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Feasibility study on applications of solar chimney and earth tube systems for BEAM/LEED assessment

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Abstract

Building Environment Assessment Method (BEAM) and Leadership in Energy and Environmental Design (LEED) aim to promote better environment performance of buildings in their life time. This study explores innovative solutions to achieve key requirement of Energy Use (EU) and Indoor Environmental Quality (IEQ) from BEAM/LEED assessments by Solar Chimney (SC) or Earth Tube (ET). EnergyPlus is used to perform the simulation of building's ventilation and energy usage under the typical Hong Kong's weather data. It's found that the SC performance is affected by the building's dimension and orientation and is also determined by solar availability and absorber surface temperature. In the most simulation cases, SC provided sufficient natural ventilation, but it also increased cooling load to the space when ambient temperature was higher than indoor. The ET performance was considerably affected by the pipe dimension and the buried depth. It's found that a single ET could decrease cooling load to the space in the summer design day 'July 21' in Hong Kong, but it couldn't provide sufficient outdoor fresh air. The result also

demonstrated that both SC and ET systems had capabilities to help achieve on-site renewable energy requirements from BEAM/LEED due to their energy saving capacities on ventilation and thermal comfort. Since SC had higher capability to provide sufficient ventilation, SC could more significantly contribute on the sections pertinent to building ventilation. Since ET had higher capability to save cooling energy, ET could more significantly contribute on the sections pertinent to energy saving in BEAM/LEED assessments, respectively.

Keywords: Solar chimney; Earth tube; LEED; BEAM; Energy use; Indoor Environmental Quality (IEQ)

1. Introduction

The Hong Kong Building Environmental Assessment Method (HK-BEAM) and Leadership in Energy and Environmental Design (LEED) developed by United States Green Building Council (USGBC) aim to improve environment performance of buildings in their life time ^[1, 2]. In HK-BEAM or LEED assessments, Energy Use (EU) and Indoor Environmental Quality (IEQ) are two essential sections. The EU section refers to the assessment regarding to energy conservation and efficiency of building service systems ^[2], while the IEQ section focuses on the assessment of indoor environment quality such as Indoor Air Quality (IAQ) and day-lighting.^[1] In this research, a feasibility study was performed in order to evaluate whether the applications of the green building systems ‘Solar Chimney (SC)’ and ‘Earth Tube (ET)’ could help meet some assessment requirement from EU and IEQ sections in BEAM/LEED.

1.1 Solar Chimney (SC)

SC is a promising strategy to enhance buoyancy driven ventilation by solar gains. SC

performance is highly affected by design parameters including absorber dimension, apertures size and gap width. (Fig. 1) Basically, equal and larger inlet/outlet apertures could provide higher airflow rate. ^[3, 4] A wider air gap of erected SC contributed to higher airflow and more significantly affected SC than the aperture size. ^[4] The optimal gap-to-height ratio is 0.5 for maximizing airflow rate.^[5] Compared with erected SC, inclined SC could capture more incident solar irradiation. Various inclined angles resulted in the change of stack pressure and the amount of solar irradiation being captured by absorber. ^[5] Moreover, airflow by inclined SC was almost independent on wind velocity. Although wind could cool down SC, airflow induced by wind could compensate the lost airflow due to the thermal loss. ^[7] The optimal chimney inclination angle was 60° for the maximum ventilation rate based on numerical model. ^[8]

The temperature distribution and airflow velocity inside of SC channel are critical to SC's performance. Normally, the temperature of incoming air, glass cover and absorber increase with incident solar radiation.^[9] Absorber temperature was higher than glass cover and incoming air between gap with a width of 0.1 m and 0.3 m.^[9] Secondly, air temperature distribution in SC channel was determined by heat transfer efficiency of absorber, especially in a narrow channel.^[9] The temperature was generally higher near the absorber surface, but it was close to the ambient temperature at the gap center when the a ventilation height was smaller than 4 m. ^[5]

Air velocity was also highly uneven across SC gap. The air velocity near absorber surface was about 2~5 times higher than gap center, but the inclined SC could reduce airflow velocity variances in SC channel. ^[10] Additionally, it was noted that a transition from laminar to turbulent airflow started from ventilation height of 3 m. ^[6]

1.2 Earth Tube (ET)

An earth tube system refers to a system uses buried pipes to deliver cold outdoor air into a building with advantages of 1) low operation energy required, 2) less fossil fuel used, 3) no requirement of refrigerants, 4) air as working fluid, and 5) simple design and easy maintenance.^[11] (Fig. 2) ET ~~thermal~~ performance is much dependent on soil surface condition, pipe length and radius. Compared with short grass covered surface, bare soil surface was able to increase system's heating capacity.^[12] Ghosal et al. also noted that overall performance of ET under bare surface was more satisfactory than glazed surface for year round use.^[13] Secondly, the study by Lee et al. showed that inlet air temperature decreased with length and increased with pipe radius.^[14] Although small radius gave better ET thermal performance, it caused larger pressure drop inside ET. Parallel layout for multiple pipes could help lower pressure drop and improve ET thermal performance.^[15]

Moreover, indoor thermal comfort could be achieved by ET without additional cooling/heating supply.^[16] Cooling load could be reduced by ET when ambient temperature was lower than indoor in hot summer. Conversely, heating load was reduced by ET when ambient temperature was higher than indoor in cold winter.^[14] Therefore, when ET was used to preheat/precool indoor air in conjunction with an air-conditioner, energy demand would be reduced for ~~living~~ thermal comfort.^[17] Furthermore, a coupled geothermal cooling system with ET and SC was feasible to provide cooling to the facility in nature without any electricity supply.^[18]

1.3 Research Objectives

From the literature review, it notes that the SC and ET are promising technologies for sustainable green building development. However, the applications of these technologies have not been yet, and also it is unknown whether the applications of the SC and ET can help achieve BEAM/LEED assessments. Therefore, this study

aims to evaluate the performance of the SC and ET, and then tests whether they can help meet the assessment requirement in EU and IEQ sections from BEAM/LEED.

2. System Modelling and Simulation

EnergyPlus collects a series of program modules to calculate energy required for thermal comfort. Heat balance on zone air is defined as: ^[19]

$$C_z \frac{\partial T_z}{\partial t} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_a - T_z) + \dot{Q}_{sys} \quad (1)$$

Where: $\sum_{i=1}^{N_{sl}} \dot{Q}_i$ is the sum of convective internal loads, $\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$ is the convective heat transfer from zone surfaces, $\dot{m}_{inf} C_p (T_a - T_z)$ is the heat transfer due to infiltration of outside air, $\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ refers to the heat transfer due to inter zone air mixing, \dot{Q}_{sys} is air system output, $C_z \frac{\partial T_z}{\partial t}$ is the energy stored in zone air, $C_z = \rho_{air} C_p C_T$

Under a steady-state, air capacitance is neglected, so system output can be simplified to ^[19]:

$$-\dot{Q}_{sys} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_a - T_z) \quad (2)$$

In this research, a test space was simulated at each time step of 15 minutes. Heat balance algorithm ‘Conduction Transfer Function (CTF)’ was employed to provide a sensible heat solution without considering the moisture storage or diffusion in construction elements.

2.1 Space Description

The test space with a size of 5 m wide, 8 m long and 3 m high was proposed as single unit from a high-rise building of Hong Kong, which initially faces north and locates at suburbs. (Table 1) Main building materials included concrete and insulator with relevant physical properties. Double glazed insulating glass was used for windows.

(Table 2) The model runs one-day simulation on a summer design day ‘July 21’ in Hong Kong. (Table 3) Designed air infiltration for the test space was 0.2 ACH.

2.2 Solar Chimney (SC) Modeling and Simulation

Output from SC is an enhanced airflow from natural ventilation. Discharge air temperature from SC is important to determine airflow rate, so temperature distribution of absorber, glass cover and flowing air within SC need be calculated at first based on the following thermal network. ^[9]

$$T_g: [S_1 A_g] + [h_{r_{wg}} A_w (T_w - T_g)] = [h_g A_g (T_g - T_f)] + [U_t A_g (T_g - T_a)] \quad (3)$$

$$T_f: [h_w A_w (T_w - T_f)] + [h_g A_g (T_g - T_f)] = \dot{q}'' A_w \quad (4)$$

$$T_w: [S_2 A_w] = [h_w A_w (T_w - T_f)] + [h_{r_{wg}} A_w (T_w - T_g)] + [U_b A_w (T_w - T_r)] \quad (5)$$

Subsequently, total airflow discharged from SC (m³/s), Q , can be evaluated from: ^[19]

$$Q = C_d A_0 \sqrt{\frac{2 \left(\frac{T_{fo} - T_r}{T_r} \right) g L}{(1 + A_r)^2}} \quad (6)$$

$$A_r = A_0 / A_i$$

Separated thermal zone must be created for SC simulation. Absorptive and insulated materials were used for SC structure. Initially, erected absorber wall was built as 1 m wide and cross sectional area of air channel was 0.3 m². (Table 4) SC is built on upper southern wall of the space unit, so we proposed most solar flux was directly distributed on absorber wall during simulation. (Fig. 3)

2.3 Earth Tube (ET) Modeling and Simulation

ET was modeled as two coupled heat transfer processes: 1) convection heat transfer between airflow in a pipe and pipe inner surface, 2) conduction heat transfer between pipe outer surface and surrounding soil environment ^[19].

Temperature of average soil surface (23 °C), amplitude of soil surface temperature (5.89 °C) and phase constant of soil surface temperature (2 days) were initialized to the system. Minimum/maximum zone temperatures were also initialized to avoid over-cooling/heating the space caused by ET system. During simulation, natural ventilation from ET did not require any fan power. Airflow rate via ET was affected by temperature differences between inside and outside environment. Designed maximum air mass flow rate of ET was preset as 0.08 m³/s. At initial condition, ET pipe was 60 m long and 0.1 m radius at 4 m deep underground. (Table 5)

3. Simulation Results and Discussion

3.1 Solar Chimney (SC)

SC's dimension, location elevation and facing directions were evaluated in this section. We analyzed three variables including chimney height, chimney width and gap width at first. The results are shown as following:

- Natural ventilation rate was rising as increased chimney height when chimney width (1 m) and gap width (0.3 m) kept constant (Fig. 4)
- Natural ventilation rate was rising as increased chimney width when chimney height (3 m) and gap width (0.3 m) kept constant (Fig. 5)
- Natural ventilation rate was rising as increased gap width when chimney height (3 m) and chimney width (2 m) kept constant (Fig. 6)

All three conditions indicated that a larger effective area of chimney channel speeded up convective heat transfer between absorber and inlet air. Most simulations provided sufficient ventilation in their working period above minimum ventilation requirement 0.3 L/s·m² for living/bedroom or office. ^[21] We also found that longer or wider

chimneys provided more service hours compared with others, but over-sized gap could cause unstable turbulent flow inside SC channel.

Secondly, there was no significant effect on ventilation rate at higher locations. (Fig. 7) but there was dramatic effect on ventilation rate at different directions. (Fig. 8) West direction gave SC the best ventilation performance compared with three others on the summer design day. Thus, solar availability and absorber surface temperature were key factors to determine SC performance.

Following a simulation on SC with a size of 3 m (H) \times 2 m (W) \times 0.3 m gap, we found that natural ventilation enhanced infiltration heat loss, resulting in a drop of ambient temperature from 35.8 °C to 33.5 °C (Fig. 9), but which does not meet thermal comfort requirement according to ASHRAE 55-2004. ^[22] On the other hand, the SC could increase cooling load for an air-conditioned space when outdoor temperature was higher than indoor A/C cooling set-point. To temporally turn off the SC for a certain period could avoid overheating the space in hot summer.

Last, power saving was also a matter of concern to use SC. Based on the simulation result, 0.096 kWh was required for a mechanical fan in 16 hours' operation (9:00 – 24:00) in order to reach the minimum ventilation rate at $0.3 \text{ L/s} \cdot \text{m}^2$ for the testing space. ^[22] 0.51 kWh was required for a mechanical fan in 16 hours' operation in order to reach the same ventilation rate as the SC. (Table 6) Therefore, a total of 93 kWh could be saved by the ventilation from SC in half-year operation. Compared with the high initial cost of SC, it may not be efficiency to use SC for building ventilation, economically.

3.2 Earth Tube (ET)

We analyzed three ET variables, including length, radius and buried depth in this section. The simulation results are shown as following.

- ET inlet temperature was falling as the increased pipe length when pipe radius (0.1 m) and buried depth (4 m) kept constant (Fig. 10)
- ET inlet temperature was falling as the increased buried depth when pipe length (60 m) and radius (0.1 m) kept constant (Fig. 11)
- ET inlet temperature was falling as the decreased radius when pipe length (60 m) and buried depth (4 m) kept constant (Fig. 12)

In summary, longer or smaller radius pipes enhanced convective heat transfer between pipe and surrounding soil, and deeper underground provided colder environment for ET. The findings also showed that ET performance couldn't be further improved as a pipe reached a certain maximum length.

Considered with both economic and performance factors, we finally simulated the ET system with 60 m long, 0.1 m radius and 4 m buried depth for the analysis of thermal comfort. As a result, the ET system provided 16.1 kW sensible cooling for the testing space to generate an average of ambient temperature at 30.5 °C against outdoor temperature at 30.1 °C, which meets thermal comfort requirement of ASHRAE 55 – 2004. ^[22] Meanwhile, it delivers outdoor air on an average of $0.013 \text{ L/s} \cdot \text{m}^2$, but which is much lower than minimum ventilation requirement at ' $0.3 \text{ L/s} \cdot \text{m}^2$ ' for living/bedroom and offices ^[21]. (Table 7) Therefore, it couldn't be considered as an acceptable ventilation system.

When the test space was air conditioned to maintain indoor temperature at 28 °C on the summer design day, it requires 18.75 kWh or 25.79 kWh cooling load with or without the ET, respectively. So, colder—~~infiltration~~ air delivered by ET can dramatically reduce cooling load for an air-conditioned space. (Table 8)

4. Feasibility Analysis

A feasibility study was performed to analyze whether applications of SC and ET could help meet assessment requirements of EU and IEQ sections in BEAM/LEED.

4.1 LEED Assessment

4.1.1 Energy and Atmosphere (EA)

EA Credit 1 ‘Optimize Energy Performance’ was created to promote energy efficiency and reduce the use of fossil fuels ^[1]. The number of credits (19 points in total) would be awarded, which depend on efficiency level of building energy use. ^[1]

As mentioned in the simulation result, the test space with SC spent more energy to maintain indoor temperature at 28 °C when the space was air-conditioned, and ventilation by SC only saved very small portion of total building energy consumption, so SC couldn’t help achieve credit requirement for ‘Optimize Energy Performance’.

However, ET system showed good cooling performance and provided acceptable thermal comfort for occupants without assistance by air conditioning in this research. Moreover, when the space maintained 28 °C in conjunction with an air conditioner, ET would help save 7.04 kWh on the summer design day, which is approx. 37.5% of total normal power consumption (25.7 kWh) for the test space. Thus, ET system had good capability to help meet credit requirement for ‘Optimize Energy Performance’.

EA Credit 2 ‘On-site renewable energy’ aims to encourage the implementation of on-site renewable energy so as to reduce environmental and economic impacts associated with fossil fuel use. ^[1] The number of credits (7 points in total) would be awarded, which depend on the percentage of applied renewable energy cost over total annual energy cost ^[1] (Table 9). Basically, both SC and ET could be considered as renewable energy systems. SC contributed on energy saving of building ventilation. ET contributed on energy saving for thermal comfort. According to data from Electrical and Mechanical Services Department of HKSAR, annual energy consumption for

private housing was 395 MJ/m². Thus, daily energy consumption for the test space of 40 m² net floor area was 15.6 kWh. In this research, SC saved 0.51 kWh for ventilation and ET saved 7.04 kWh for space cooling to maintain room temperature at 28 °C on the summer design day, respectively. Therefore, energy savings by SC and ET were approx. 3.3% and 45.6% of total daily energy consumption, respectively. Thus, both SC and ET have good capabilities to help meet credit requirement of ‘On-site Renewable Energy’.

4.1.2 Indoor Environmental Quality (IEQ)

IEQ Credit 2 ‘Increased Ventilation’ intends to provide additional outdoor air ventilation for improvement of indoor air quality (IAQ).^[1] This credit indicates that ventilation space needs comply with minimum requirements from ASHRAE Standard 62.1 (2007) section 4 to 7, and if space is naturally ventilated, it also needs comply with ASHRAE 62.1 (2007) paragraph 5.1.^[1] In this study, most SC simulations provided sufficient natural ventilation during daytime. The most optimal design of SC was 3 m high, 2 m wide and 0.3 m wide air gap, which provides on an average ventilation rate of $1.59 \text{ L/s} \cdot \text{m}^2$ from 9:00 to 24:00. This rate is approx. 5 times higher than minimum acceptable ventilation rate for living/bedrooms and offices ($0.3 \text{ L/s} \cdot \text{m}^2$).^[21] However, SC performance particularly depended on solar radiation availability and temperature on absorber surface, so ventilation by SC was halted at midnight. Under such situations, SC was better to be used in commercial buildings due to the high ventilation demand during daytime. On the other hand, the most optimal design of ET had 60 m long and 0.1 m radius pipe buried at 4 m deep underground, which could not provide enough ventilation for the testing space.^[21] Consequently, only SC had good capacity to help meet assessment requirement of ‘Increased Ventilation’.

4.2 BEAM Assessment

4.2.1 Energy Use (EU)

Similarly, EU credit 6 ‘Renewable Energy Systems’ intends to promote building energy consumption obtained from renewable energy sources. ^[2] The number of credits (5 points in total) would be awarded, which depends on the percentage of total building energy consumption used from renewable energy. ^[2] (Table 10) Since compared with EA Credit 2 from LEED, the entry level to award this BEAM credit is easier than EA Credit 2 from LEED, both SC and ET systems could help meet the assessment requirement of EU credit 6 ‘Renewable Energy Systems’.

EU credit 13 ‘Energy Efficient Building Layout’ ^[2] is used to enhance building energy efficiency through architectural design and planning. Five strategies are introduced from this credit: ^[2]

1. Built form and building orientation
2. Optimum spatial planning
3. Natural ventilation
4. External shading devices
5. Shading devices for major atrium façade windows or skylight

Since sufficient natural ventilation could be achieved by SC, it could help meet the third strategy as above.

4.2.2 Indoor Environmental Quality (IEQ)

IEQ 10 ‘Background Ventilation’ attempts to ensure that an occupied premise uses natural ventilation to provide a minimum of background ventilation for IAQ control. ^[2] One credit is awarded when adequate natural ventilation is applied. ^[2] IEQ 11 ‘Localized Ventilation’ is used to prevent exposure of building occupants to concentrated indoor sources of pollutants. ^[2] One credit is awarded when an adequate ventilation system is provided for locations where indoor pollution sources are highly

generated. ^[2] Another credit is awarded when a general exhaust system is provided for future tenants. ^[2] IEQ 12 ‘Ventilation in Common Areas’ intends to ensure adequate ventilation in common areas to avoid cross-contamination. ^[2] One credit is awarded when adequate ventilation is provided for common area. ^[2] One bonus credit is awarded if natural ventilation is used. ^[2]

SC had good ventilation functions for living spaces but the performance was dramatically dependent on solar radiation availability. Therefore, SC had capacity to help meet the assessment, but the performance depends on the actual condition of solar availability. Additionally, SC is generally quieter than alternatives during operation, so it also has capacity to help meet the requirement of IEQ 20 ‘Background Noise’.

5. Conclusion

Performance and feasibility analysis showed both SC and ET were significantly affected by the dimension and ambient environment. Natural ventilation by SC was enhanced by increased chimney dimension and air gap, and varies in different facing direction.

Longer or wider SC could provide more service hours compared with others, but over-sized air gap could cause unstable turbulent flow inside SC channel. On the other hand, the performance of ET was enhanced as increased pipe length, radius and buried depth.

During operation period in the summer design day of Hong Kong, SC had good capacity to provide sufficient ventilation for living space. However, ventilation performance by SC was also quite dependent on solar availability and absorber surface temperature. On the other hand, ET only delivered outdoor air on an average

of $0.013 \text{ L/s} \cdot \text{m}^2$ in the research study, but which was much lower than minimum ventilation requirement at ' $0.3 \text{ L/s} \cdot \text{m}^2$ ' for living/bedroom and offices ^[17]. Therefore, it couldn't be considered as an acceptable ventilation system.

In addition, SC could save ventilation energy but had potential to take more cooling energy for thermal comfort on the summer design day of Hong Kong. The ventilation energy saved by SC was only very small portion of total daily energy consumption, so it was not an economic way to use SC for building ventilation. Moreover, SC could increase cooling load for an air-conditioned space when outdoor temperature was higher than indoor A/C cooling set-point. To temporarily turn off the SC for a certain period could avoid overheating the space in hot summer. On the other hand, ET had higher capacity than SC to save thermal energy on the summer design day of Hong Kong. Colder air delivered by ET could significantly reduce cooling load for the space.

Based on the performance of SC and ET on ventilation and energy saving, both of them had capability to help meet the assessment requirement of 'On-site Renewable Energy' from BEAM/LEED. Since SC has higher capability to provide sufficient ventilation, SC could more significantly contribute in the sections pertinent to building ventilation, including IEQc2 'Increased Ventilation' from LEED, and IEQ 10 'Background Ventilation', IEQ 11 'Localized Ventilation' and IEQ 12 'Ventilation in Common Areas' from BEAM. Since ET has higher capability to save cooling energy, ET could more significantly contribute on the sections pertinent to energy saving, including EAc1 'Optimize Energy Performance' from LEED.

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Nomenclature

A_i, A_o	cross sectional area of inlet and outlet to airflow channel (m^2)
A_g	area of glass (m^2)
A_w	area of wall (m^2)
A_r	ratio of A_o to $A_i A_w$ area of wall (m^2)
C_d	coefficient of discharge of air channel inlet
C_p	zone air specific heat
C_T	sensible heat capacity multiplier
h_g	convective heat transfer coefficient between glass cover and air channel ($W/m^2 K$)
h_{rwg}	radioactive heat transfer coefficient between wall and glass cover ($W/m^2 K$)
h_w	convective heat transfer coefficient between inclined wall and air channel ($W/m^2 K$)
\dot{m}_{inf}	mass flow rate of air infiltration (kg/s)
\dot{m}_i	mass flow rate of inter zone air mixing (kg/s)
\dot{q}''	net heat gain by air stream (W/m^2)
S_I	solar radiation heat flux absorbed by glass cover (W/m^2)

S_2	solar radiation heat flux absorbed by vertical wall (W/m ²)
T_a	ambient temperature (K)
T_f	mean temperature of air in channel (K)
T_{fo}	air temperature at outlet of channel (K)
T_g	mean glass temperature (K)
T_w	mean absorber wall temperature (K)
T_r	uniform room temperature (K)
T_{si}	sky temperature (K)
T_z	zone temperature (K)
T_{zi}	inter zone temperature (K)
U_b	overall heat transfer coefficient between inclined wall and room (W/m ² K)
U_t	overall heat transfer coefficients from top of glass cover (W/m ² K)

Figure captions

Fig. 1 Vertical and inclined solar chimney

Fig. 2 Earth tube system

Fig. 3 Solar Chimney (SC) model for simulation

Fig. 4 Effect of SC height

Fig. 5 Effect of SC width

Fig. 6 Effect of SC gap width

Fig. 7 Effect of elevation

Fig. 8 Effect of facing direction

Fig. 9 SC zone temperature profile

Fig. 10 ET inlet temperature with different pipe length

Fig. 11 ET inlet temperature with different pipe radius

Fig. 12 ET inlet temperature with buried depth

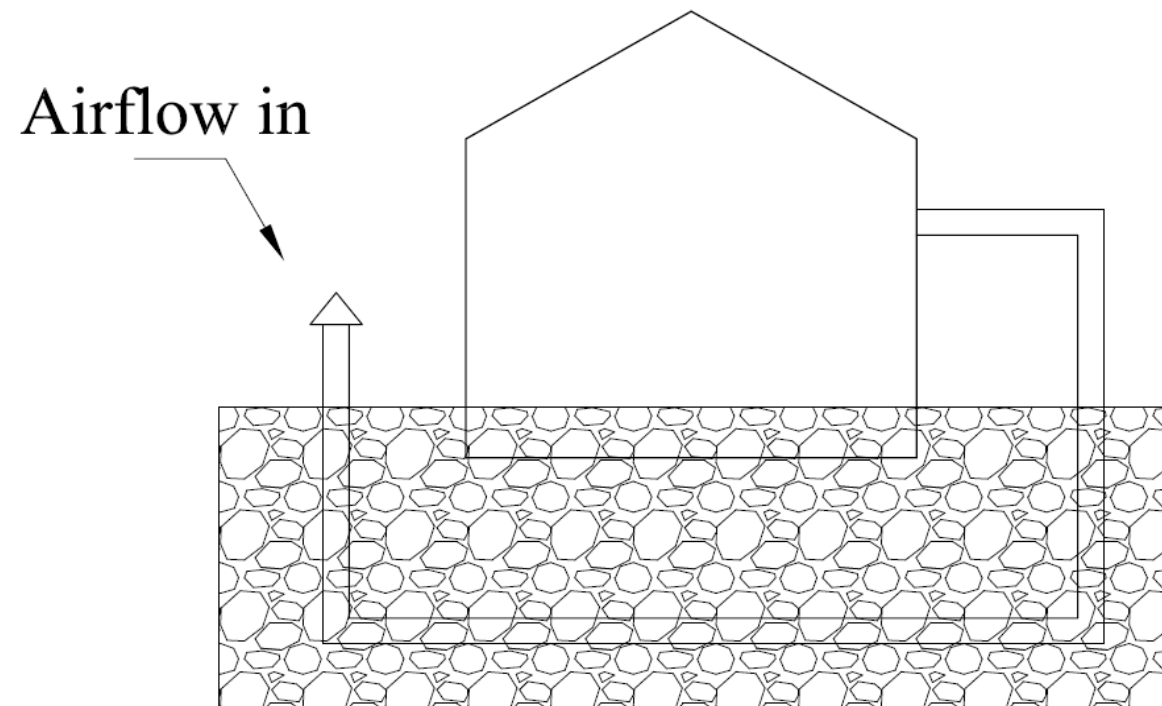


Fig. 2 Earth tube system

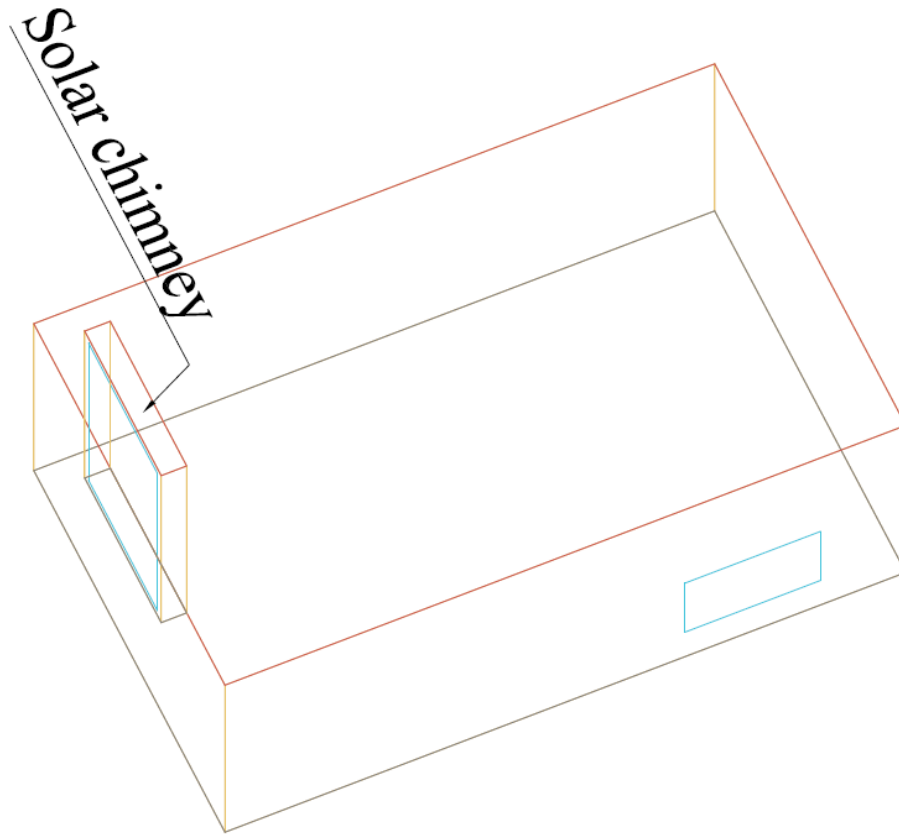


Fig. 3 Solar chimney (SC) model for simulation

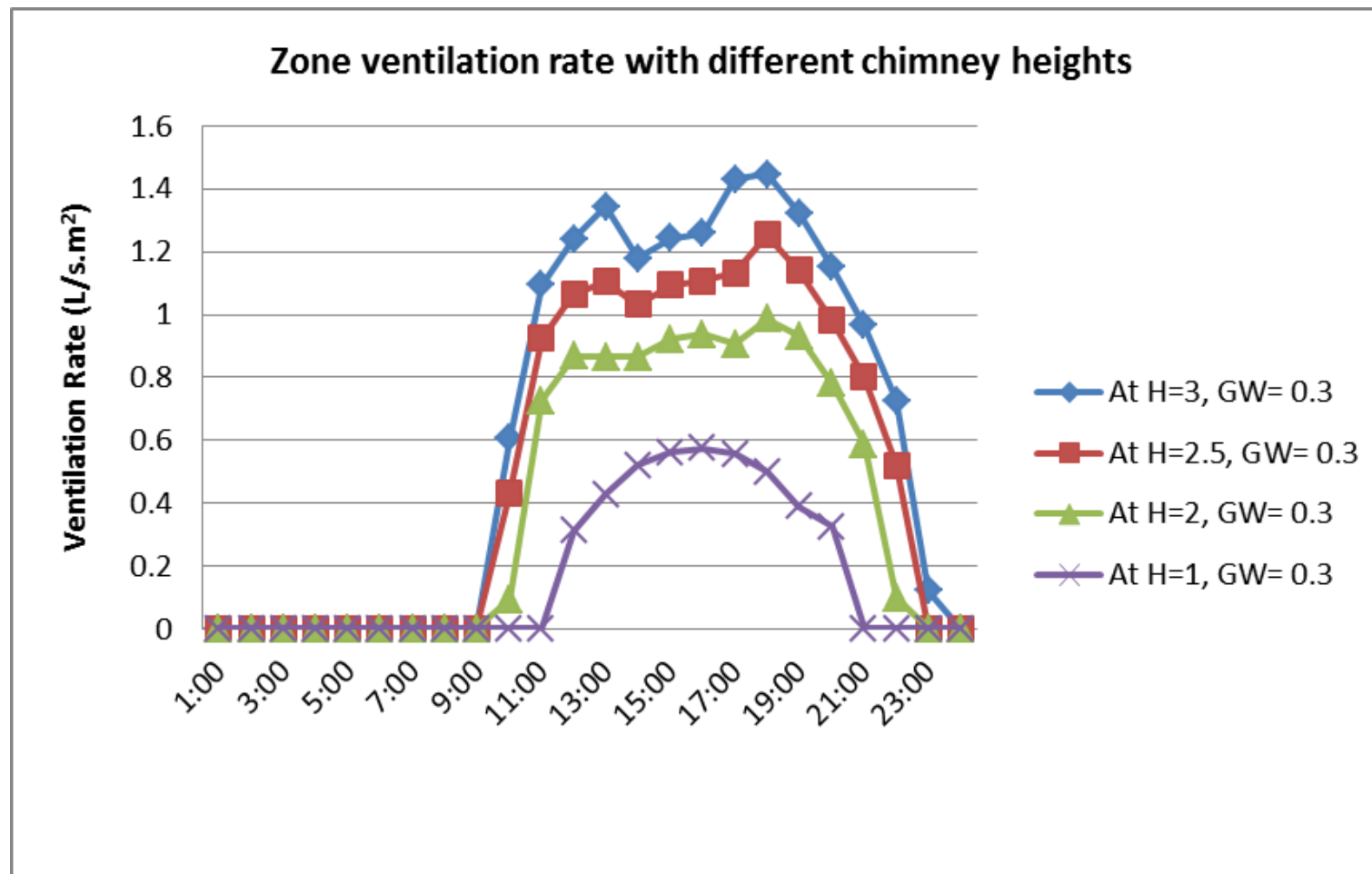


Fig. 4 Effect of SC height

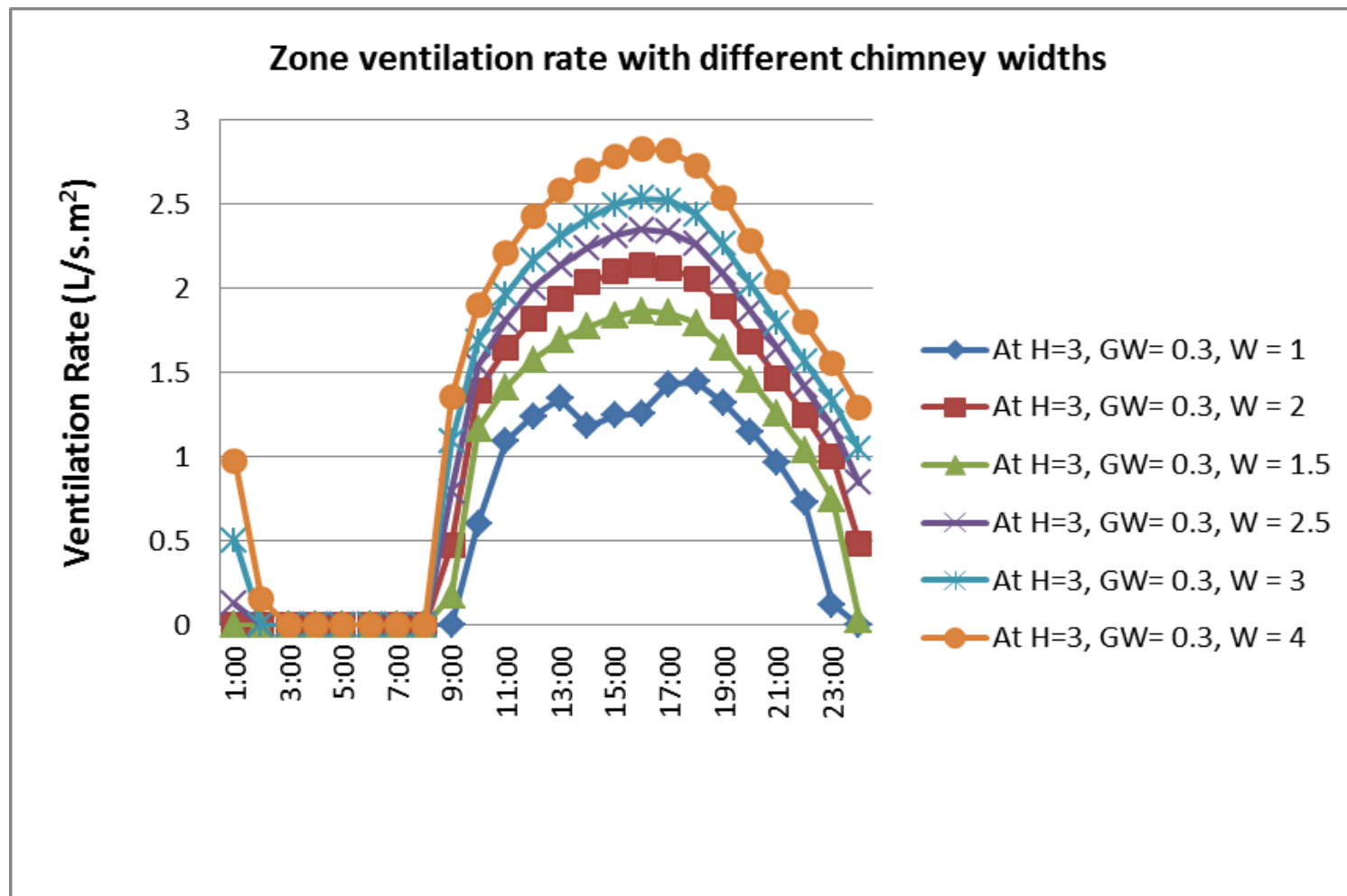


Fig. 5 Effect of SC width

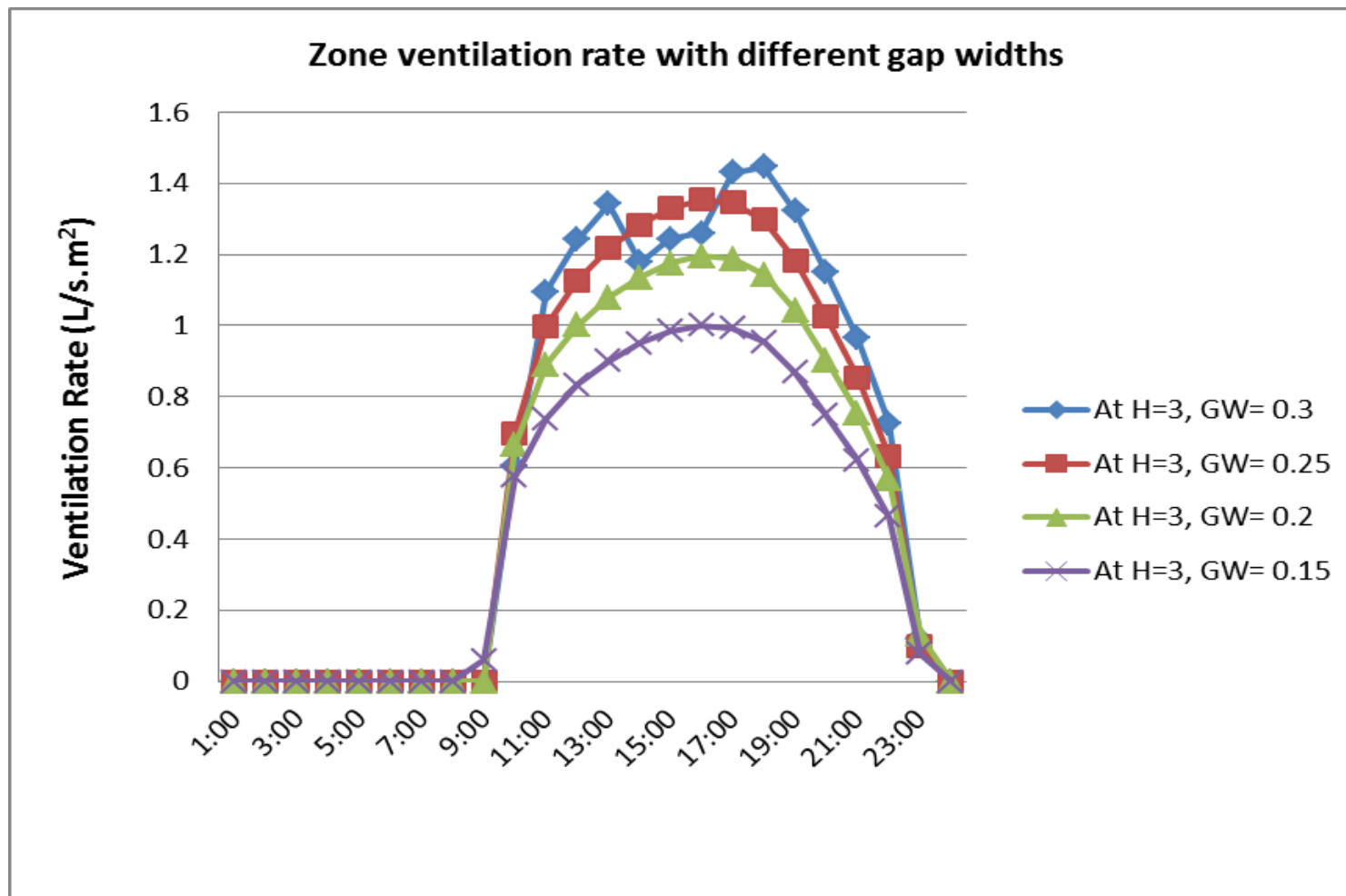


Fig. 6 Effect of SC gap width

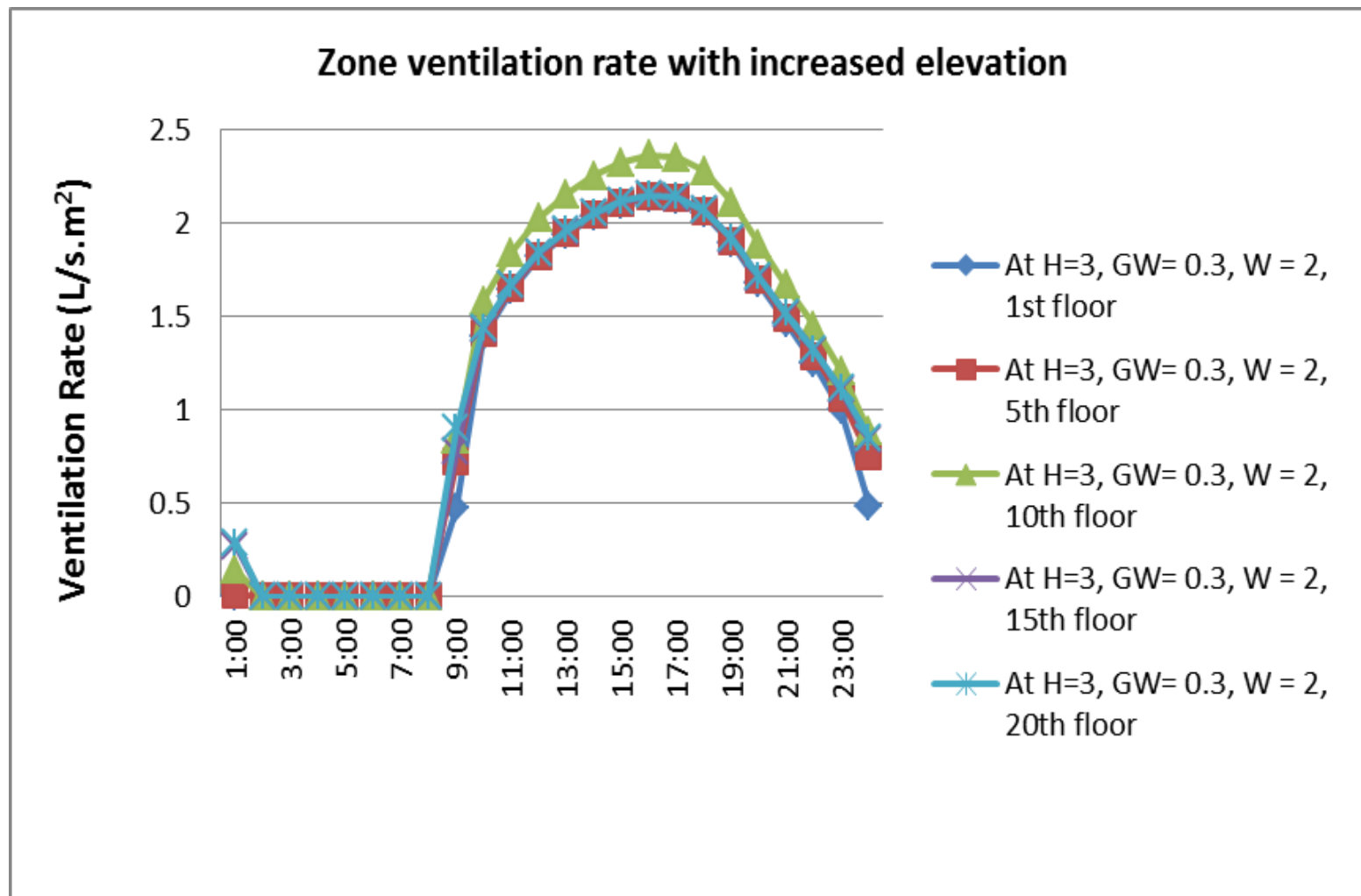


Fig. 7 Effect of elevation

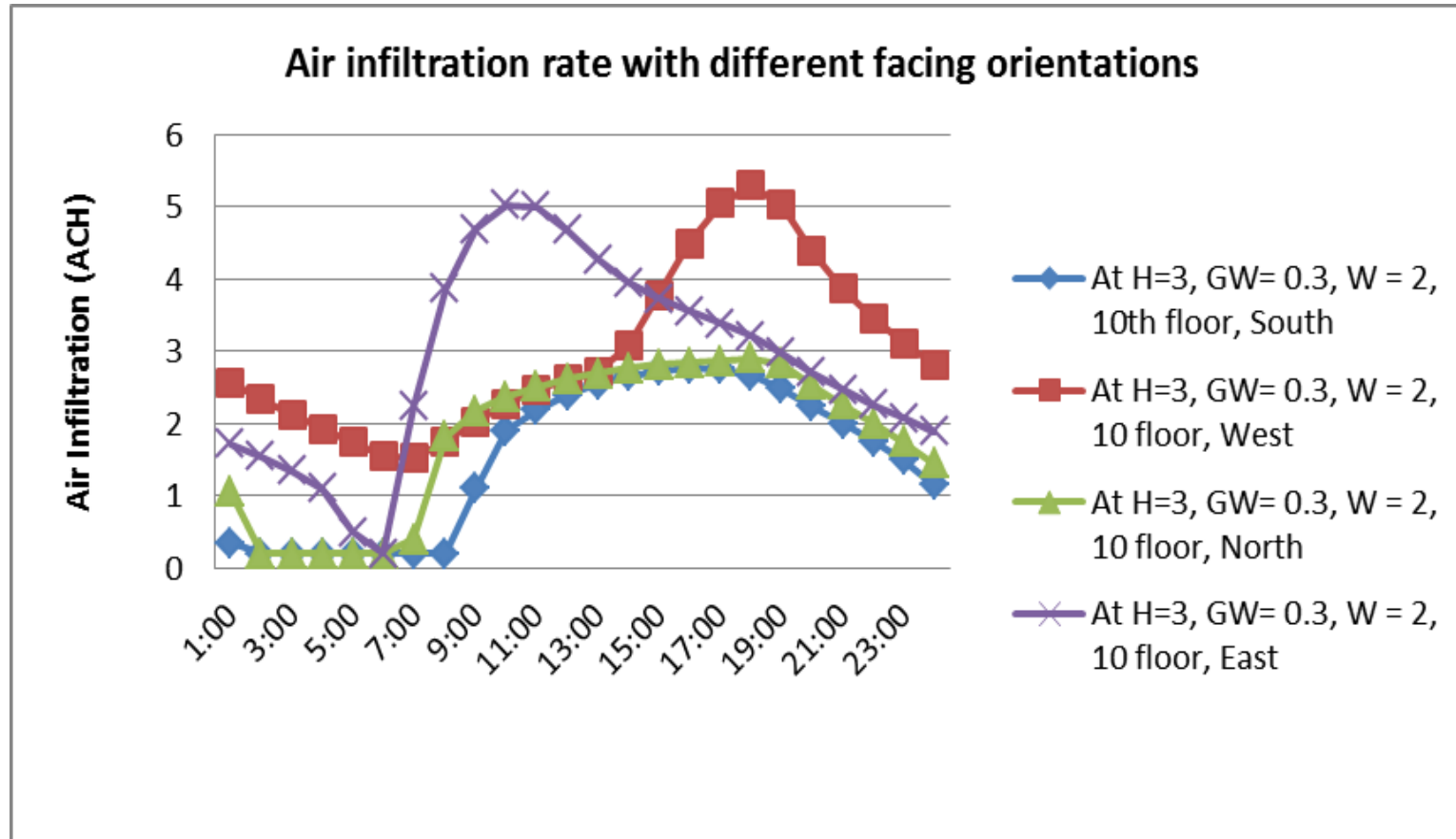


Fig. 8 Effect of facing direction

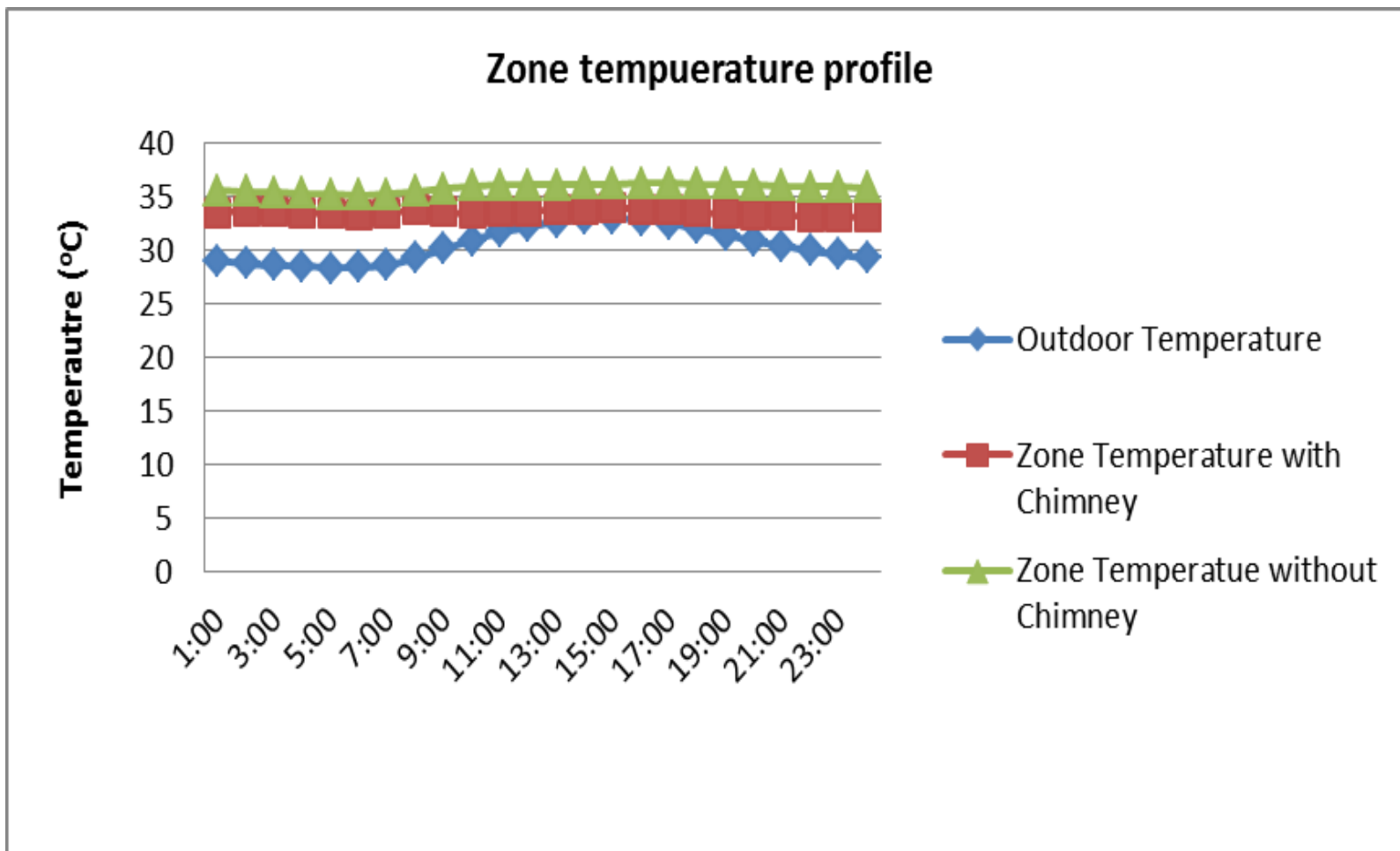


Fig. 9 SC zone temperature profile

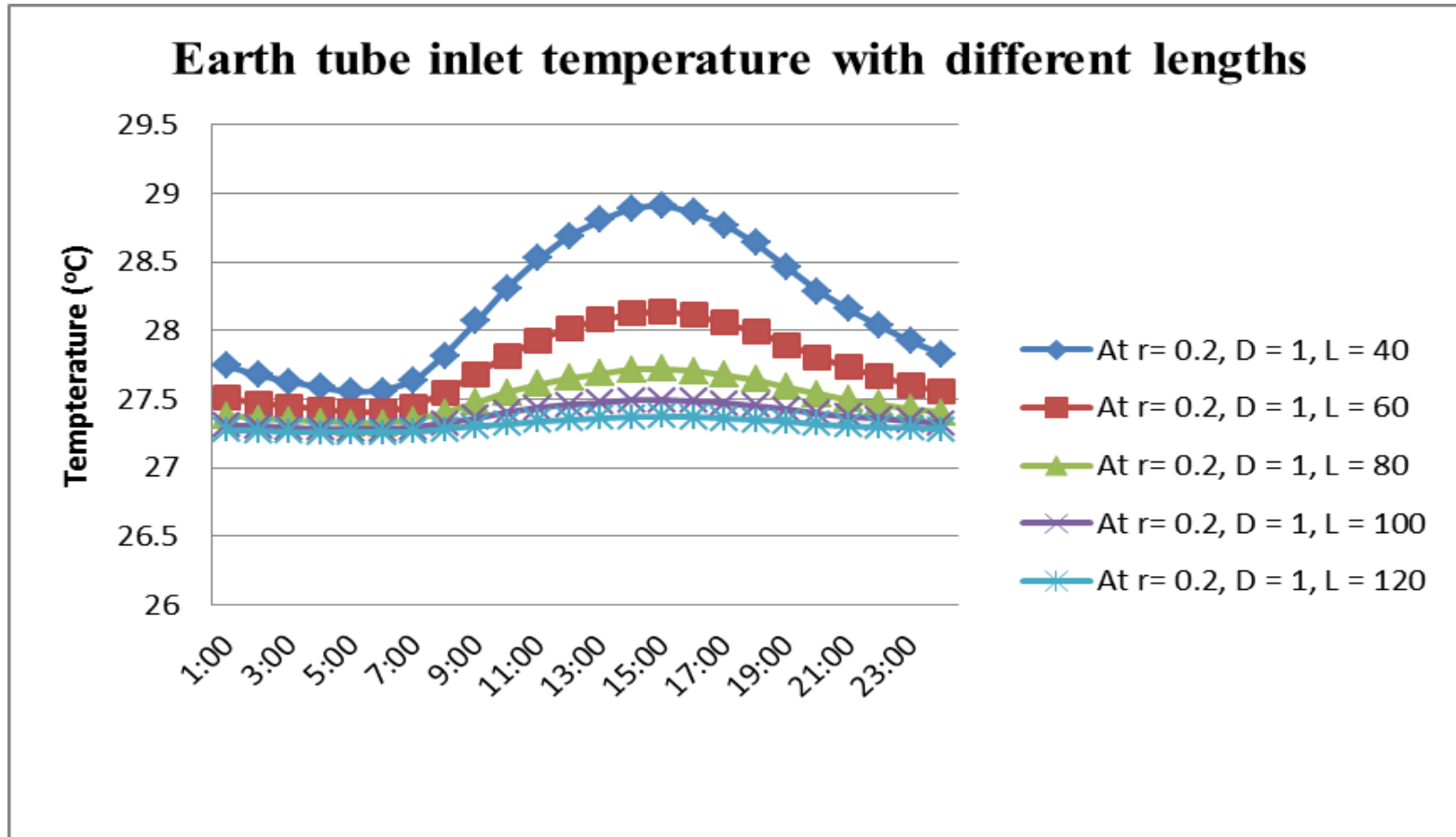


Fig. 10 ET inlet temperature with different pipe length

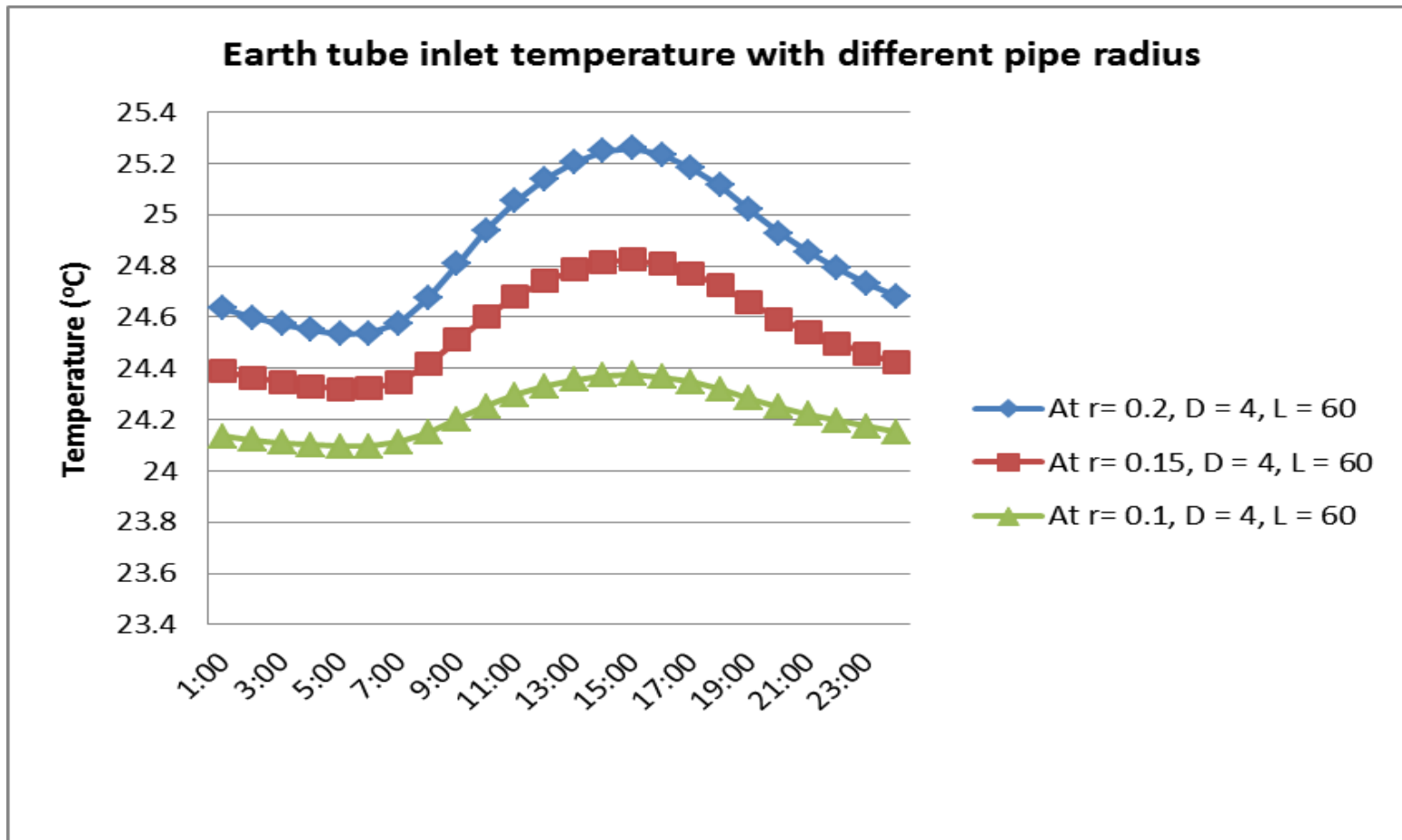


Fig. 11 ET inlet temperature with different pipe radius

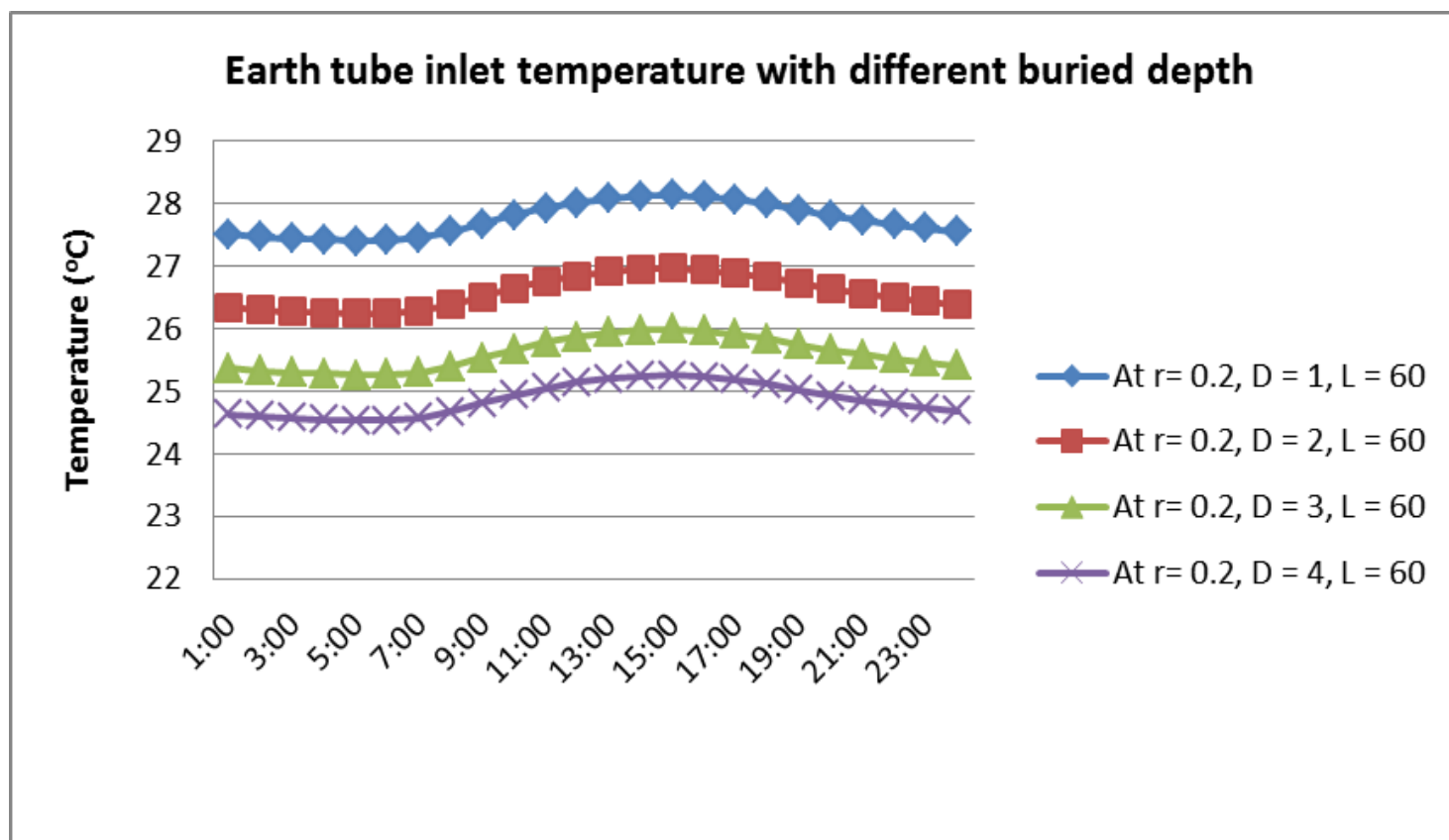


Fig. 12 ET inlet temperature with buried depth

Table captions

Table 1: Basic building parameters

Table 2: Building construction

Table 3: Design day ^[16]

Table 4: Setup for solar chimney (SC)

Table 5: Setup for earth tube (ET)

Table 6: Energy efficiency profile of SC from simulation

Table 7: Temperature profile and air infiltration of ET from simulation

Table 8: Energy efficiency profile of ET from simulation

Table 9: Renewable energy percentage for award points from LEED ^[1]

Table 10: Renewable energy percentage for award points from BEAM ^[2]

Table 1: Basic building parameters

Building		
Field	Unit	Object
Name		ABuilding
North Axis	deg	0
Terrain		Suburbs
Loads Convergence Tolerance Value		0.039999
Temperature Convergence Tolerance Value	delta C	0.25
Solar Distribution		Full Interior & Exterior
Maximum Number of Warm up Days		25
Minimum Number of Warm up Days		6

Table 2: Building Construction

Construction							
Name	Inner Surface	Double Pane Window	Floor	Roof	SGL CLR low iron 3 mm	Thermal Chimney Out	Outside Surface
Outside Layer	C7-8 in LW Concrete block	Glass clear sheet 1/8 IN	Concrete sand & gravel 4 IN	Concrete sand & gravel 4 IN	Glass low iron 3 mm	E8-5/8 in plaster or GYP board	A1-1 IN Stucco
Layer 2	E8-5/8 in plaster or GYP board	WinAirB1 airspace resistance		E6- 1/2 in GYP sheathing board		C7-8 IN LW Insulation	B12-3 IN Insulation
Layer 3		Glass-clear sheet 1/8 IN				B3-2 IN Insulation	B12-3 IN Insulation
Layer 4						B3-2 IN Insulation	C7-8 IN LW Insulation
Layer 5						B12-3 IN Insulation	E8-5/8 in plaster or GYP board
Layer 6						B12-3 IN Insulation	
Layer 7						A1-1 IN Stucco	
Layer 8						Tabor Solar Absorber	

Table 3: Design day ^[16]

Field	Units	Object
Name		Hong Kong Ann Clg 1% Condns DB=> MWB
Maximum Dry-Bulb Temperature	C	33
Daily Dry-Bulb Temperature Range	DeltaC	4.7
Humidity Indicating Conditions at		
Maximum Dry-Bulb	Varies	26.3
Barometric Pressure	Pa	100547
Wind Speed	m/s	5
Wind direction	Deg	240
Sky Clearness		1
Rain Indicator		0
Snow Indicator		0
Day of Month		21
Month		7
Day Type		SummerDesignDay
Daylight Saving Time Indicator		0
Humidity Indicating Type		WebBulb

Table 4 Setup for SC zone

Field	Units	Objects
Name		Thermal Chimney
Zone Name		Chimney Zone
Available Schedule Name		SolarChimneyAvail
Width of the Absorber Wall	m	1
Cross Sectional Area of Air Channel Outlet	m ²	0.3
Discharge Coefficient		0.8
Zone 1 Name		Living Zone
Distance from Top of Solar chimney to Inlet 1		3
Relative Ratios of Air Flow Rates Passing through Zone		1
Cross Sectional Areas of Air Channel Inlet 1	m ²	0.3

Table 5 Setup for ET

Field	Units	Objects
Zone Name		Living Zone
Schedule Name		Earth Tube Avail
Design Flow Rate	m ³ /s	0.08
Minimum Zone Temperature when Cooling	°C	0
Minimum Zone Temperature when Heating	°C	40
Delta Temperature	°C	0.1
Earth tube Type		Natural
Fan Pressure Rise	Pa	0
Fan Total Efficiency		1
Pipe Radius	m	0.1
Pipe Thickness	m	0.01
Pipe Length	m	60
Pipe Thermal Conductivity	W/m-K	50
Pipe Depth Under Ground Surface	m	4
Soil Condition		Heavy & Saturated
Average Soil Surface Temperature	°C	23
Amplitude of Soil Surface Temperature	°C	5.89
Phase Constant of Soil Surface Temperature	days	2
Constant Term Flow Coefficient		0.606
Temperature Term Flow Coefficient		0.03636
Velocity Term Flow Coefficient		0.1177
Velocity Squared Term Flow Coefficient		0

Table 6 Energy efficiency profile of SC from simulation

Time on 07/21	Ambient temperature (°C)	Fan Electric Demand [W] at 0.3 $L/s \cdot m^2$ from 9:00 to 24:00	Fan Electric Demand [W] at 1.56 $L/s \cdot m^2$ from 9:00 to 24:00	Cooling load with SC (kWh) maintained at 28 °C	Cooling load without SC (kWh) maintained at 28 °C
01:00:00	28.97	0	0	1.56	0.98
02:00:00	28.75	0	0	1.47	0.95
03:00:00	28.59	0	0	1.39	0.92
04:00:00	28.45	0	0	1.32	0.90
05:00:00	28.34	0	0	1.26	0.87
06:00:00	28.36	0	0	1.22	0.85
07:00:00	28.60	0	0	1.37	0.95
08:00:00	29.22	0	0	1.68	1.10
09:00:00	30.08	6	31.8	2.00	1.20
10:00:00	30.91	6	31.8	2.26	1.24
11:00:00	31.65	6	31.8	2.45	1.23
12:00:00	32.21	6	31.8	2.54	1.18
13:00:00	32.62	6	31.8	2.60	1.14
14:00:00	32.91	6	31.8	2.69	1.14
15:00:00	33.00	6	31.8	2.74	1.14
16:00:00	32.82	6	31.8	2.73	1.15
17:00:00	32.48	6	31.8	2.66	1.14
18:00:00	32.05	6	31.8	2.57	1.16
19:00:00	31.43	6	31.8	2.38	1.14
20:00:00	30.84	6	31.8	2.19	1.12
21:00:00	30.39	6	31.8	2.05	1.10
22:00:00	29.96	6	31.8	1.92	1.09
23:00:00	29.60	6	31.8	1.80	1.06
24:00:00	29.27	6	31.8	1.70	1.04
Total		96	508.8	48.55	25.79

Table 7 Temperature profile and air infiltration of ET from simulation

Time on 07/21	Ambient temperature (°C)	Zone temperature (°C)	Earth tube inlet temperature (°C)	Sensible cooling rate [W]	Earth Tube (1.88 m ³) Air Volume Flow (ACH)
01:00:00	28.97	29.90	24.13	667.56	2.95
02:00:00	28.75	29.80	24.12	658.76	2.96
03:00:00	28.59	29.70	24.11	650.57	2.97
04:00:00	28.45	29.61	24.10	642.18	2.97
05:00:00	28.34	29.52	24.10	633.08	2.97
06:00:00	28.36	29.44	24.10	621.33	2.96
07:00:00	28.60	29.56	24.11	618.65	2.94
08:00:00	29.22	29.89	24.15	643.50	2.92
09:00:00	30.08	30.34	24.20	632.93	2.61
10:00:00	30.91	30.46	24.25	677.91	2.75
11:00:00	31.65	30.40	24.30	702.31	2.98
12:00:00	32.21	30.33	24.33	704.20	3.03
13:00:00	32.62	30.24	24.35	698.97	3.07
14:00:00	32.91	30.22	24.37	698.55	3.10
15:00:00	33.00	30.23	24.38	700.29	3.11
16:00:00	32.82	30.25	24.37	700.31	3.09
17:00:00	32.48	30.26	24.35	698.08	3.06
18:00:00	32.05	30.31	24.32	697.13	3.02
19:00:00	31.43	30.31	24.28	691.58	2.96
20:00:00	30.84	30.29	24.25	682.84	2.92
21:00:00	30.39	30.40	24.22	667.87	2.75
22:00:00	29.96	30.22	24.19	685.40	2.89
23:00:00	29.60	30.16	24.17	682.37	2.92
24:00:00	29.27	30.08	24.15	681.08	2.94
Average	30.48	30.08	24.23	672.39	2.95

Table 8 Energy efficiency profile of ET from simulation

Time on 07/21	Ambient temperature (°C)	Cooling load with earth tube (kWh) at 28 °C	Cooling load without earth tube (kWh) at 28 °C
01:00:00	28.97	0.62	0.98
02:00:00	28.75	0.56	0.95
03:00:00	28.59	0.50	0.92
04:00:00	28.45	0.44	0.90
05:00:00	28.34	0.38	0.87
06:00:00	28.36	0.33	0.85
07:00:00	28.60	0.49	0.95
08:00:00	29.22	0.78	1.10
09:00:00	30.08	0.98	1.20
10:00:00	30.91	1.08	1.24
11:00:00	31.65	1.08	1.23
12:00:00	32.21	1.00	1.18
13:00:00	32.62	0.91	1.14
14:00:00	32.91	0.91	1.14
15:00:00	33.00	0.92	1.14
16:00:00	32.82	0.92	1.15
17:00:00	32.48	0.92	1.14
18:00:00	32.05	0.95	1.16
19:00:00	31.43	0.91	1.14
20:00:00	30.84	0.88	1.12
21:00:00	30.39	0.85	1.10
22:00:00	29.96	0.82	1.09
23:00:00	29.60	0.78	1.06
24:00:00	29.27	0.73	1.04
Total		18.75	25.79

Table 9: Renewable energy percentage for award points from LEED ^[1]

Percentage Renewable Energy	Point (s)
1%	1
3%	2
5%	3
7%	4
9%	5
11%	6
13%	7

Table 10: Renewable energy percentage for award points from BEAM ^[2]

Percentage Renewable Energy	Point (s)
0.5 %	1
1 %	2
1.5 %	3
2 %	4
2.5 %	5