regarding the thermal performance, the investigation on the limiting factors which affects the performance of ETS was carried out. As in this study the simulation was predicated upon the constant features of the soil (homogeneous properties and invariable temperature), and the operation time of the system was fixed, the influence of pipe diameter and inlet air velocity were therefore being the main subjects of interest. **Fig. 7** was a presentation of the air temperature (at pipe centre) along the pipe using different pipe diameters with identical inlet velocity at 4m/s. It was observed that the smallest pipe diameter of 0.1m obtained the lowest temperature at outlet (about 295K) and as the pipe diameter grew larger the air temperature at outlet increased as well (the outlet temperature even grew up to 300K when D=0.4m). This can be explained by the fact that when the diameter becomes larger and flow velocity is constant, the amount of air going through the pipe per unit time increases, meaning more heat needs to be dissipated into the surrounding soil and thus more soil is required to achieve the same low outlet temperature. Therefore, it was safe to conclude that smaller pipe diameter is able to produce better thermal performance. However, small pipe diameter is not necessarily ideal in all cases since small diameter is highly likely to lead to greater pressure loss along the pipe and thus increased energy spending on fan power. In addition to the growing operation costs and risks of wear at work, small pipe may not satisfy the fresh air intake requirement stipulated by relevant regulations.

The influence of inlet velocity on the air temperature along the tube was shown in **Fig. 8** where the diameters also ranged from 0.1m to 0.4m. It was expected that the air temperature along the pipe increased with higher inlet velocity due to reduced contact time between surrounding soil and airflow. This reduction in contact time would inevitably result in insufficient heat exchange and higher outlet temperature ensued. Nevertheless, like what was discussed in the previous section, the cooling capacity is not necessarily reduced with a higher inlet velocity as a larger amount of air could pass through in a unit time, which might keep the total cooling capacity at a high level. A relatively low velocity is usually preferred but it is necessary to choose it taking into account the other parameters such as pressure drop along the pipe, fresh air requirement etc. As to select a fitting system configuration to optimize the energy saving potential and thus reducing energy consumed by conventional air-conditioning systems or even replacing them completely, it is essential to examine the amount of heat transferred between the surrounding soil and airflow along the pipe. **Fig. 9** shows the total amount of energy transferred from airflow to soil along the pipe with different inlet velocities and pipe diameters. Evidently, when the pipe diameter was large (D=0.4m) or the inlet velocity was high (v=4m/s) the system exhibited considerably larger heat transfer rate, which was on the contrary to the influence of diameter and inlet velocity acted upon the outlet temperature (where small pipe and low velocity caused lower outlet temperature). As previously explained, this greater heat transfer was due to more air passing through per unit time, albeit a smaller temperature difference (see Eqn. (12)).

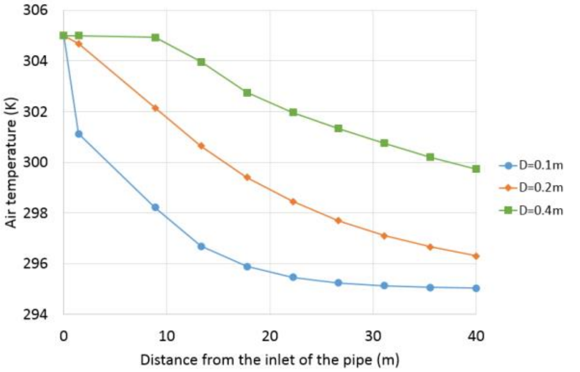

Fig. 7 Air temperature from inlet along pipe using different pipe diameters (cooling mode)

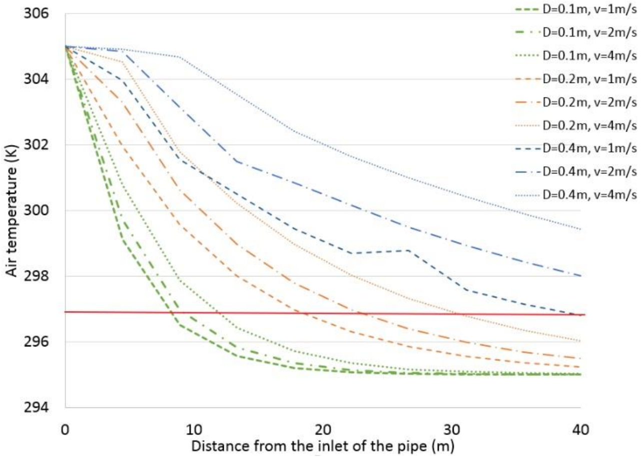

Fig. 8 Air temperature from the inlet along the pipe with different inlet velocities and pipe diameters (cooling mode)

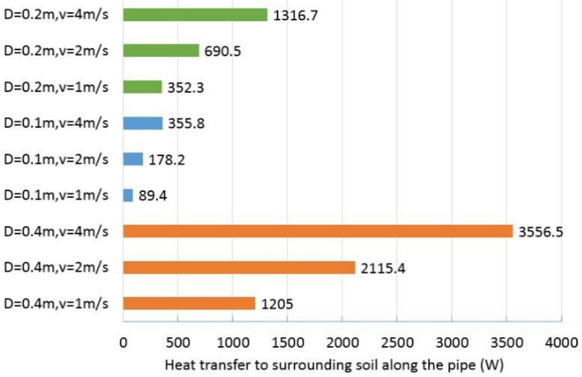

Fig. 9 Total heat transfer between soil and airflow in the pipe with different simulation parameters (in cooling mode)

Apart from the quantity of heat transferred between airflow and soil, the temperature at outlet is also of paramount importance as the air temperature has to be cooled down to certain level, otherwise the employment of conventional air-conditioning is entailed. According to CIBSE (2006), the comfortable temperature for the majority of room types is 24^{o}C, which necessitates the maximum temperature at outlet should be lower than 297K (heat gain from the surrounding in the distribution was omitted). Hence, the model with diameter of 0.2m, inlet velocity of 0.4m/s was deemed the most qualified and was selected as the model to be used in following investigation on energy saving potential in Ningbo, China.

ENERGY CONSERVATION POTENTIAL

The energy saving potential can be expressed as the amount of heat transfer exchanged between soil and airflow during working period. With reference to Eqn. (13), the total amount of heat transfer can be calculated by multiplying the heat transfer rate along the pipe and time of operation, assuming the E-tube system worked 10 hours in a day, 30 days in a month. So theoretically, as suggested by Eqn. (16) the ETS was able to save up to 1185kWh during summer period in Ningbo, China.

Kokogiannakis et al. (2011) used EnergyPlus software to project the energy consumption for an average office building in Ningbo from June to August (see **Fig. 10**) and predicted the energy demand for cooling was around 1435kWh for summer period. Besides, Hartmann (2011) in his study predicted the use of solar cooling and electric system had the potential of reducing the cooling load up to about 718kWh in summer period. The comparison between the projected energy demand and energy conserved using alternative systems was presented in **Fig. 10**. It was observed that the E-tube system comprised of one duct was capable of saving substantially more energy than solar cooling and electric system and was estimated being able to replace up to 86% of energy demand in Ningbo.

Notice the conditions used and assumptions made in this study were not exactly identical to those studies conducted by Hartmann (2011) and Kokogiannakis et al. (2011) but the discrepancy was insignificant. In addition to the sum of energy conserved, the energy conservation potential can also be assessed in terms of COP where higher value denotes a system with better effectiveness. The COP for refrigeration circle is generally around 3-7 and the COP achieved for the E-tube system as shown above was 3.3 (consistent with some results in literature) . Therefore, it could be concluded that the use of ETS in Ningbo was effective and promising. However, in reality the soil temperature near the pipe would increase a few degree after long operation due to reduced thermal capacity of soil and thus smaller COP value. The possibility of cumulative condensate emerged during operation might as well contribute to deterioration of the effectiveness of the system (heat is given out to airflow during condensation). Provided that the ETS was assumed to operate intermittently (10 hours in a day) where soil thermal capacity could be restored to original state, and provided that the constant soil temperature was taken higher than the average dew point temperature during summer period (from meteorological data), the result calculated in Eqn. (14) was considered acceptable.

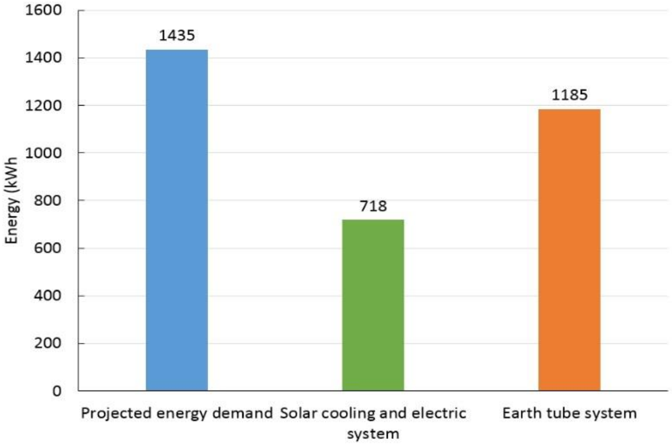

Fig. 10 Comparison with projected energy demand (Kokogiannakis et al.) and solar cooling and electric system (Hartmann) (for summer season)

CONCLUSION

Reasonable comparison between projected energy demand and energy saving potential of alternative systems had been presented in this study and proved that earth tube systems have the potential to become effectual energy saving technologies in buildings in Ningbo, China. Also, the study presented an insight into some factors that would impact upon the thermal performance of the system. The specific findings were:

- The outlet temperature increased with the inlet velocity as a result of reduced contact time between soil and airflow.
- The outlet temperature increased when the diameter of the pipe was larger due to more airflow was passed through.
- A balance between outlet temperature required and volumetric airflow rate stipulated by regulations needed to be established, provincially, the system with diameter of 0.2m, inlet velocity of 4m/s obtained the optimum result and was taken as the model to be installed in Ningbo.
- The ETS was estimated being able to provide cooling of 1185kWh in summer period (i.e. 86% of the projected energy demand) in Ningbo and attained a COP of 3.3.

Despite the potential variability in soil conditions as well as the accumulation of condensate within the pipe in practice, the results indicated that for summer period in Ningbo, the ETS could be used to provide adequate cooling as a means to reduce the energy consumption by conventional air-conditioning systems. If the system is to achieve the effective operational and thermal performance, there are nonetheless still some important factors that need to be taken into account. For instance, dry soil in some locations does complicate the process where the nonlinearity of the soil is exacerbated, reducing thermal conductivity in soil to a low level. The effectiveness of the system is also likely to diminish due to condensation in the pipe which can result in unfavourable increase in outlet temperature. Thus, further investigation into the ramifications of these factors is required to make better use of ETS.

ACKNOWLEDGEMENT

The authors would acknowledge sincere appreciation to the financial supports from the Beijing Key Lab of Heating, Gas Supply, Ventilating and Air Conditioning Engineering, Zhejiang Natural Science Foundation (LQ16E060001), and BIM-GIS Application in Green Built Environment, funded by Ningbo Science and Technology Bureau (2015B11011).

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