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CONCEPTUAL DEVELOPMENT OF THE EARTH TUBE COOLING SYSTEM FOR A TALL BUILDING

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ABSTRACT

Earth tubes are earth-to-air heat exchangers that are frequently utilized in energy conscious low-rise buildings, but are scarcely reported for tall buildings. The feasibility of applying earth tube cooling to tall buildings in a hot summer and cold winter climate zone was studied in this paper. Firstly, the designed cooling load of a tall building was obtained from the energy simulation using the baseline and the modified models with applicable energy efficiency measures. Based on the load, the required cooling capacity, the overall section area and the effective length of the earth tube system was deduced from the heat transfer and fluid flow calculation analytically. Then the performance of the earth tube system was crosschecked and verified via the Computational Fluid Dynamics (CFD) simulation. In the CFD simulation, earth tubes with different diameters and lengths, as well as a full-scale earth tube model with surrounding soil above the depth of constant temperature, were investigated. The outlet air temperatures of the full-scale models were computed with the consideration of different axial distances between adjacent tubes. Meanwhile, multiple conceptual design schemes and the tunnel construction method for the earth tube system were proposed from the perspective of performance enhancement, constructability, efficiency and economy. It revealed that earth tube systems are conditionally feasible for some tall buildings if their design guidelines for climate, underground spaces, construction method, friction of tube interior surface, optimization of effective length and axial distance, as well as synergy with other energy efficiency measures are followed. Even the cooling capacity of earth tubes degrade with time due to the accumulated heat underground, but in a hot summer and cold winter climate zone it can still possibly produce cooled air for a tall building with a Floor Area Ratio of less than 7 effectively in summer.

KEYWORDS

earth tube, energy efficiency, tall building, cooling capacity, overall section area, effective length

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1. INTRODUCTION

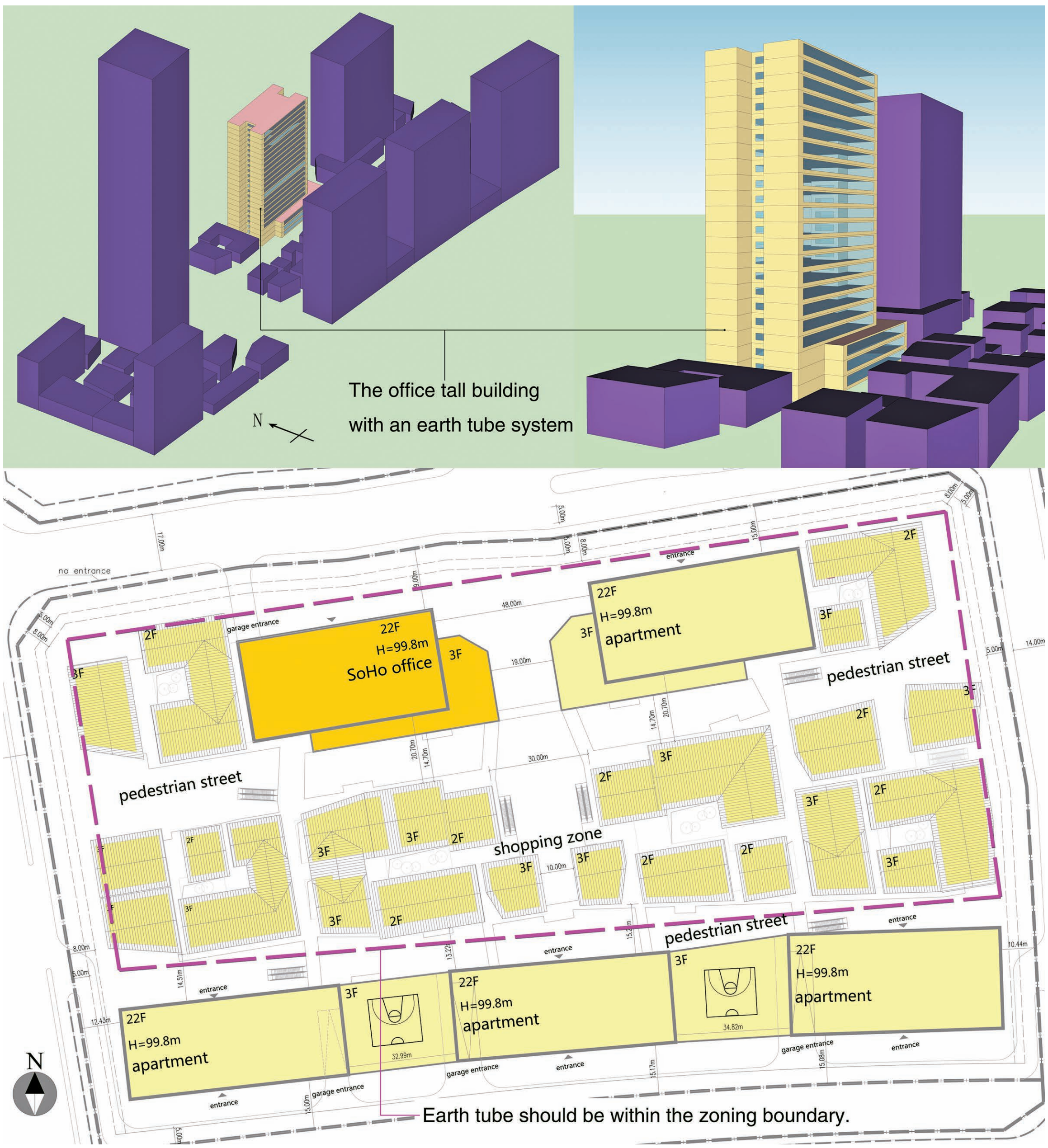
With the development of global warming, the need to cool buildings is significantly growing in climate zones with hot summers, which accounts for increasing building energy consumption in these regions, especially for large commercial buildings (Henley, 2015). Passive cooling technology, such as earth tube, has gained increased attention in the field of sustainable building research for producing durable, economical and energy efficient cooling. Earth tube, also named as an earth-to-air heat exchanger, or ground tube heat exchanger, is an underground tube system that can take advantage of the stable temperature of the earth. It captures heat from underground soil in winter and dissipates heat into soil in summer to moderate the outdoor air for ventilation. Earth tubes are usually made of baked clay tiles, concrete tubes, steel ducts, polyvinyl chloride or high-density polyethylene plastic pipes.

Prototypes of earth tubes for cooling can be found in many desert vernacular architectures. Passive cooling by earth tubes have been studied in the 1990s with improved computing technology. For example, the thermal performance of earth tubes was simulated in the TRNSYS environment based on a numerical model produced by Mihalakakou G. et al. (1994). A similar numerical model of an earth-air-tunnel system coupled with a small building was developed using the finite difference method in Matlab (Kumar, et al., 2003). The cooling and heating potential of an earth tube system for buildings was numerically studied in Energyplus, and verified via experimental data (Lee, et al., 2008). Thermal performance of earth tubes combined with a greenhouse was investigated by Tiwari in India, and the results were in accordance with the experimental testing for a similar greenhouse system in Greece (Tiwari, et al., 1998). The influence of environmental and geometrical factors on the energy efficiency of earth tubes was analyzed via finite elements method. It showed that pipe diameter, placement depth, number of parallel pipes, bypass system, soil thermal physical parameters, ground area shading and surface cover of the earth tube system can all influence the energy efficiency of the tested building (Trząski and Zawada, 2011). An earth tube ventilation system was also tested, and the results showed that it could contribute 62% peak heating load reduction and 86% peak cooling load reduction respectively (Darkwa, et al., 2011). Clara Peretti et al. (2013) also researched characteristics and design strategies of earth tubes coupled with building ventilation, but the case studies provided by them were also low-rise, small buildings. Investigation of a coupled geothermal cooling system with earth tube and solar chimney was retrieved, and the system was proved to be effective with a high airflow rate (Yu, et al., 2014). Cooling performance assessment of an earth tube system in a tropical greenhouse was also done (Mongkon, et al., 2014). The indoor thermal comfort can be achieved by the combined effect of building thermal mass and earth tube ventilation (Yang and Zhang, 2014). Experiments on the periodically fluctuating air temperature in a building with earth tubes were performed to validate the numerical model for the coupling effect of earth tube ventilation and building thermal mass (Yang and Zhang, 2015). The earth tube for a Net Zero Energy Building in the Mediterranean climate was developed recently, and the possibility of obtaining net zero energy use for a low-rise building was proved (Ascione, et al, 2016).

Nonetheless, in the above research all the buildings with earth tubes are low-rise, small buildings. There is little research for a large-scale building, especially a tall building, equipped with an earth tube system. Even for the 29-storey Epcor Tower in downtown Edmonton, Canada, which has a large earth tube system (David, 2016) there remains a lack of researche on earth tube utilization in tall buildings.

Tall buildings can produce significantly more heating and cooling loads than small buildings. They need a huge volume of underground space for a large-scale earth tube system. As a result, the land coverage area of the earth tube system becomes larger. Their scale, layout and other geometrical features significantly affect the cooling capacity and energy performance. For example, the longer the buried earth tubes are, the more interior surface friction effect is met by airflow, which requires more fan power to propel it. On the other hand, with the increased

FIGURE 1. The mass model of the tall building and its surrounding buildings was established for energy simulation (Source: produced by the author); the site plan of the tall building (Source: Suzhou Wanyi Real Estate Development Co. Ltd.).



section area, the friction loss can be attenuated to some extent for fan power energy saving. Since there are many unanswered questions involving large-scale earth tube systems for tall buildings, research on them is important.

2. COOLING LOAD ANALYSIS ON A TALL BUILDING IN HOT SUMMER AND COLD WINTER CLIMATE ZONE

There is a tall building in a commercial zone in Suzhou, China. The building is designed to be a nearly 100m high office tower that has 22 stories and 38,368m^2 floor area above ground. The floor-to-floor height of the building is 4.5m, suitable for office function. The tall building is planned along the north boundary of the office zone, surrounded by other buildings from the east, south and west. A paved pedestrian area is adjacent to the building, serving as its entrance plaza from the south. The mass model of the tall building and its surrounding buildings are shown in Figure 1. The surrounding buildings are modeled since they can cause a shading effect on the tall building. The tall building is intended to achieve more energy efficiency via earth tube cooling technology in summer. The area within the zoning boundary available for the earth tube system is about 28,000m^2.

The tall building is located in Suzhou, China, (north latitude: 31.32 degree, east longitude: 120.63 degree), which belongs to the hot summer and cold winter climate zone. The typical summer and winter months are July and January respectively. Weather data comes from the Chinese Standard Weather Data (CSWD) file (Energyplus, 2016). The weather data is one of the critical inputs into the energy simulation model of the tall building and the CFD model of the earth tube system. It can be perceived in Figure 2 that the local monthly average outdoor air temperature in July fluctuates between 25.9°C and 29.5°C. In Figure 3 the hourly dry-bulb air temperature in July and August varies from 20.9°C to 35.2°C.

Soil temperature is one of the decisive factors for the cooling effect calculation of earth tubes. Soil temperature data is obtained from local geothermal drilling tests and are partly presented in Figure 4. The annual fluctuation at the depth of 0.5m is almost coincident with the

FIGURE 2. Monthly average outdoor air temperature per hour at Suzhou, China (Source: Chinese Standard Weather Data).

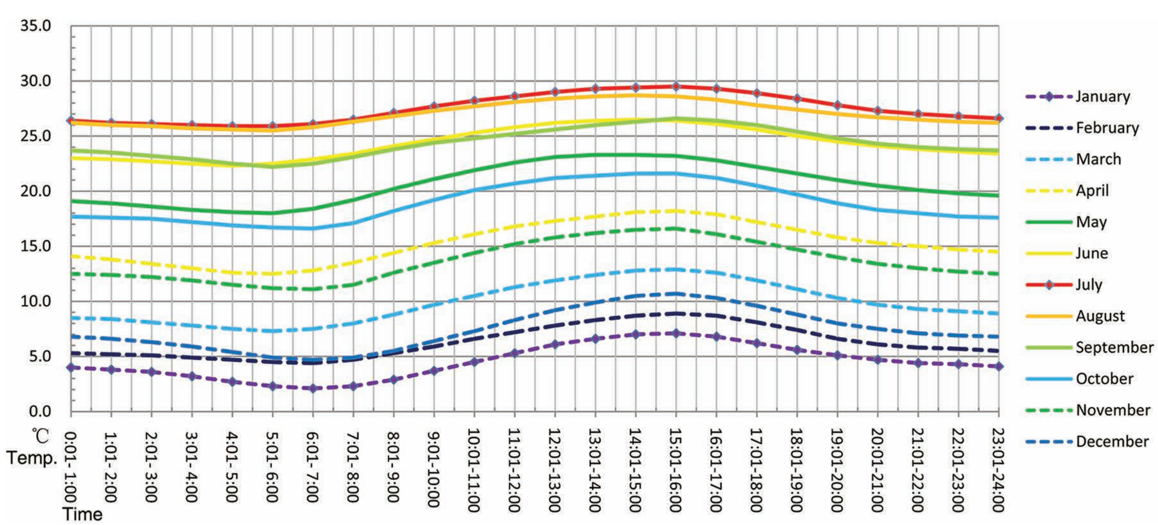
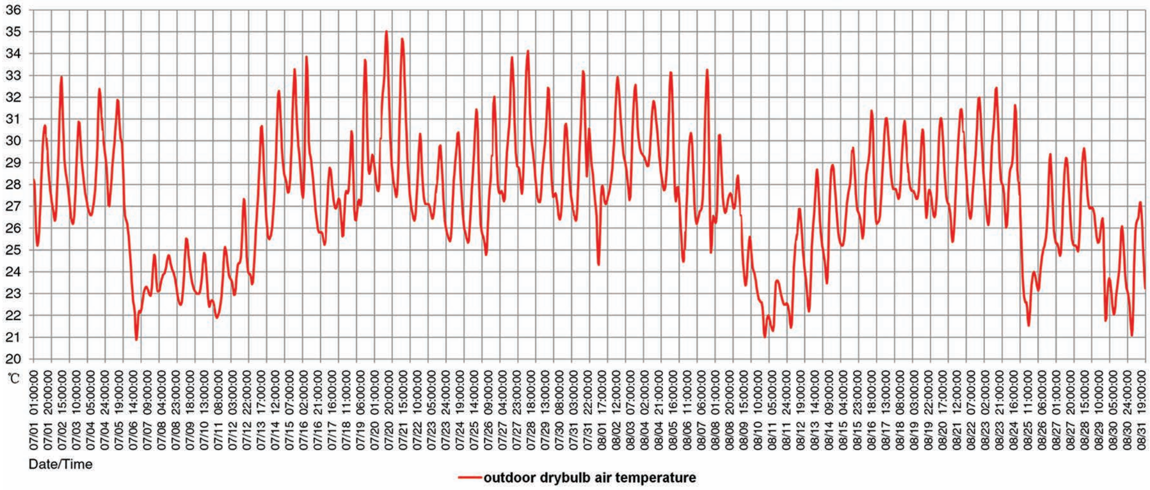
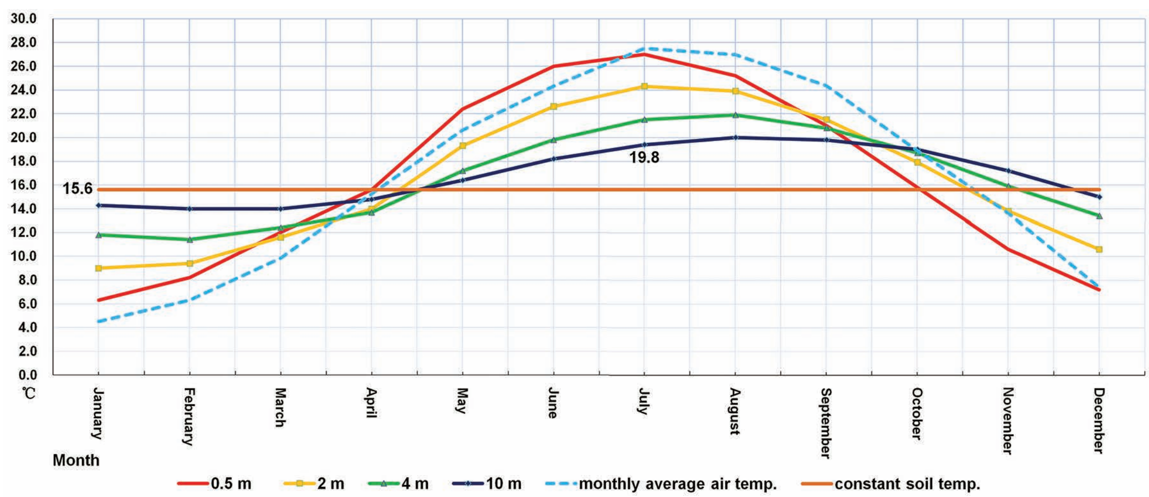


FIGURE 3. Hourly outdoor dry-bulb air temperature in July and August for Suzhou, China (Source: Chinese Standard Weather Data).



fluctuation of the monthly average air temperature except for about half a month time lag. With increasing depth, there is a distinct decreasing of soil temperature fluctuation and an increasing time lag. The soil temperature at 10m depth underground varies from 14.0°C to 20.1°C throughout the year. Therefore, the average monthly variation of soil temperature at 10m depth underground is about 0.5°C, and the daily temperature variation is only 0.017°C, which can be considered as a steady state thermal environment. In July, the monthly average soil temperature at 10m depth underground is 19.8°C, and the constant soil temperature is 15.6°C, which are utilized in the earth tube cooling system performance calculation.

FIGURE 4. Undisturbed monthly average soil temperature at different depths underground compared with the monthly average air temperature for Suzhou, China (Source: Chinese Standard Weather Data).



The major part of the earth tube system is going to be constructed along with the basement floors of the tall building that are located at a depth of 10m below ground level. Meanwhile, soil moisture content is high at the construction site, and heat transfer due to moisture infiltration is enhanced. The exterior surface temperature of an earth tube can approach the soil temperature almost instantaneously.

Cooled air through the earth tube is supplied into the office spaces at each floor of the tall building by means of displacement or mixing ventilation in order to balance the internal cooling load. The maximum cooling capacity of the earth tube system should be in accordance with the peak hourly cooling load of the tall building. To determine the peak hourly cooling load of the building, energy simulation was performed using an established whole building energy model in Energyplus.

In the first simulation model based on the Design Standard for Energy Efficiency of Public Buildings (GB50189, 2015), the window-to-wall ratio of the south, east, west and north facades of the tall building are specified as 60%, 30%, 30% and 30%, respectively, according to the facade design requirements. Walls, floors, and roofs of the model adopted the heat transfer coefficients (U-values) of the standard building components in Table 1. Windows and other glazing areas of the model adopted the heat transfer coefficients (U-values) and Solar Heat Gain Coefficients (SHGC) of the standard windows in Table 1 as well. The first model is defined as the baseline model, then all the subsequent models are modifications of the baseline one by integrating more thermal insulation, more thermal mass, solar shading devices, adopting a highly reflective cool roof, applying double skin facades, and increasing the indoor cooling set-point from 25°C to 28°C for saving energy. The purpose of doing energy simulation using the baseline and the modified models is to figure out the reduced peak hourly cooling load which is intended to be totally or partially balanced by the earth tube cooling system.

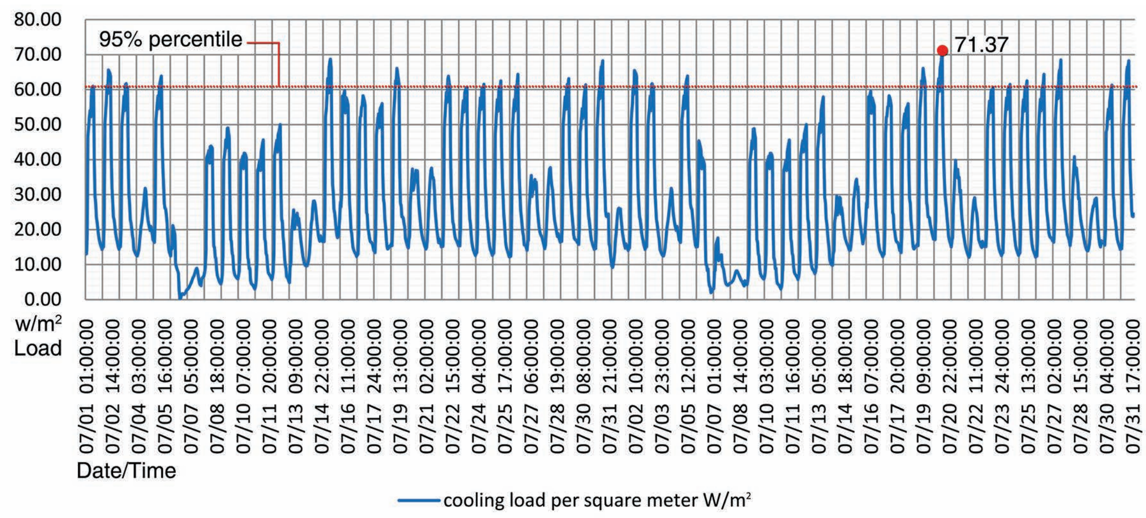
Through multiple energy simulation runs with the building models, the hourly cooling load per unit area of the tall building is acquired and presented in Figure 5. It indicates that the unit area maximum cooling load for the baseline model of the tall building is 71.37W/m^2, and the threshold value of the cooling load per unit area for the 95% guaranteed hours is 60.85W/

TABLE 1. Maximum values of the heat transfer coefficients and Solar Heat Gain Coefficients for the standard envelopes in hot summer and cold winter climate zones (Source: GB50189-2015).

Envelopes		Heat Transfer Coefficient (U-value) (W/m^2 K)	Solar Heat Gain Coefficient: (SHGC) East, south, west/north
Roof	TII* ≤ 2.5	0.4	Not applicable
Wall	TII ≤ 2.5	0.6	Not applicable
Window	WWR* ≤ 0.2	3.5	Not applicable
	0.2 < WWR ≤ 0.3	3.0	0.44, 0.44, 0.44/0.48
	0.3 < WWR ≤ 0.4	2.6	0.4, 0.4, 0.4/0.44
	0.4 < WWR ≤ 0.5	2.4	0.35, 0.35, 0.35/0.4
	0.5 < WWR ≤ 0.6	2.2	0.35, 0.35, 0.35/0.4

*TII: thermal inertia index; WWR: window to wall ratio

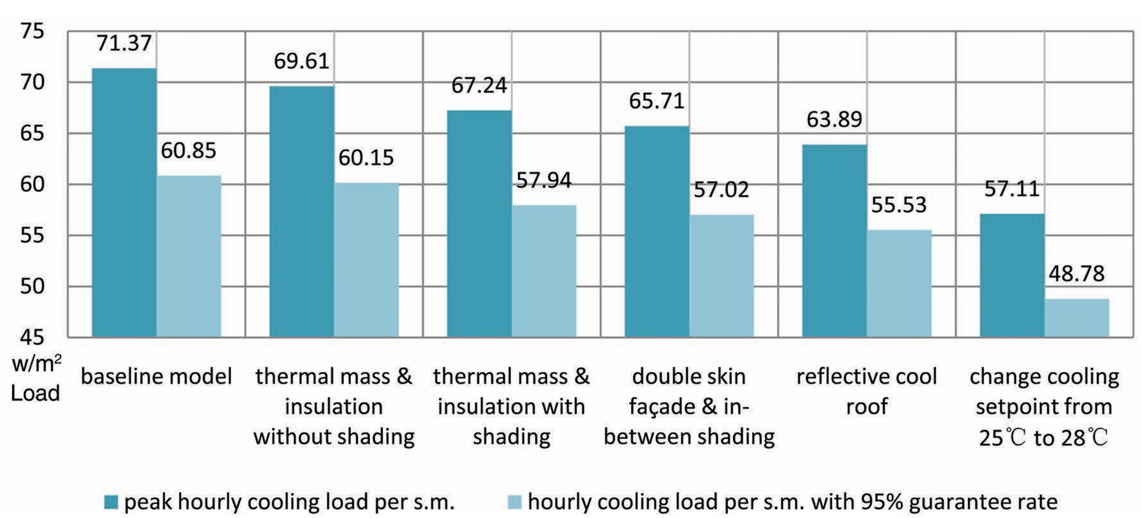
FIGURE 5. Hourly cooling load per unit area of the tall building baseline model in July (Source: produced by the author).



m². Therefore, if the earth tube cooling system could produce 60.85W cooling power per unit area, its guarantee rate for cooling the baseline tall building in July is 95%. Some typical energy saving measures are superimposed on the baseline energy model of the tall building, and their unit area maximum hourly cooling load in July, as well as the corresponding load intensity with 95% guarantee rate, are calculated and shown in Figure 6.

This demonstrates that changing the cooling setpoint from 25°C to 28°C is more effective than using other energy efficiency measures. Even though the 28°C cooling setpoint may compromise the indoor thermal comfort for a few occupants, it is still an officially advocated energy efficiency measure and acceptable for most cases. It also implies that the surrounding buildings seem to produce considerable shading effect to reduce the cooling load of the tall building in

FIGURE 6. Maximum hourly cooling loads per unit area and the corresponding load intensities with 95% guarantee rate for the baseline model and the modified models with the applicable energy efficiency measures (Source: produced by the author).



summer, so that the contribution from the additional shading devices on its facade becomes marginalized. Based on the above cooling load analysis with consideration of applicable energy efficiency measures, the design unit area cooling load of the tall building can be determined as $48.78 W/m^2$, the possible cooling load with the energy efficiency measures. Subsequently, the total design cooling load of the tall building with $38{,}368 m^2$ conditioned floor area is calculated as 1,880,032W, which should be equal to the design cooling capacity of the earth tube system plus the air conditioning system of the tall building.

3. THERMAL AND FLUID FLOW CALCULATION FOR THE EARTH TUBE COOLING SYSTEM

In conceptual development, the overall section area and the effective length of the earth tube cooling system are studied quantitatively at first. In the simplified calculation, it is assumed that the earth tube cooling system can provide cooled air at the temperature equal to the soil temperature at 10m depth underground, partially or totally meeting the design cooling load. Any residual cooling load is expected to be handled by the air conditioning system.

3.1 Overall Section Area of the Earth Tube Cooling System

The total volumetric flow rate of the earth tube cooling system, as well as the overall section area, can be determined according to the design cooling load or the required fresh air. The forced ventilation through the earth tube system to maintain the cooling load equilibrium is also a major source of indoor fresh air supply for sustaining a healthy indoor environment. The overall fresh air required is associated with the total number of occupants and the building function, which is usually indicated by Air Change per Hour (ACH) of the building.

There are two scenarios for the volumetric flow rate of the earth tube system: for cooling and health purposes. If the required volumetric flow rate of the earth tube system for balancing the design cooling load is not less than the required volumetric flow rate of the fresh air, the earth tube system can supply all fresh air. If the required volumetric flow rate for cooling purpose is less than the volumetric flow rate of the required fresh air, additional fresh air should be supplied. The extra cooling load due to the additional outdoor fresh air can also be met by supplying more cooled air from the earth tube system so that the central air condition system can save energy. The volumetric flow rate of the earth tube for the design cooling load is given by (1):

$$\bar{V}_c = \frac{q_0 \eta}{C_p \rho \left(T_{\text{in}} - T_{\text{out}}\right)} \tag{1}$$

Meanwhile, the volumetric flow rate of the fresh air supply is specified as (2):

$$\bar{V}_f = \frac{ACH\, A_0\, H_{fc}}{3600} \tag{2}$$

If $\bar{V}_c \geq \bar{V}_f$, the total section area of all the earth tubes can be expressed as (3):

$$A_{\text{all}} = \frac{q_0\, \eta}{C_P\, \rho\, u \left(T_{\text{in}} - T_{\text{out}}\right)} \tag{3}$$

If $\bar{V}_c < \bar{V}_f$ and the additional cooling load of the outdoor fresh air is balanced by supplying more cooled air from the earth tube system, there are the following equations (4), (5) and (6):

$$C_p\rho\bar{V}_2\left(T_{\text{ex}} - T_{\text{in}}\right) = C_p\rho\bar{V}_3\left(T_{\text{in}} - T_{\text{out}}\right) \tag{4}$$

$$\bar{V}_1 + \bar{V}_2 + \bar{V}_3 = \bar{V}_f \tag{5}$$

$$A_{\text{all}}u = \bar{V}_c + \bar{V}_3 \tag{6}$$

Based upon the above equations, the overall section area of the earth tube cooling system under the condition of $\bar{V}_c < \bar{V}_f$ is figured out as (7):

$$A_{\text{all}} = \frac{q_0\,\eta}{C_P\rho\,u\left(T_{\text{ex}} - T_{\text{out}}\right)} + \frac{ACH\;A_0H_{fc}\left(T_{\text{ex}} - T_{\text{in}}\right)}{3600u\left(T_{\text{ex}} - T_{\text{out}}\right)} \tag{7}$$

Here $\bar{V}_c$ is the volumetric flow rate of the earth tube for the design cooling load of the building (unit: m^3/s). q_0 is the total design cooling load of the building (unit: W). η is the ratio of the total design cooling load that is intended to be met by the earth tube cooling system (dimensionless). C_P is the specific heat capacity of the cooled air (unit: J/KgK, 1005J/KgK is used in the calculation). ρ is the density of the cooled air (unit: Kg/m^3, $1.2Kg/m^3$ is adopted for air). T_{in} is the cooling setpoint of the conditioned interior space (unit: K). T_{out} is the outlet temperature of the earth tube system (unit: K). $\bar{V}_f$ is the volumetric flow rate of the required fresh air supply from outdoors (unit: m^3/s). ACH is the air change per hour of the building (unit: $hour^{-1}$). A_0 is the total conditioned floor area of the building (unit: m^2). H_{fc} is the floor-to-ceiling height of the building (unit: m). A_{all} is the overall section area of all the earth tubes (unit: m^2). u is the mean velocity of the air in the earth tubes (unit: m/s). $\bar{V}_2$ is the volumetric flow rate of the fresh air supply from outdoors via other fresh air inlets of the building except the earth tubes (unit: m^3/s). $\bar{V}_3$ is the volumetric flow rate of the additional cooled air from the earth tube for balancing the extra cooling load due to $\bar{V}_2$ (unit: m^3/s). T_{ex} is the outdoor air temperature (unit: K).

Under the design condition in summer, q_0 is 1,880,032W, T_{in} is 28°C, T_{out} is 19.8°C (the soil temperature at the 10 meter depth underground), ACH is 3.0, A_0 is $38{,}368m^2$, H_{fc} is 2.7m. Assume the ratio η is 1.0, which means that the design cooling load of the tall building is completely met by the earth tube system. $\bar{V}_c$, the volumetric flow rate of the earth tube system for the design cooling load, should be $190.1m^3/s$. Meanwhile, the volumetric flow rate of the specified fresh air supply from outdoors ($\bar{V}_f$) is $86.3m^3/s$, which is less than $190.1m^3/s$. This indicates that compared with ventilation for health, more exterior fresh air is needed to be cooled by the earth tube system for balancing the total design cooling load of the tall building.

There are two typical ventilation schemes for the earth tube cooling system. Scheme 1: the earth tube system is designed to meet the total cooling load of the tall building with a 95% guarantee rate. In this case, the volumetric flow rate of the earth tube system is $190.1m^3/s$. Scheme

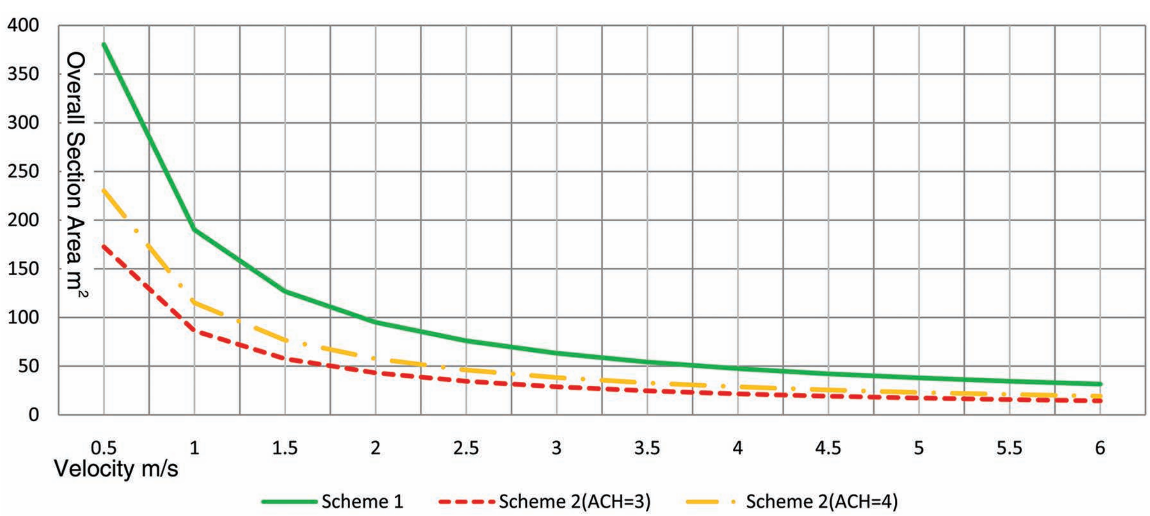
2: the earth tube system is designed only for cooling the required fresh air, and the residual cooling load of the building is met by the air conditioning system. In Scheme 2, if the *ACH* is 3.0, the volumetric flow rate of the earth tube system is 86.3m^3/s, and the ratio η is 0.45; if the *ACH* is 4.0, the volumetric flow rate of the earth tube system is 115.1m^3/s, and the ratio η is 0.61. The overall section area of the earth tube cooling system in Scheme 1 and Scheme 2 are displayed in Figure 7. In the research, the conventional air velocity range inside the earth tube is assumed to vary from 2.5m/s to 3.5m/s with the consideration of the optimal performance of the ventilation fans, and the average velocity can be set as 3m/s. If the velocity of the supply air is 3m/s, the total section area of the earth tube cooling system in Scheme 1 is 63.4m^2, and the area in Scheme 2 varies from 28.8m^2 to 38.4m^2 while the *ACH* increases from 3 to 4.

Considering the convenient size for the earth tube structure and the ventilation fan, the diameter of the tube section is better to be within the range of 1.0m to 2.0m, thus the section area of an individual earth tube is from 0.785m^2 to 3.142m^2. As a result, there should be 20 to 81 earth tubes in Scheme 1, 9 to 37 earth tubes in Scheme 2 when the *ACH* is 3, and 12 to 49 earth tubes in Scheme 2 when the *ACH* is 4. Depending on the above preliminary calculation, the overall section area and the rough number of earth tubes in the two typical design schemes are determined for the subsequent modeling.

3.2 Effective Length of the Earth Tube Cooling System

Effective length of an earth tube can be defined as the length from the air inlet to the nearest position with negligible heat transfer between the ventilated air and the ambient soil. The intake air passing through the effective length of an earth tube can be gradually cooled down to the ambient soil temperature. If the length of an earth tube surpasses the effective length, the air temperature is always equal to the ambient soil temperature, and cannot be cooled down further. In summer the portion of an earth tube beyond the effective length does not contribute to cooling down the intake air, but producing more friction and fan power loss that decreases the overall energy efficiency of the earth tube system.

FIGURE 7. Overall section area of the earth tube cooling system in Scheme 1 and Scheme 2 (Source: produced by the author).



For simplification, an individual earth tube is supposed to be a single straight circular duct with uniform section shape, horizontally embedded in soil underground. The cooling effect of the intake air can be calculated using Newton's Law of Cooling as (8).

$$q = h_s A_s \left(T_m - T_s\right) \tag{8}$$

Here q is the heat flow rate between the intake air and its ambient environment (unit: W). h_s is the average heat transfer coefficient (unit: W/m^{2}K). A_s is the heat transfer surface area, which is the interior surface area of the earth tube (unit: m^2). T_m is the temperature of the main airflow, which is close to the average temperature of the whole air body (unit: K). In calculation the characteristic temperature is defined for air thermal property specification, and it is equal to the average value of the intake air temperature T_{ex} and the outlet air temperature T_{out}, namely $(T_{\text{ex}} + T_{\text{out}})/2$. T_s is the interior surface temperature of the earth tube (unit: K).

Set the effective length as L_e, so the heat transfer time corresponding to the effective length is L_e/μ. The temperature variation of intake air due to the heat transfer q within the time is presented in the equation (9).

$$h_s A_s \left(T_m - T_s\right)\frac{L_e}{u} = C_p \rho A_0 L_e \left(T_{\text{ex}} - T_m\right) \tag{9}$$

Here A_0 is the section area of an earth tube (unit: m^2), which is equal to the overall section area A_{all} divided by the number of the tubes N. The diameter of a circular tube is D (unit: m^2). D_h is the hydraulic diameter of the tube (unit: m), which is equal to D for a circular tube. Based upon the above settings, the effective length L_e is deduced as (10):

$$L_e = \frac{u C_p \rho D_h \left(T_{\text{ex}} - T_m\right)}{4 h_s \left(T_m - T_s\right)} \tag{10}$$

Therefore, if the average heat transfer coefficient h_s is known, the effective length L_e can be calculated. H_s can be derived from the Nusselt number N_u, which is the ratio of convective to conductive heat transfer across the boundary. According to the definition of N_u, heat transfer coefficient h_s is related with N_u as (11):

$$N_u = \frac{h_s D}{\lambda} \tag{11}$$

For the fully developed laminar flow in a circular tube with uniform surface temperature, N_u is a constant as (12) (Incropera, and DeWitt, 2002). Under this condition, Reynolds number R_e is less than 2000.

$$N_u = 3.66 \quad \left(if\ R_e \le 2000\right) \tag{12}$$

For turbulent flows, there is the Gnielinski equation. It is an empirical correlation for convective heat transfer calculation in tubes (Incropera, and DeWitt, 2007).

$$N_u = \frac{(f/8)\left(R_e - 1000\right)P_r}{1 + 12.7(f/8)^{1/2}\left(P_r^{2/3} - 1\right)} \tag{13}$$

Here λ is the thermal conductivity of the stagnant fluid (unit: W/mK). f is the Darcy friction factor (dimensionless) which is defined for the calculation of friction loss of fluid flow in tubes and channels. R_e is the Reynolds number (dimensionless), which is used to predict the flow type. P_r is Prandtl number (dimensionless), which is the ratio of momentum diffusivity to thermal diffusivity. The Gnielinski equation is valid when $0.5 \le P_r \le 2000$ and $3000 \le R_e \le 5 \times 10^6$ is satisfied.

For laminar flow in a circular tube, the Darcy friction factor f is given by:

$$f = \frac{64}{R_e} \quad \left(if\ R_e < 2000\right) \tag{14}$$

For turbulent flow in a circular tube, the Darcy friction factor can be obtained from the implicit Colebrook equation (The Engineering Toolbox, 2016), or from the explicit correlations such as Haaland equation (Haaland, 1983), Serghides' solution (Serghides, 1984) or Altshul-Tsal equation (Tsal, 1989). In the research, Colebrook equation (15) is only used for verification of the calculated Darcy friction factors. Since Serghides solution (18) and (19) is relatively accurate in contrast to the Altshul-Tsal equation (16) & (17), Serghides solution is applied to calculate the Darcy friction factor most often. The Altsual-Tsal equation is only used for crosschecking.

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{R_e\sqrt{f}}\right) \tag{15}$$

$$\begin{cases} f = f_0 & \left(\text{if } f_0 \ge 0.018\right) \\ f = 0.85f_0 + 0.0028 & \left(\text{if } f_0 < 0.018\right) \end{cases} \tag{16}$$

$$f_0 = 0.11\left(\frac{\varepsilon}{D_h} + \frac{68}{R_e}\right)^{0.25} \tag{17}$$

$$\begin{cases} \varphi_1 = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{12}{R_e}\right) \\ \varphi_2 = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51\varphi_1}{R_e}\right) \\ \varphi_3 = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51\varphi_2}{R_e}\right) \end{cases} \tag{18}$$

$$f = \left(\varphi_1 - \frac{(\varphi_2 - \varphi_1)^2}{\varphi_3 - 2\varphi_2 + \varphi_1} \right)^{-2} \tag{19}$$

In these equations, ε is the absolute roughness of the interior surface material of earth tubes (unit: m). It can be measured as the average height of surface rough elements. Absolute roughness values of some typical pipe materials listed in Table 2 are utilized in research (Neutrium, 2016).

Given the calculated Darcy friction factor f via Serghides solution, N_u, h_s, the effective length L_e can be determined using the above equations, and cooling capacity q_0 of a single earth tube can be calculated using (20) simultaneously.

$$q_0 = C_P \rho u \left(\frac{\pi}{4} D_h^2 \right) (T_{\text{in}} - T_{\text{out}}) \tag{20}$$

In a case study, it is assumed that the earth tube cooling system is made of reinforced concrete tubes. Special coatings are spray-painted on the interior surface of the tubes to reduce the risk of accumulating moisture content, bacteria and fungi. The interior diameter of the tube varies from 1.0m to 2.0m, matching the size of conventional ventilation fans. The individual section area, effective length and cooling capacity of different earth tubes are calculated and displayed in Figure 8 with the following assumption: the maximum hourly air temperature in July is 35.2°C, the corresponding soil temperature at 10 meter depth underground is 19.8°C, the air velocity in the earth tube is 3m/s, and the cooling setpoint for the tall building is 28°C.

In Figure 8, it can be perceived that with the earth tube diameter increasing, the effective length and the cooling capacity of the earth tube increase accordingly. The cooling capacity is irrelevant to the effective length since the earth tubes with different effective lengths can produce the same outlet air temperature that is equal to the ambient soil temperature. The roughness level of an earth tube is an influential factor for enhancing the earth-to-air heat transfer, shortening the effective length and saving construction materials and land use. The effective lengths of rough concrete earth tubes are 62% to 65% of the effective length of fine concrete earth tubes with the same section. It also implies that interior ribs and other structures for enhancing internal heat transfer contribute to minimizing the effective length, which is economically

TABLE 2. Absolute roughness values of some typical pipe materials.

Materials	Absolute roughness ε (m)
Drawn brass, copper, stainless steel	$1.5 \times 10^{-6} - 1 \times 10^{-5}$
Flexible rubber tube (wire reinforced)	$3 \times 10^{-4} - 4 \times 10^{-3}$
Galvanized steel	$2.5 \times 10^{-5} - 1.5 \times 10^{-4}$
Cast iron	$2.5 \times 10^{-4} - 1 \times 10^{-3}$
Concrete (fine/rough)	$2 \times 10^{-4} - 8 \times 10^{-4}/8 \times 10^{-4} - 3 \times 10^{-3}$

beneficial for an earth tube system because excavation usually accounts for the major cost of its construction.

4. CONCEPTUAL DESIGN SCHEMES OF THE EARTH TUBE COOLING SYSTEM

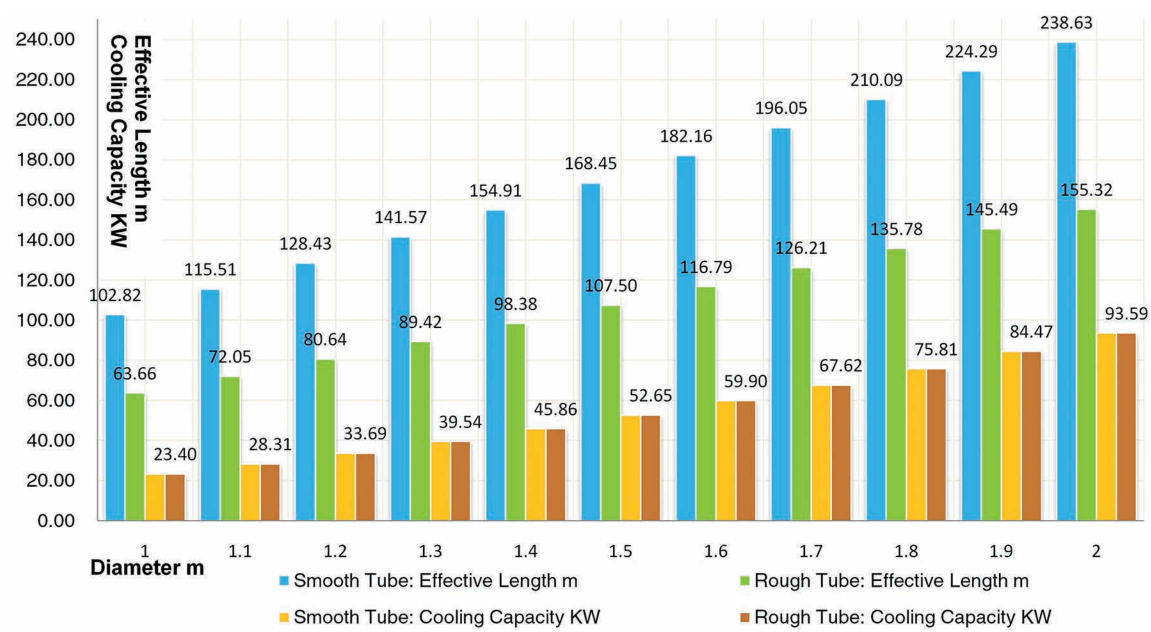
In the conceptual development, feasible geometric sizes and construction methods of the earth tube system for the tall building are studied for achieving the intended thermal performance and enhancing constructability and resource efficiency.

4.1 Geometric Size

Earth tubes achieve their thermal performance at the cost of underground spaces. In most cases, underground space is the major limitation to restrain the successful application of earth tubes. The space for an earth tube system is associated with its geometric sizing parameters such as section area, tube length and axial distance between adjacent tubes. Given the climate data and the soil temperature, the overall section area and the effective length can be determined according to the design cooling capacity. Assuming that the earth tubes are all circular tubes with the consideration of structural efficiency and construction convenience, the diameter and the number of tubes can be calculated from the overall section area explicitly. Therefore, axial distance between adjacent tubes is the only undetermined sizing parameter from the above calculation for the system geometric definition. The optimal axial distance of adjacent tubes is affected by the heat dissipation efficiency in soil, which is investigated via the detailed CFD simulation in the next section.

Multiple conceptual design schemes of the earth tube system for the tall building are developed, and one of the typical cases is presented in Figure 9. The system consists of 9 branches of

FIGURE 8. Effective length and cooling capacity of earth tubes with different diameters and roughness when the air velocity is 3m/s (Source: produced by the author).

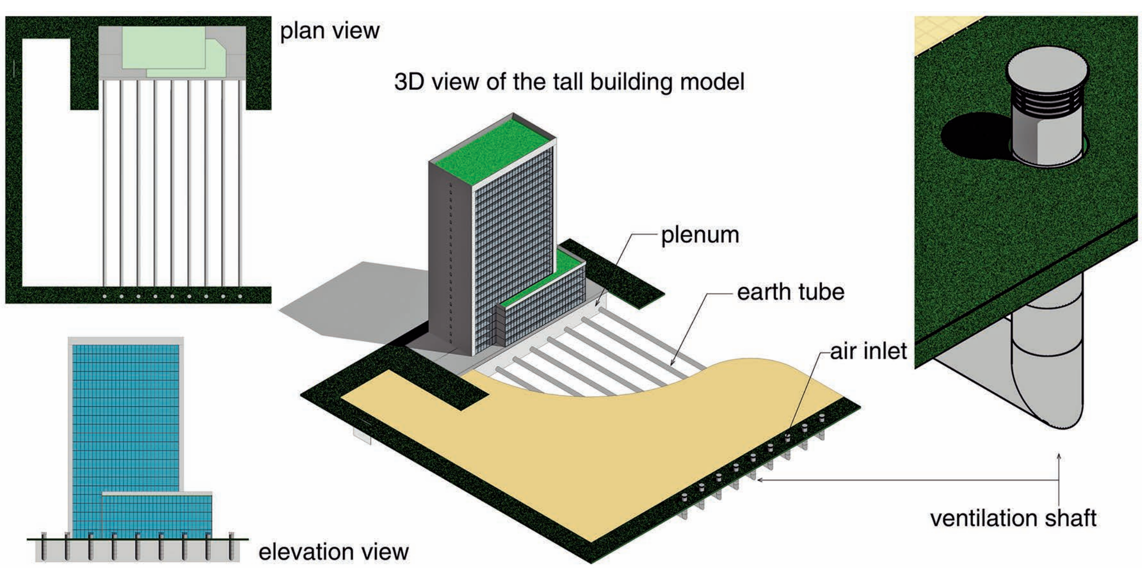


155m long rough concrete tubes. Each tube is connected to the fan powered ventilation shaft on one end, and the underground plenum in the basement on the other end. Diameters of the earth tubes are all 2m, and the axial distance between the adjacent tubes can be a specific distance between 2.2m and 20m, with the optimal one being around 4m for this type of earth tube system.

It should be mentioned that the earth tube cooling system with 9 tubes is only designed for meeting the required fresh air cooling load of the tall building when the *ACH* is 3, and the residual cooling load is handled by the central air conditioning system of the building. In this case, 45% of the total design cooling load can be met by the earth tube system. If the total design cooling load is expected to be balanced with 95% guarantee rate by this type of earth tube systems, 20 rough concrete tubes are required. Thus, the land coverage of the optimal earth tube system with 9 tubes and 20 tubes are 5,304m^2 and 12,168m^2 respectively. Both of the land areas are less than 28,000m^2, the area of the land within the zoning boundary available for the earth tube system. The land coverage of the earth tube systems are 13.8% to 31.7% of the overall conditioned floor area of the tall building.

Assume that the conditioned floor area of a tall building is equal to its total floor area, and the underground space of the land of a building can completely be used for an earth tube cooling system. According to the above case studies, for tall buildings in hot summer and cold winter climate zones with Floor Area Ratio greater than 7, it becomes more difficult to use the earth tube cooling system to meet the required fresh air cooling load if the *ACH* is 3. For tall buildings with Floor Area Ratio near or less than 3, it becomes much easier to use the earth tube cooling system to deal with the total cooling load of a tall building. In the China construction market, Floor Area Ratios for tall building projects are usually greater than 2, for super tall building projects it is usually greater than 6. Therefore, utilizing the earth tube cooling systems to handle the cooling load of a tall building in hot summer and cold winter climate zones is theoretically feasible in terms of underground space requirement.

FIGURE 9. One of conceptual design cases of the earth tube cooling system with 9 concrete tubes for the tall building (Source: produced by the author).



4.2 Construction Method

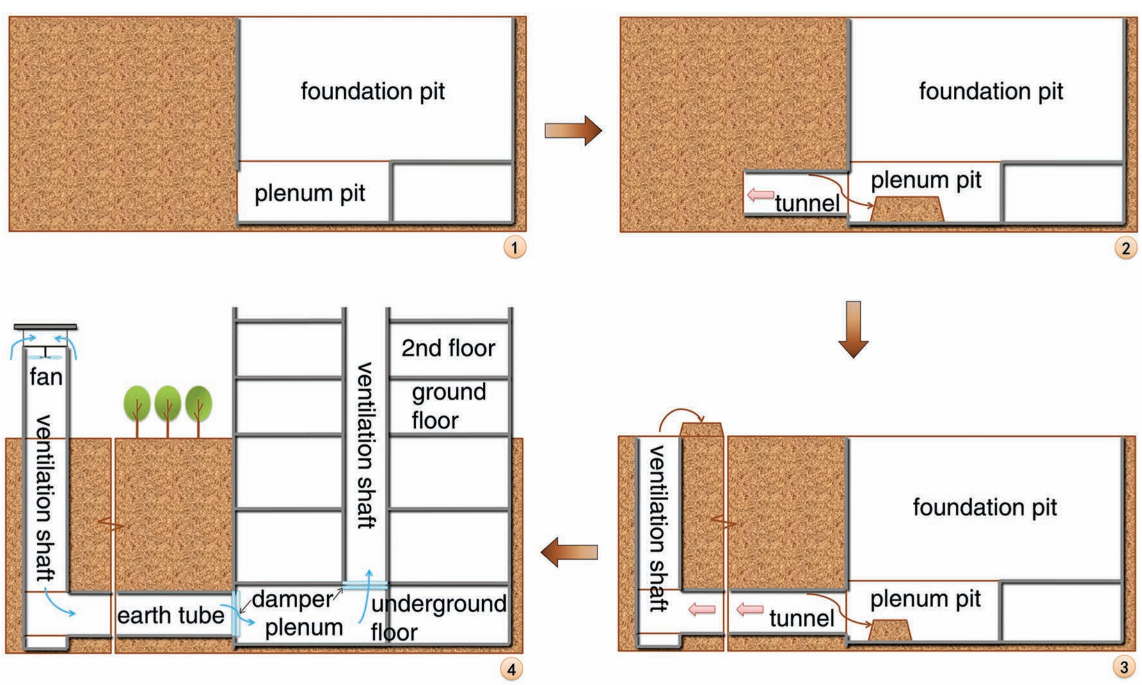
In order to avoid the massive excavation, the tunnel construction method is going to be applied for large-scale earth tube systems, rather than the conventional excavation-and-backfill construction method for small ones. The general sequence of the tunnel construction method for the earth tube system is illustrated in Figure 10. It begins with the plenum pit excavation, forming the wall for the operation side of the tunnel construction. Then suitable tunnel construction means can be applied, for example, drilling, shield driving, and pipe jacking and so on.

The tunnels can be constructed from the plenum room and the rooms at the bottom of the ventilation shafts concurrently, and be joined together in the middle for improving the overall construction efficiency. The earth tube system can be built in conjunction with the basement floors of the tall building, which also enhances constructability and efficiency significantly. Extra earth tubes can be added in a renovation project if there are enough construction spaces, and the excavated soil and mud can be removed from the basement, which is more flexible than the conventional construction means for earth tubes. Based on the excavated soil calculation of many earth tube system plans, it shows that the excavated soil due to the tunnel construction is about 6% to 8% of the soil excavated in the excavation-and-backfill construction for the similar earth tube systems. It clearly demonstrates the economic advantage of the tunnel construction method for large-scale earth tube systems.

5. CFD SIMULATION OF THE EARTH TUBE COOLING SYSTEM FOR PERFORMANCE VERIFICATION

CFD simulations of the cooling effect of the earth tube systems with different diameters, lengths and axial distances between adjacent tubes were performed in the research. The purpose of the

FIGURE 10. General sequence of the tunnel construction method for the earth tube system of the tall building (Source: produced by the author).



simulation is to verify the above calculation results, and obtain the relationship between the geometric sizing parameters and the cooling effect. For simplification, only the air volumes of earth tubes were modeled, and tube walls combined with the surrounding soil function as a whole.

5.1 Earth Tubes with Different Diameters and Lengths

In one scenario, there are 39 earth tube models with 2m diameter circular sections and different lengths from 50m to 240m modeled for fluid flow and heat transfer simulation; in another scenario, 13 earth tube models with 1m diameter circular sections and different lengths from 50m to 110m were created under the same condition. In these models, the inlet air temperature is set to the maximum hourly air temperature in summer: 35.2°C. The corresponding soil temperature during the same period at 10m depth underground is 19.8°C, which approximates the interior surface temperature of the earth tubes. The air velocity in the earth tubes is 3m/s, the average air velocity produced by the ventilation fans.

Simulated temperature profiles of the earth tubes with the circular sections of 2m diameter are displayed in Figure 11, and the corresponding results of the earth tubes with 1m diameter circular sections are displayed in Figure 12. It can be observed that the air temperature along the earth tubes drops nonlinearly, more temperature drop per unit length occurs near the air inlet, and gradually decreases.

FIGURE 11. Temperature profiles of the earth tubes with 2m diameter and various lengths from 50m to 240m (Source: produced by the author).

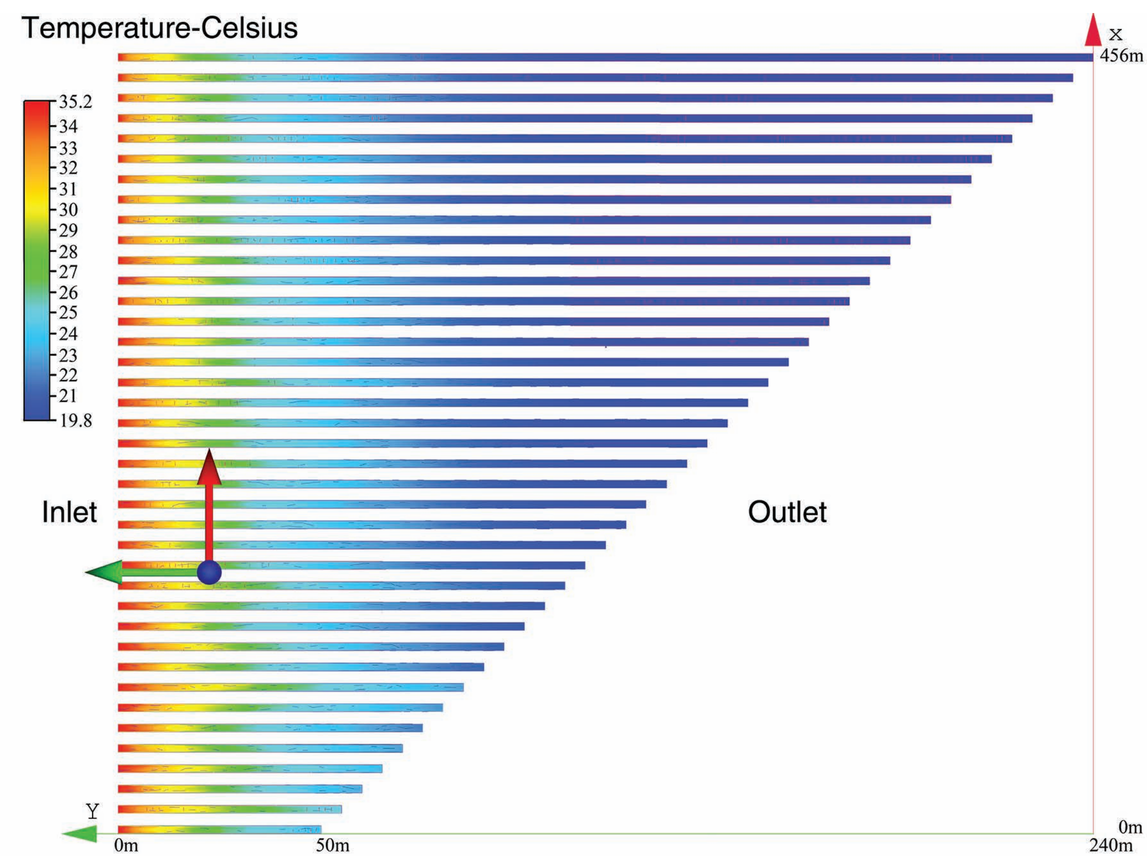
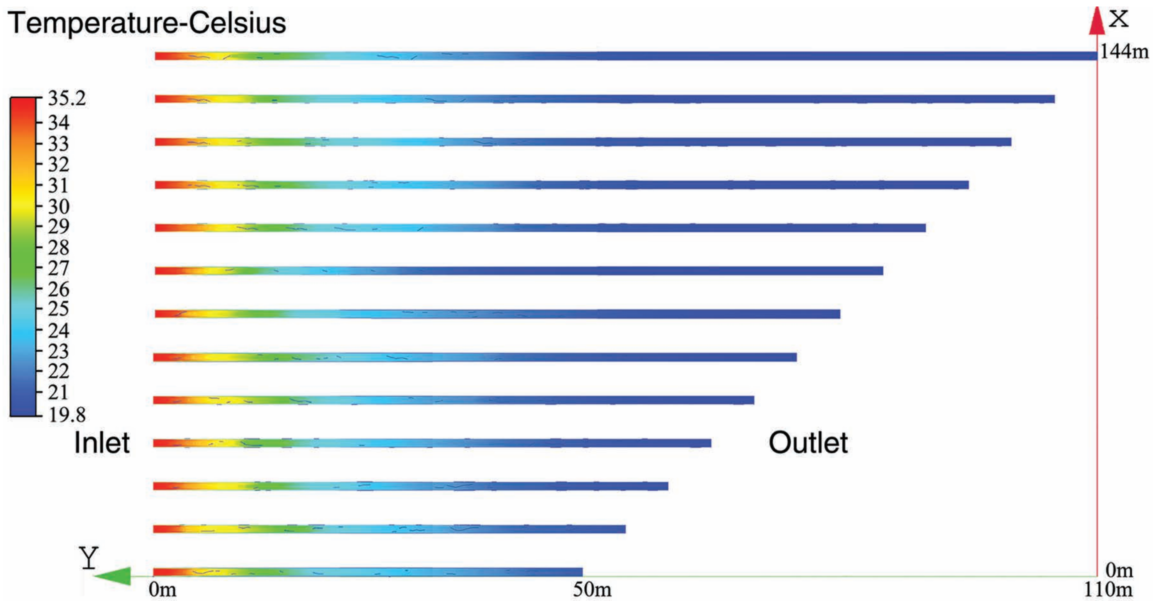


FIGURE 12. Temperature profiles of the earth tubes with 1m diameter and various lengths from 50m to 110m (Source: produced by the author).



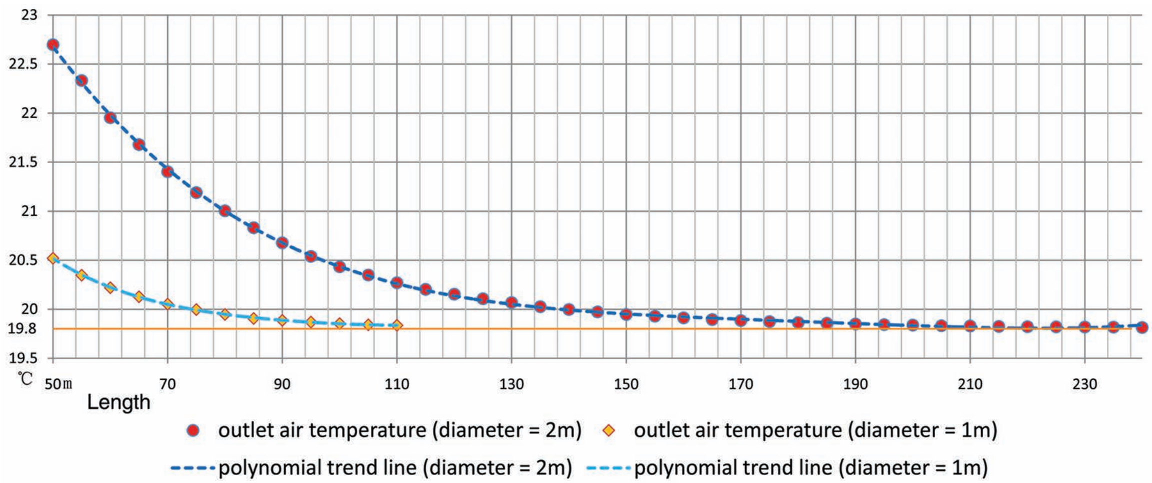
The average integral outlet air temperature for all earth tubes with the same diameter and different lengths is also calculated based upon the CFD simulation results and plotted in Figure 13. This indicates that when the diameter of the earth tube is 2m, and the length approaches 240m, the outlet air temperature is close to 19.8°C, the ambient soil temperature. When the diameter of the earth tube is 1m, and the length increases to 105m, the outlet air temperature is also close to 19.8°C. The similar relationship between the outlet air cooling capacity and the earth tube length can also be perceived in Figure 8. For example, In Figure 8 it shows that for the fine earth tubes with 2m diameter circular sections, the effective length is 238.63m, close to the simulation result 240m with a difference of 0.57%. When the diameter of the fine earth tubes is 1m, the effective length is 102.82m, close to the simulation result 105m with a difference of 2.08%. In the CFD simulations, absolute roughness heights were set to default at 0m, which means fine tubes. This reveals that the similar cooling effect of the earth tubes can be predicted from both the simplified calculation and the CFD simulation. In other words, the above analytical method for calculating the overall section area and the effective length of an earth tube system can be verified by the CFD simulation results.

In Figure 13, the trend lines of the outlet air temperature of the earth tube models imply that the cooling capacity variation per unit length of the earth tubes decrease with the increasing length. For example, if the diameter of the earth tube is 2m, the temperature drops from 22.7°C to 21.4°C when the length increases from 50m to 70m, while the corresponding temperature drops from 19.82°C to 19.81°C when the length increases from 220m to 240m. Consequently, there is a cost effective length for an earth tube, beyond which increasing length becomes uneconomical for cooling.

5.2 Earth Tube Systems with Different Axial Distances between Adjacent Tubes

Full-scale models of the earth tube systems with different axial distances between adjacent tubes were generated for airflow and heat transfer simulation. The same material properties,

FIGURE 13. Outlet air temperatures of the earth tubes with 2m and 1m diameters decrease with the increasing length (Source: produced by the author).



boundary conditions and initial settings were defined in these models for checking the cooling capacity variation, which is indicated by the outlet air temperature variation, due to the axial distance change.

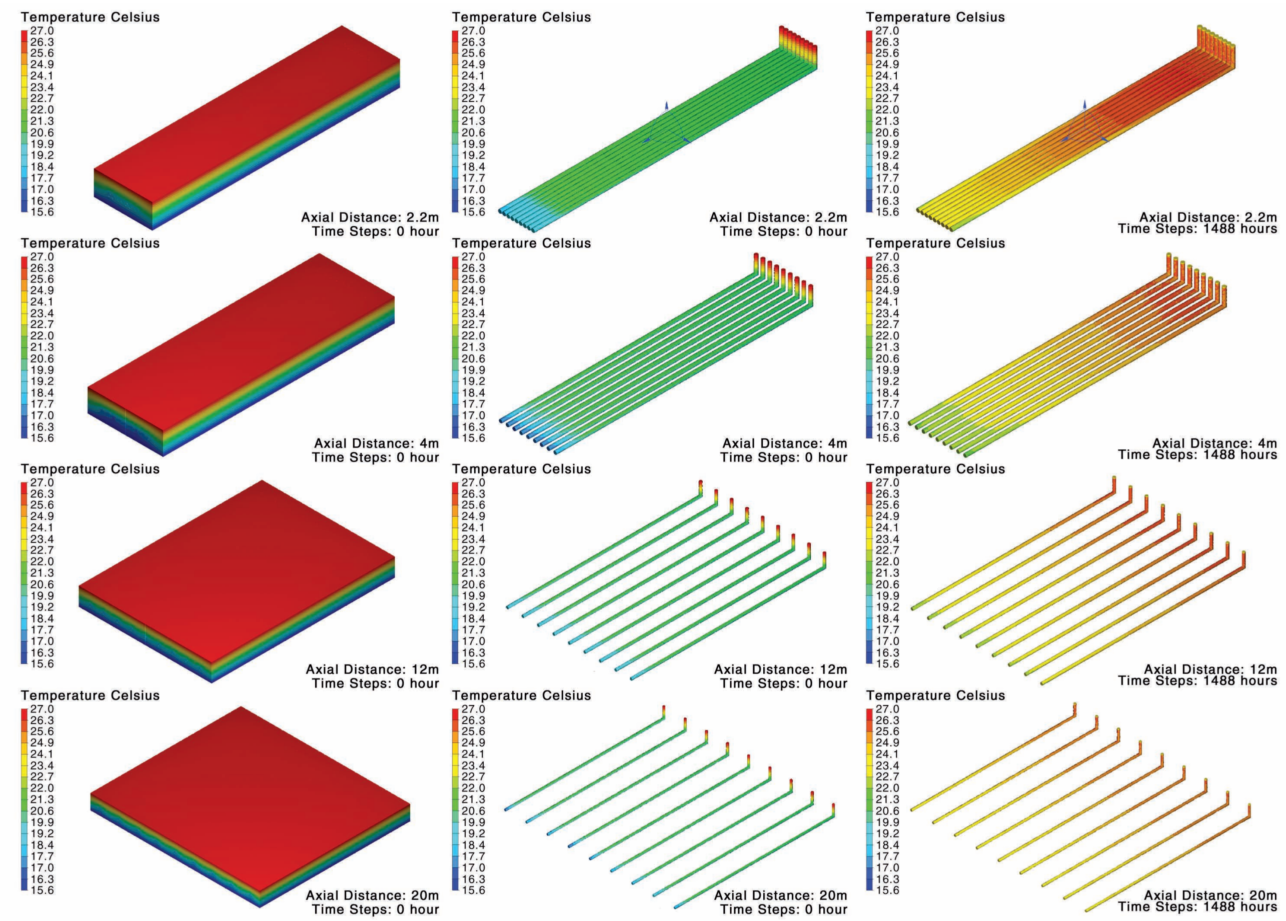
The earth tube systems were modeled according to the diameters and the corresponding effective lengths in Figure 8. Thermal properties of the wet soil were acquired from published documents (Hamdhan, Barry, 2010): bulk density is 1730Kg/m^3, thermal conductivity is 1.52W/mK, and specific heat is 2362J/KgK.

The earth tubes are embedded in the soil layer above the depth of constant temperature, which is equal to the annual average air temperature, 15.6°C. The temperature of the top surface of the soil layer approximates the daily average air temperature in summer, which is about 27°C. Thus, the undisturbed vertical soil boundary has a linear temperature profile from 27°C to 15.6°C. It is assumed that the ventilation fans of the earth tube systems start to operate at the beginning of July, and continue to run throughout July and August, the two typical summer months. The inlet air temperature adopts the local hourly dry-bulb air temperature from the weather data file, which is presented in Figure 3. The simulation run period is from July 1 to August 31, overall 1,488 hours in summer.

The initial undisturbed vertical temperature distribution across the soil layer with the earth tubes was achieved after a steady state simulation with the assumption that the ventilation fans were not in the operation state, namely the inlet airflow velocity was 0m/s. Then the transient simulation model of the earth tube system was activated with the above boundary conditions and initial settings except that the ventilation fans started to run, and the inlet airflow velocity was set to 3m/s, the average airflow speed in the earth tubes. Temperature, velocity and heat flux data were reported from the transient simulation model at hourly time steps for analysis.

The temperature distributions of four typical earth tube systems embedded in soil at the start time step (time step: 0 hour) and the end time step (time step: 1,488 hours) in the transient simulations are displayed in Figure 14. The earth tube systems consist of 9 tubes with 2m diameter circular sections, and the 2.2m, 4m, 12m and 20m axial distances between adjacent tubes respectively. It shows that before the running of the ventilation fans, there is stagnant

FIGURE 14. The temperature distributions of the four earth tube systems embedded in soil at the start time step and the end time step of the transient simulation. The axial distances between adjacent tubes are 2.2m, 4m, 12m and 20m respectively (Source: produced by the author).

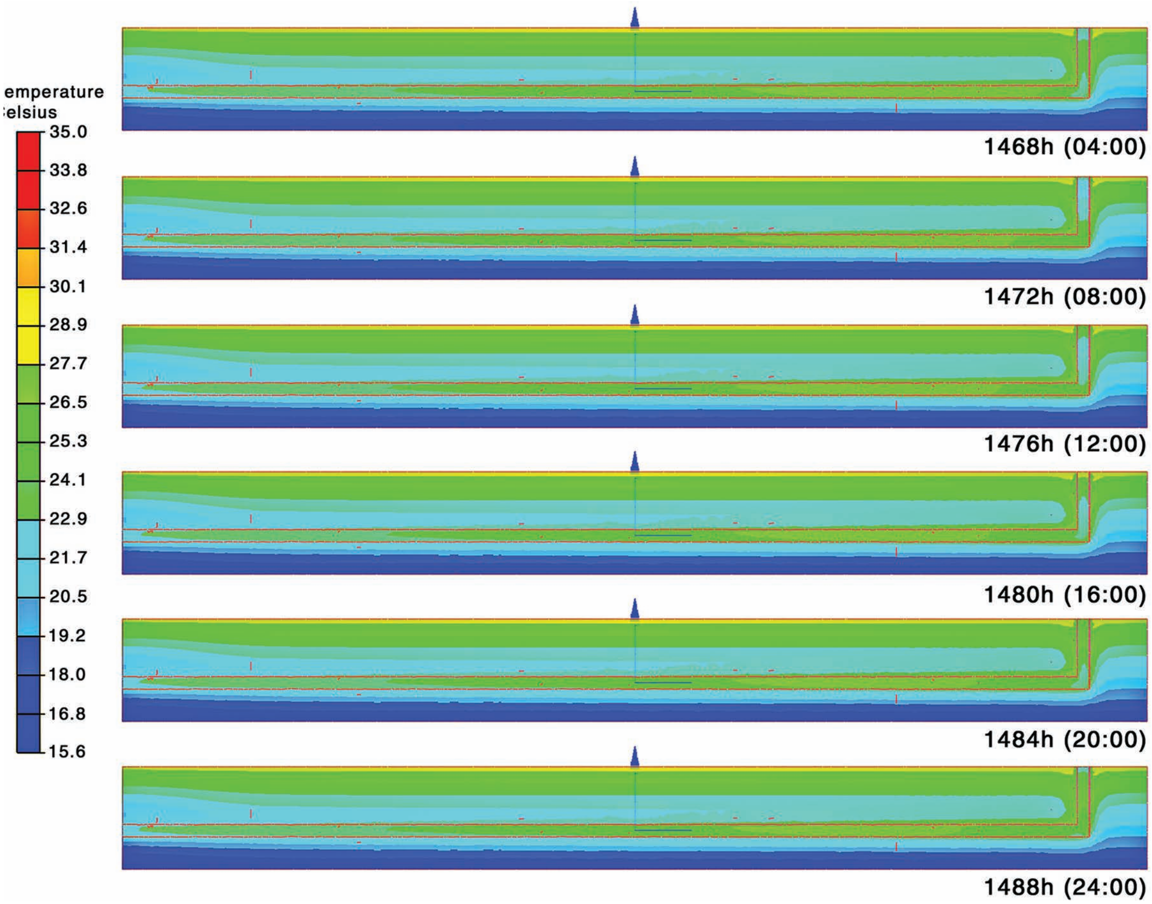


air in the earth tubes with the temperature fields similar to that of the surrounding soil. After 1,488 operation hours, the airflows in the earth tubes have higher temperatures compared with the initial status due to the transferred heat from the outdoor air and the accumulated heat in the surrounding soil.

In Figure 15 diurnal temperature variations of the earth tube systems in the transient simulation is demonstrated by the longitudinal section temperature profile changes from the time step 1,468 hours to the time step 1,488 hours (axial distance: 4m). A distinct temperature gradient impulse occurs near the inlet of the earth tube and is attenuated gradually along the tube.

The temperature distributions of the earth tube systems with different axial distances between adjacent tubes at the start time step and the end time step of the transient simulation can also be seen from the longitudinal sections of the four earth tube systems in Figure 16. The four earth tube systems have similar temperature profiles at the beginning of July. After 1,488 hours of operation, the temperature profiles of them are different, and the system with 2.2m axial distance between adjacent tubes tends to produce a more distinctive temperature gradient along the earth tube because of the additional restraints of lateral heat dissipation in the surrounding soil. However, the exported data show that the average air temperatures of the earth

FIGURE 15. Variations of the longitudinal section temperature profiles of the earth tube system embedded in soil from the time step 1,468 hours to the time step 1,488 hours (axial distance: 4m). (Source: produced by the author).



tube systems with 2.2m, 4m, 12m and 20m axial distances between adjacent tubes at the start time step are 20.2°C, 20.1°C, 20.1°C and 20.2°C, respectively, while the average temperatures of them at the end time step are 25.0°C, 24.3°C, 24.4°C, 24.5°C, respectively.

This implies that dense layouts of earth tubes can impede heat dissipation in soil, but larger axial distances between adjacent tubes may not always result in more effective heat dissipation in soil. The increased thermal resistance and thermal mass due to the larger soil volumes between the adjacent tubes may restrain the heat transfer towards the subsoil layer of constant temperature. In Figure 17, the transversal temperature profiles of the outlet surfaces of the four earth tube systems with different axial distances between adjacent tubes at the time step 1,488 hours are displayed. It implies that large gaps between adjacent tubes cannot always generate more cooling effect.

The outlet air temperatures of all the individual earth tubes, as well as the average outlet air temperatures of the earth tube systems, are displayed in Figure 18. The temperatures of the outlet air from the earth tube systems increase gradually due to the accumulated heat in soil. Nonetheless, the average outlet air temperature of the earth tube system with 4m axial distance between adjacent tubes varies from 17.3°C to 22.4°C, while the average outlet air temperature of

FIGURE 16. The temperature distributions on the longitudinal sections of the four earth tube systems embedded in soil at the start time step and the end time step of the transient simulation. (Source: produced by the author).

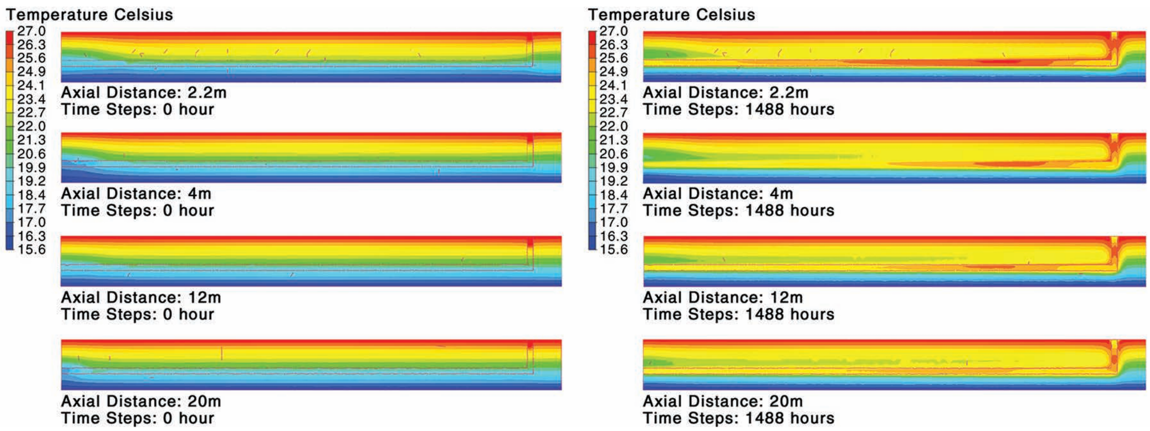
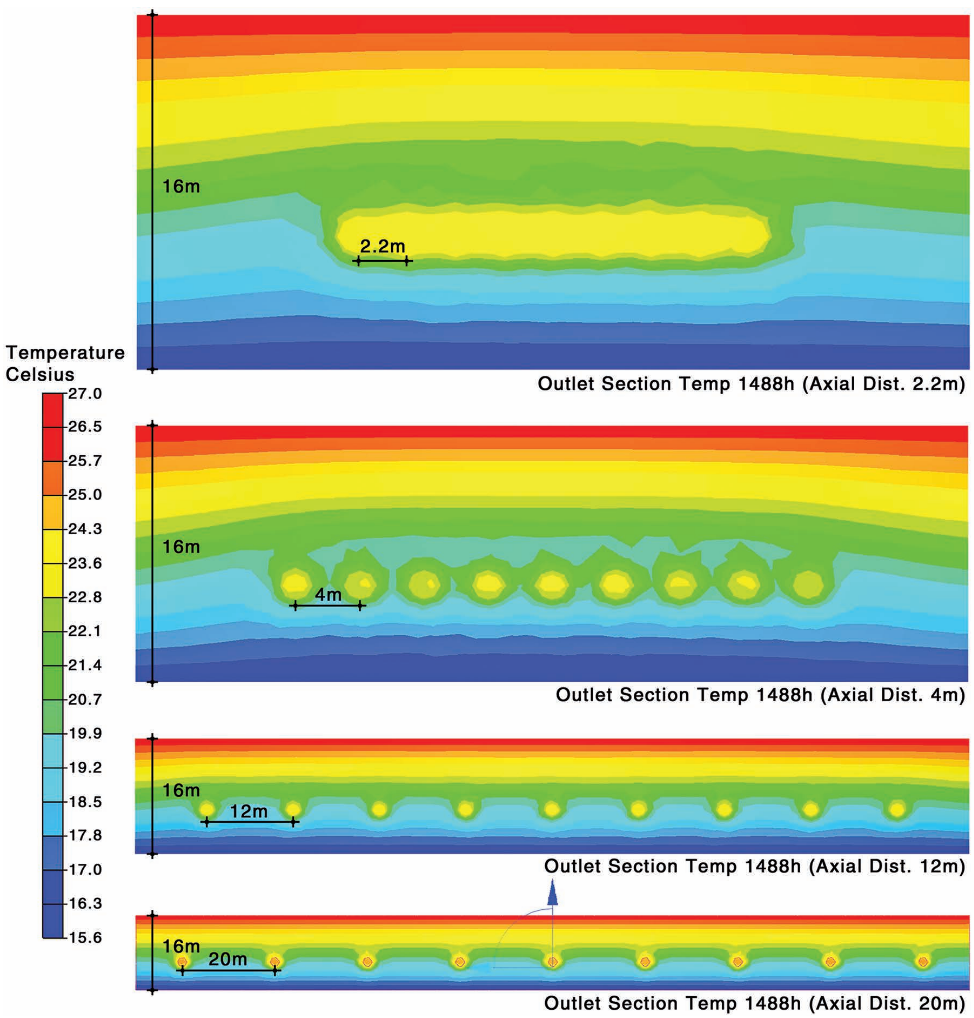


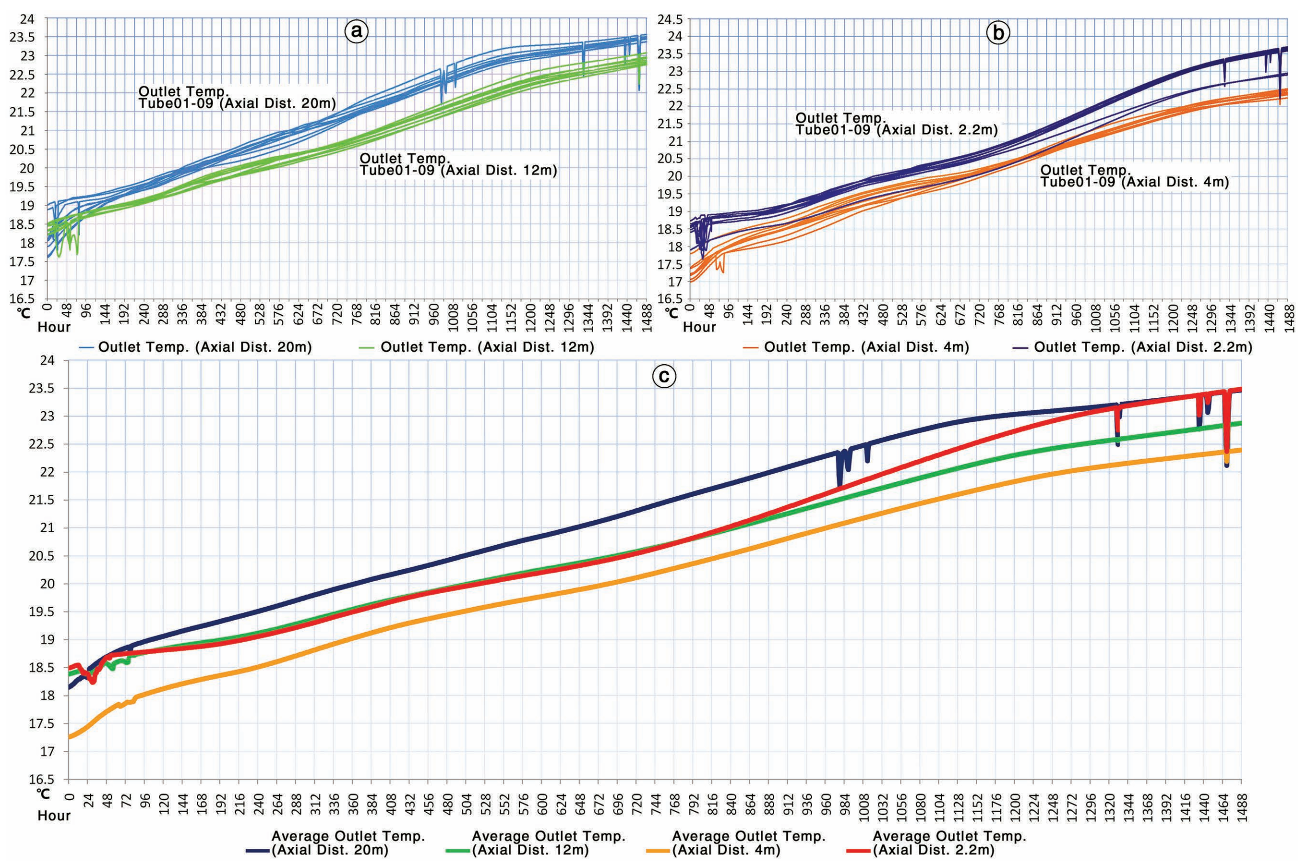
FIGURE 17. Transversal temperature profiles of the outlet surfaces of the four earth tube systems embedded in soil at the time step 1,488 hours. (Source: produced by the author).



the system related with 20m axial distance varies from 18.2°C to 23.5°C. There is a temperature difference around 1°C. These simulation results still imply an acceptable outlet air temperature produced by the earth tubes for cooling the tall building at the end of August since the cooling setpoint is 28°C. It also manifests that the earth tube system with the axial distance around 4m can produce a little better cooling effect due to the relatively lower outlet air temperature in summer.

More simulation results from other case studies also reveal that the optimum axial distance between adjacent tubes of an earth tube system located at 10m depth underground with horizontal layout is around 2 times of the tube diameter. Usually the axial distance change of an earth tube system can affect the outlet air temperature a little, from 0°C to 1°C or so. For the same earth tube systems, the outlet air temperature obtained via the CFD simulation with the consideration of cooling effect degradation in summer is close to the calculated outlet air temperature at the beginning of July, and 2.5°C to 3.5°C higher than the calculated temperature at the end of August. The cooling capacities of the earth tubes at the end of August can degrade to 57% to 70% of the original calculated cooling capacities.

FIGURE 18. Outlet air temperature variations of the earth tube systems embedded in soil throughout July and August. Outlet air temperature variations of the individual earth tubes (axial distance: 20m, 12m for Figure 18a; axial distance: 4m, 2.2m for Figure 18b). Figure 18c: The average outlet air temperature variations of the earth tube systems with 9 tubes (axial distance: 20m, 12m, 4m, 2.2m) (Source: produced by the author).



6. CONCLUSIONS

Earth tube cooling technology is a climate-dependent energy efficiency measure for sustainable buildings. The effectiveness of earth tube cooling needs to be verified for tall buildings since the massive cooling load generated within a tall building requires a great deal of cooled air from a large-scale earth tube system, which occupies a massive underground space. Through heat transfer calculation and CFD simulation, it is concluded that earth tube cooling systems are technically feasible for some tall buildings in hot summer and cold winter climate zones as long as the following design guidelines are followed.

Firstly, as the earth tube systems for small buildings, the earth tube cooling systems for tall buildings are also climate-dependent. In summer, the more temperature difference between the underground soil and the outdoor air, the better for earth tube cooling systems to achieve high performance.

Secondly, earth tube cooling systems of a tall building are heavily dependent on underground spaces, which are associated with the geometric sizing parameters such as the overall section area, the effective length and the axial distance between adjacent tubes. For tall buildings with a Floor Area Ratio no more than 7, it is feasible to utilize the earth tube system to deal with the fresh air cooling load in hot summer and cold winter climate zones. If the Floor Area Ratio of a tall building is no more than 3, it is even possible to meet the total cooling load with 95% guarantee rate via the earth tube cooling system. Numerous case studies show that the land coverage area of an earth tube cooling system for a tall building in hot summer and cold winter climate zones is usually less than the overall conditioned floor area of the building. Usually the land coverage area for an earth tube system is 30% to 50% of the conditioned floor area of the connected tall building.

In order to avoid massive excavation for the earth tube cooling system of a tall building, it is advisable to apply the tunnel construction method, rather than the conventional excavation-and-backfill construction method. Otherwise, the economic benefit from energy saving may diminish due to the inefficient massive excavation. Earth tubes with simple straight routes are better than the ones with curvature forms because they are easier to drill.

It is also beneficial to increase the interior surface friction of earth tubes for enhancing airflow heat exchange and shortening their effective lengths. The measures include but are not limited to increasing the roughness of the interior surface material, forming interior ribs. The effective length of the rough concrete earth tubes can reduce from 62% to 65% of the effective length of the fine concrete earth tubes. The reduced effective length of an earth tube system results in a compact layout, which is advantageous for tall buildings within limited construction sites.

It should be noted that an earth tube system with a horizontal layout and suitable gaps between adjacent tubes can dissipate heat more efficiently. However, increasing gaps cannot always generate better cooling performance because of the increased thermal resistance and thermal mass of the soil between earth tubes, which may decrease the efficiency of heat dissipation towards the subsoil layer of constant temperature. Therefore, an optimum axial distance between adjacent tubes exists for enhancing the cooling effect of outlet air. For example, the optimum axial distance between adjacent tubes of an earth tube system embedded in soil is 10m depth underground, and in form of the horizontal layout, is around 2 times of the tube diameter. Usually, the axial distance change of an earth tube system can affect the outlet air temperature a little, from 0°C to 1°C or so.

Finally, it is crucial to make the synergy of an earth tube system and other energy efficiency measures in a tall building for the integrated performance improvement. Earth tube cooling systems can function effectively in summer if the cooling load has been reduced to an achievable level using other energy efficiency measures except earth tubes, such as the application of high performance building envelopes, solar shading devices, cool roofs and adopting the suitable but relatively higher cooling setpoint temperature.

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