CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 3

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 3*. Department of Civil Engineering, Aalborg University.

Performance Prediction Method and System Design Method for Earth-to-air Heat Exchangers

Tomoki Inagaki[#1], Gyuyoung Yoon[#2], Hideharu Niwa[*3]

[#]*Nagoya City University*
2-1-10, Kitachikusa, Chikusa-ward Nagoya-city, Aichi, Japan,
[1]it15g02@sda.nagoya-cu.ac.jp
[2]yoon @sda.nagoya-cu.ac.jp
[*]*Nikken Sekkei Research Institute*
2-18-3, Iidabashi, Chiyoda-ward, Tokyo, Japan
[3]niwah@nikken.jp

Abstract
This study describes a proposed performance prediction and system design method for Earth-to-air heat exchangers. First, a parameter study was performed via simulation using various system specifications. A thermal performance index was derived as a ratio of the tube's heat transfer area and the introduced air volume. A regression equation was introduced that including the new thermal performance index and supported subsequent prediction of outlet air temperatures for Earth-to-air heat exchangers.
Second, a conceptual system design method was developed. This proposed design method can be applied in both the schematic design and design development/contract documentation phases. The system scale and associated heat exchange quantities would be estimated in the schematic design phase; specific system design parameters would be determined using the regression results in the design development/contract documentation phase.

Keywords – earth-to-air heat exchanger;performance prediction; desing method; outlet air tempreture; exchange heat quantity

1. Introduction

In Japan, global warming and the destabilization of energy supply and demand have recently focused attention on zero energy building (ZEB) design. Energy conservation through the suppression of energy loads and the application of passive methods is fundamental in ZEB designs. In such circumstance, indoor heat load is decreased through increased efficiency of OA equipment and improved thermal performance of building fabric[(1]. The ratio of outdoor air load to air conditioning load may increase because of a constant outdoor air load. Therefore, outdoor air load countermeasures become more important.

An Earth-to-air heat exchanger system is one useful method for reducing outdoor air load. This passive system precools and preheats introduced fresh air using the thermal capacity of the soil. Established design methods for this system are essential for widespread implementation. Moreover, outlet air temperature and heat exchange quantity, must be accurately predicted for design of air conditioning system design reflected a reduction in outdoor air load.

In previous studies, Hokoi[2] and Ishihara[3] predicted outlet air temperature and heat exchange quantities via parameter study using result of simulations with numerical model. Because the methods in these prior studies used a fixed the design parameters, each changes to system specifications require remaking the design method. As such, these methods do not readily support comparisons of system performance with different design parameters.

Based on these prior shortcomings, this study aimed to develop a performance prediction and system design method that allows designers to freely change and determine the system design parameters early in the design phase. This study describes the proposed thermal performance index for a system that relates design parameters to explanatory variables. Next, this study presents the proposed performance prediction method for outlet air temperature using this index. Lastly, the proposed system design procedures are introduced.

2. Study outline

In prior studies, parameter study was performed using annual simulation results from numerical calculations with standard design parameters[4]. In this study, we developed a thermal performance index for a system that reflects each design parameter. The outlet air temperature for an Earth-to-air heat exchanger was predicted using regression equations with the performance index as explanatory variables. Last, we developed a thermal performance prediction method and system design procedures using regression equations.

Annual outlet air temperature for each systems of 128 cases was calculated using numerical model. Table 1 summarizes the range of values for the design parameter used in this study. A three-dimensional simple heat conduction numerical model considering only sensible heat was used for this simulation[5]. The validity of this model has been previously verified. This study considered cooling season conditions, using calculated values from the summer period. Prior research guided decisions regarding the range of design parameter values as follows:

(1) Although the optimum tube diameter varies widely with tube length, tube cost, airflow velocity, and air volumes, tube diameters of 0.15 m–0.45 m appear to be most appropriate[6].

(2) Buried tube depth is generally 2 m, considering drilling costs and

construction difficulty[7].

(3) Tube airflow velocity should be approximately 2 m/s to limit pressure drops in the system[8].

In addition, the system operation schedule was set to correspond to the general operating hours of office buildings in Japan.

Table 1 Range of design parameter values for simulation

Region	Osaka(Japan)
Ground surface situation	Covered by lawn (no direct solar radiation)
Soil property	Sandy
Tube material	Polyvinyl chloride
Tube length	20m, 40m, 60m, 80m
Tube diameter	0.35m, 0.5m
Tube buried depth	0.3m, 0.5m, 1.0m, 2.0m
Tube airflow velocity	0.5m/s, 1.0m/s, 2.0m/s, 3.0m/s
Operating period and time	June-Sept.(summer) Dec.-Mar.(winter) Other (interim period) Running time：12h (8:00~20:00)

(In Osaka Japan: the average temperature 16.3 ° C, a highest temperature 36.5 ° C, and lowest -2.6 ° C Source: SMASH standard weather data)

3. Proposed concept and index

The outlet air temperature and heat exchange quantity are necessary performance considerations for design of an Earth-to-air heat exchanger. As such, simple methods to accurately predict these performance considerations are required.

Figure 1 shows summer outlet air temperatures of a tube in descending order. In this case, tube length was 80 m, buried tube depth was 1 m, airflow velocity was 0.5 m/s, average outdoor air temperature was 27.6° C, and maximum outdoor air temperature was 36.5°C during summer operation. The maximum outlet air temperature was 23.2° C and the average outlet air temperature was 20 °C. Consequently, the accumulated heat exchange quantity could be estimated using Eq. (1) that multiplies the system operating time, the introduced outdoor air volume, and the difference between the average outdoor air temperature ($\theta_{a\,50\%}$) and the average outlet air temperature($\theta_{d\,50\%}$). The maximum outlet air temperature ($\theta_{d\,0\%}$) is essential for calculate the maximum heat load. Comparatively, the highest 2.5%, 5%, and 10% of summer outlet air temperatures may be used in design if lack of air conditioning system capacity is allowed.

Average and maximum outlet air temperatures are important parameters for evaluating performance and designing Earth-to-air exchanger systems because of prediction for heat exchange quantity using Eq.(1). To facilitate their use in design of this system, we developed a simple prediction method.

$$Q_s = 3.6 \cdot (c\rho/1000) \cdot (\theta_a - \theta_{d50\%}) \cdot t \cdot V \quad [\mathrm{MJ}] \qquad (1)$$

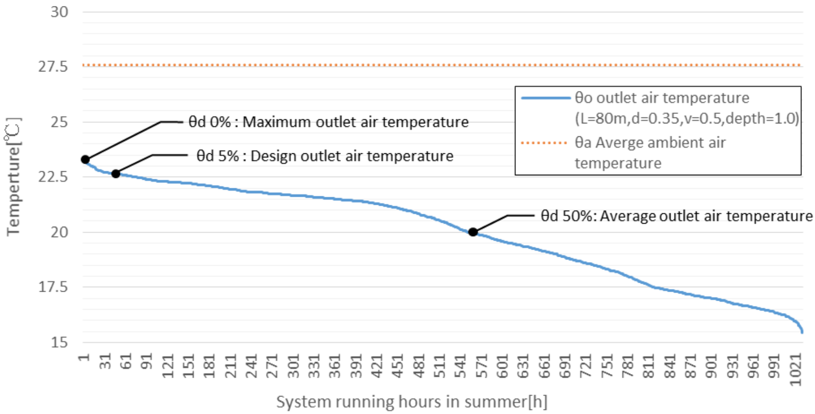

Figure 1 Outlet air temperature in descending order

A prior study using simulation confirmed that larger heat transfer tube areas resulted in lower outlet air temperatures. Similarly, lower introduced outdoor air volumes resulted in lower outlet air temperatures. On the basis of these earlier findings, the outlet air temperature can be predicted by regressive approximation using the index shown in Eq. (2).

In this relationship, the magnitude of decreased outlet air temperature per unit tube length is small for longer tubes. Outlet air temperatures rise with higher air velocities, but the magnitude of increased outlet air temperatures is small for fast airflow velocity.

As shown in Eq. (3) and Eq. (4), exponent values were added to tube length and airflow velocity to reflect the observed thermal characteristics. The exponent (a and b) values depend on the length and velocity ranges considered.

$$A/_V = (l' \cdot d \cdot \pi)/\{v' \cdot (d/2)^2 \cdot \pi\} \qquad (2)$$

$$l' = l^a \qquad a<1 \qquad (3)$$

$$v' = v^b \qquad b<1 \qquad (4)$$

The regression equation used to predict the design outlet air temperature with the thermal performance index (A/V) as the explanatory variable is shown in Eq. (5). We defined the regression equation as a quadratic relationship with design outdoor temperature as a constant term. If a lower system capacity is permitted, the constant term should assume the highest 2.5%, 5%, or 10% of outdoor air temperatures for design purposes. Lower A/V values result in lower cooling effects and outlet air temperatures close to outdoor air temperatures. An applicable range of A/V is 50–800 m^2s/m^3.

$$\theta_{d\,x\%} = c_1(A/V)^2 + c_2(A/V) + \theta_{a\,x\%} \tag{5}$$

In Eq. (5), θ_d is outlet air temperature, θ_a is outdoor air temperature, and x is the magnitude of design allowance defined as 0% (maximum), 2.5%, 5%, or 10%.

We estimated the exponents (a and b) and coefficients (c_1 and c_2) in Eqs. (3)–(5) using the least-squares method. Table 2 shows these values for various buried tube depths. Figure 2 compares simulated and predicted (using the regression equation) values of outlet air temperature. These values correspond well with the maximum observed error between the two estimates, i.e., −0.35° C.

Table 2 Estimated exponents and coefficients for Eq. (2)–(5)

	Depth	a	b	c_1	c_2
Design outlet air temperature ($\theta_{d\,5\%}$)	0.3m	0.88	0.73	7.07E-06	-0.015
	0.5m			6.72E-06	-0.016
	1.0m			6.34E-06	-0.018
	2.0m			6.38E-06	-0.020

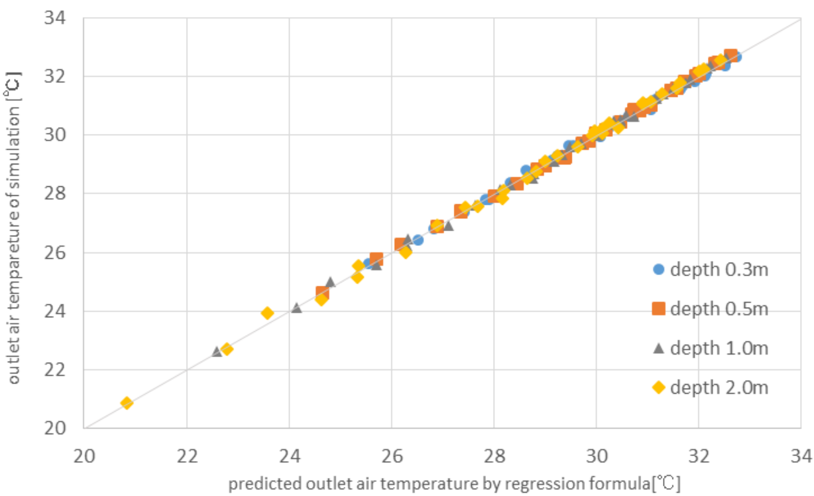

Figure 2 Comparison of simulated and predicted (using regression) outlet air temperatures

4. Proposed design procedure

In the previous section, outlet air temperature was accurately predicted using regression and the thermal performance index (A/V) as the explanatory variable for heat exchange performance of Earth-to-air heat exchanger systems. Given this successful prediction outcome, the proposed system design procedure was developed using the new thermal performance index.

Figure 3 shows the conceptual diagram of the proposed system design procedure. Design procedures can be considered separately in the schematic design phase and the design development/contract documentation phase. In the schematic design phase, many design considerations are undefined. Useful information likely consists only of basic building and site conditions such as the building coverage and floor-area ratio.

In the schematic design phase, it is possible to determine the scale of and desired effects from an Earth-to-air heat exchanger. In particular, Eq. (1) should be used early in the schematic design phase to initiate estimation of the maximum outdoor air volume that a system can accommodate and the resultant thermal effect (heat exchange quantity). The maximum outdoor air volume that a system can accommodate is further determined using the introduced outdoor air ratio shown in Eq. (6). Incidentally, Eq.(6) shows the ratio of accommodated outdoor air to ventilation requirements.

$$\mu = v \cdot (d/2)^2 \cdot \pi \cdot n / S_s \cdot \beta \cdot p \cdot V_r \tag{6}$$

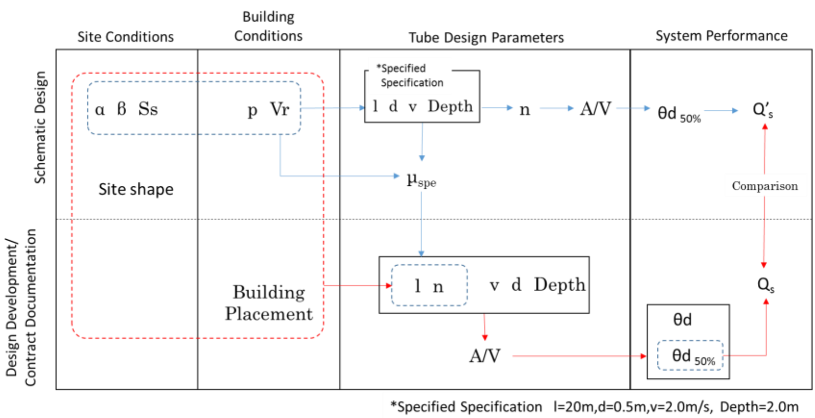

Figure 3 Conceptual diagram of system design procedure

Next, introduced system effects can be evaluated using heat exchange values for initial specified conditions; design parameters are not yet fixed in the schematic design phase.

Initial specified conditions in this study considered the following values:

Tube length = 20 m
Tube diameter = 0.5 m
Tube airflow velocity = 2 m/s,
Tube buried depth = 2 m

Estimated heat exchange values under initial specified conditions were assumed to maximize introduced system effects. This step supports determination of a target value in the subsequent design development and contract documentation phase.

If multiple Earth-to-air heat exchangers are needed, the required quantity can be calculated using Eq. (7) and assuming a tube spacing of 5 m.

$$\mathrm{n} = S_s(1-\alpha)/(5 \cdot l) \tag{7}$$

Figure 4 graphically depicts the relationship between building coverage, floor-area ratio, and the introduced outdoor air volume ratio for a site area of 3500 m^2 with system of initial specified specification. The introduced outdoor air volume ratio for the specified specification, supporting determination of the maximum introducible outdoor air volume, can be readily determined in the schematic design phase.

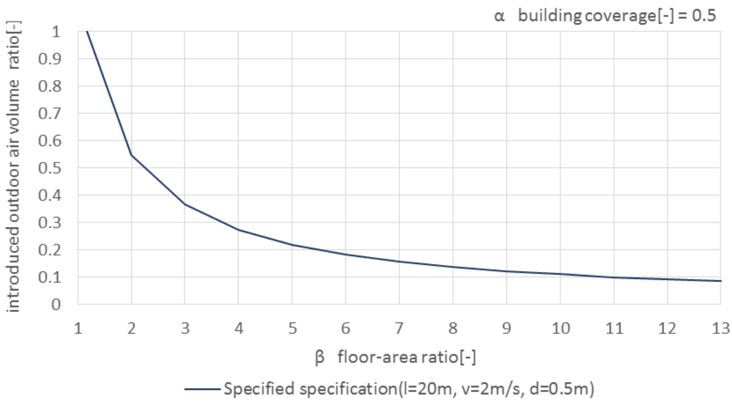

Figure 4 Relationship between building coverage, floor-area ratio, and introduced outdoor air volume ratio

In the design development/contract documentation phase, a designer can set a target value for system performance using estimation in previous phase. The heat exchanger length, diameter, and buried depth required to achieve the target heat exchange value should be finalized. Because these parameters can influence airflow velocity and the quantity of required heat exchangers, some trial and error may be required to achieve the target heat exchange value.

5. Conclusion

We proposed a system design concept for an Earth-to-air heat exchanger using the new thermal performance index. This design procedure can be applied in both the schematic design and design development/contract documentation phases. In the future, we will consider development of a regression equation each of outlet air temperatures (the highest 2.5%, 10%, and 50%) and the applicability of the proposed system design procedures in field design work.

Nomenclature

l	:	Length of tube	[m]	α	:	Building coverage	[−]
v	:	Velocity in tube	[m/s]	β	:	Floor-area ratio	[−]
d	:	Diameter of tube	[m]	Ss	:	Site area	[m^2]
n	:	Number of tubes		p	:	Personal density	[Person/m^2]
V	:	Introduced volume of fresh air	[m^3/h]	Vr	:	Ventilation requirement	[m^3/Person･h]
μ	:	Introduced outdoor air ratio	[−]	C	:	Specific heat of air	[kJ/kg･K]
θ	:	Temperature	[℃]	ρ	:	Density of air	[kg/m^3]
t	:	Operating time	[h]				
Q'_s	:	Assumed maximam accumulated exchange heat quantity in summer [MJ]					
Qs	:	accumulated exchange heat quantity in summer [MJ]					

Subscript a: Ambient air d: Design outlet air o: Outlet air x%: Top x% of period
spe:Specified specification

References

[1] Y.Fujikawa, G.yoon. Study on Decreasing of Electric Power Consumption and Air-Conditioning Load by Renewal of OA Equipments. J.Technol. AIJ, No.47, pp193-198, Feb, 2015

[2] S.Hokoi, S.Ueda et al. Study of cooling effect of cool tube. Summaries of Technical Papers of Annual Meeting. AIJ, pp495-496, Aug, 1995

[3] Z.Qingyuan and O.Ishihara. Discussion on the Exit Temperature and Cooling Enargy of Cooling Tubes for Design. J. Archit, Planh, Environ Eng., AIJ, NO.477, pp.11-18, Nov, 1995

[4] T. Inagaki, G. Yoon et al, a Study on Performance Prediction and Design Method of Earth-to-air Heat Exchanger. Summaries of Technical Papers of Annual Meeting. SHASE, pp 53-56, Sep, 2015

[5] G.Yoon, H.Tanaka. Study on the Design Precedure of the Muliti-Cool/Heat System. solar energy, No.83, pp 1415-1424, Aug, 2009

[6] Earth cooling tubes, EREC Reference Briefs, U.S. Department of energy

[7] H.Tarumi, Y.Minohara, Surveillance Study on the Subterranean Thermal Use Effect of a Heat&Cool Tube Residence. J. Environ., AIJ, No651, pp.423-429, May, 2010

[8] M. Zimmermann et al. Technology selection and early design guidance, Low Energy Cooling, Annex28, IEA Energy conservation in building and community systems program