Reducing Effect of Latent Heat Load by Fresh Air Heat Load Reduction System Using Underground Double Floor Space

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Abstract
This paper presents a feasibility study of a fresh air load reduction system by using an underground double floor space. The fresh air is introduced into the double slab space and passes through the opening bored into the footing beam. The air is cooled by the heat exchange with the inside surface of the double slab space in summer, and heated in winter. Then the heat is transferred to the adjacent soil through foundation slab, wall and to the room just above the mat through floor slab. This system not only reduces sensible heat load of the fresh air by heat exchange with earth but also reduces latent heat load of the fresh air by ad/de-sorption of underground double slab concrete. In this paper, we used a model for evaluation of fresh air latent heat load reduction by hygroscopic of air to earth exchange system taking into account coupled heat and moisture transfer of underground double floor space. In conclusion it shows the validity of the proposed method for a design tool and the quantitative effect of the system.

Keywords: fresh air load reduction system; latent heat load; heat and moisture transfer; hygroscopic

Introduction
In this study, the feasibility of a fresh air load reduction system using underground double floor space (it is called “earth tube” in the following) is investigated experimentally and numerically. The system gets cooling and heating effect to fresh air by heat exchange between the wall surface of the space that contacts with soil and the fresh air introduced into it.

The reducing effect of fresh air sensible heat load was clarified by experiments on earth tube for long term and numerical analysis using simple 2-dimensional thermal diffusion model. The validity of this model was confirmed by comparison with field measurements [1, 2]. On the other hand, influence of weather condition, location of building, underground water, condensation in tube wall, and moisture content in tube wall are different. It has an influence on sensible and latent heat removal. Generally, the internal space of the earth tube is with high humidity.

Under the condition that the tube wall surrounding air of the earth tube is in saturation, it has been examined on the change of air temperature and humidity by latent heat of vaporization. Kimura et al showed large heat removal experimentally in the case of vapor transfer between the tube surface and the air [3]. Sodha et al calculated the tube air temperature and humidity using a model that considers the wet-tube surface [4]. Matsumoto et al proposed a model considering simultaneous heat and moisture transfer in the ground for an analysis of thermal and hygric behaviors of the thermal well and the underground space [5]. Ueda et al analytically investigated the cooling effect of the cool tube, considering sensible and latent heat [6]. These studies were shown that the sensible heat removal more increases by latent heat of vaporization, but latent heat load also increases by humidifying air in the earth tube.

However, when the ground-water table position in the place where it is installed is considerably deep (ex. top of the hill and so on.), it is anticipated that the inclusion of moisture in the tube wall is in the hygroscopic range. In this case, it is also expected that not only the sensible heat load but also the latent heat load are reduced by this system. Therefore under the condition of dry earth tube, the analysis considering coupled heat and moisture transfer is performed to evaluate the reducing effect of fresh air latent heat load by the system.

Outline of the theoretical model
Although high temperature and humidity air had been introduced to earth tube in the past summer, it was confirmed that the condensation was not generated at the tube surface [7]. In this case, because the tube wall keeps low moisture content relatively, it could be assumed that moisture transfer in tube wall is hygroscopic humidity [8].

Generally speaking, the thermal properties such as thermal conductivity, specific heat and latent heat
vaporization are strongly dependent on change of moisture content. However, when the moisture content is low with a narrow range of hygroscopic humidity, it is possible to deal with their coefficients as a constant value except for \( \kappa \) and \( \nu \) (see Eq. (8), (9)). In other words, generally, it is necessary to use a nonlinear equation considering the change of \( \kappa \) and \( \nu \) depending on temperature and humidity.

The shape in the under floor space using earth tube is considerably complicated. Therefore, it is simplified as shown in Figure 2. To purpose simple 2-dimensional model, we shall additionally assume that:

1. The moisture is transmitted only in the concrete slab, and there is no moisture transport in the soil.
2. The temperature deep in the ground remains constant and equal to the annual average outdoor air temperature.

Under these assumptions, the equations of the heat transfer surrounding the under floor and of coupled heat and moisture transfer in it is described by the following set of equations.

- The equation of energy conservation of the soil is:
  \[
  c_r \rho_r \frac{\partial T_s}{\partial t} = \lambda \left( \frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2} \right) \tag{1}
  \]

- The equation of hygroscopic humidity of the tube wall is:
  \[
  (c'_r \rho'_r + \kappa) \frac{\partial X_c}{\partial t} = \lambda' \left( \frac{\partial^2 X_c}{\partial x^2} + \frac{\partial^2 X_c}{\partial y^2} \right) + \nu \frac{\partial T_c}{\partial t} \tag{2}
  \]

- The equations expressing the heat and moisture balance of the air in the earth tube are:
  \[
  c_p \rho_V \frac{\partial T_a}{\partial t} = -c_p \rho_V V H \frac{\partial T_a}{\partial x} + \alpha(T_{ca} - T_a) + \alpha'(X_{ca} - X_a) \tag{4}
  \]
  \[
  \rho'_V \frac{\partial X_a}{\partial t} = \rho'_V V H \frac{\partial X_a}{\partial x} + \alpha'(X_{ca} - X_a) + \alpha'(X_{ca} - X_a) \tag{5}
  \]

The boundary condition placed on heat transfer is given as:

\[
\alpha(T_a - T_{ca,cl}) = \lambda_{ca,cl} \frac{\partial T_{ca,cl}}{\partial y} \tag{6}
\]

\[
\alpha'(X_a - X_{ca,cl}) = \lambda'_{ca,cl} \frac{\partial X_{ca,cl}}{\partial y} \tag{7}
\]

The route of airflow in underground double floor space used as this system is complicated, and the airflow is a turbulent flow fundamentally. Therefore, from a viewpoint of a design, airflow was assumed as a simple laminar flow in it, and the velocity of the airflow is constant at average measured value.

Simulation summary and condition
In this examination, length and section of double slab space assumed to be 60mL and 7mW*1.4mH based on the installed earth tube of the actual building. Outdoor air temperature and humidity used in this analysis are measured values (The ambient data in a part period (6 MAY ~ 20 JUN) was not obtained, so outdoor air temperature and humidity data during this part were interpolated in Nagoya standard weather data supported in the HASP.)

The room temperature above the under floor space is the seasonal average of measured value, because their variations during each season are very small. The air velocity in earth tube is also the measured average value. Summary of calculation is shown in Table 1.

Using the time-forward, diffusion-central and convection-upwind, finite-difference method solves the basic equations. The number of divided mesh is 40(x-direction)*66(y-direction). The time interval for calculation is 5 seconds. The moisture content of
boundary curve in adsorptive tube wall is shown in Figure 3.

Using this boundary curve, the values of \( \kappa \) and \( \nu \) are described by the following.

\[
\kappa = \rho_w \frac{\partial \theta}{\partial \phi} \times \frac{\partial \phi}{\partial X} = \rho_w \frac{\partial \theta}{\partial X} \tag{8}
\]

\[
\nu = -\rho_w \frac{\partial \theta}{\partial \phi} \times \frac{\partial \phi}{\partial T} = \rho_w \frac{\partial \theta}{\partial T} \tag{9}
\]

in addition,

\[
\frac{\partial \theta}{\partial \phi} = \frac{147.5(1 - \ln(\phi)/0.0453)^{1/1.67}}{(1/1.67) \times 0.0453} \tag{10}
\]

\[
\frac{\partial \phi}{\partial X} = (X + 0.622) \times P_{sv} \tag{11}
\]

\[
\frac{\partial \phi}{\partial T} = \frac{\phi}{P_{sv}} \times \frac{\partial P_{sv}}{\partial T} \tag{12}
\]

\[
\phi = \frac{PX}{P_{sv}(0.622 + X)} \tag{13}
\]

Properties used for simulation is shown in Table 2.

**Validity of numerical model**

Comparisons of the variation of outlet temperature during 7 days in summer and winter are shown in Figure 4 and 5, respectively. As shown in both figures, calculated results almost agree with measured values in summer and winter. Its difference is less than 0.5°C. Comparisons of the variation of outlet humidity during 7 days in summer and winter are shown in Figure 6 and 7, respectively.

The mean difference between measurement and calculation in summer and winter is 0.5g/kg. D.A., 0.2g/kg.

| Table 1. The condition of simulation |
|-------------------------------------|
| Length of tube | 60m |
| Sectional area of tube | Width: 7m, Height: 1.4m |
| Air conditioning period | June ~ September in summer, December ~ March in winter |
| Air conditioning schedule | 8:00~18:00 except Sunday |
| Indoor temperature and humidity | Summer: 26°C, 50% uniformity, Winter: non-air conditioning period: 15°C, air conditioning period: 18°C, 50% |
| Inter-phase: mean value between summer and winter season |
| Air velocity in tube | Air conditioning period: 0.18 m/s, non-air conditioning period: 0.09 m/s |
| Disturbance | Outside-air temperature, long wave radiation, solar radiation |
| Temperature deep in the ground | 14.3°C |
| Heat transfer coefficient in indoor | 9.3 W/m²K |
| Heat transfer coefficient in tube | \( \alpha = 6.2 + 4.2 \times v \) [W/m²K] |
| Finite-difference schema | Convection: the upwind method, Diffusion term: central-difference, Time term: forward-difference. |

| Table 2. Property used for simulation |
|--------------------------------------|
| \( c_s \rho_s \) | 2800 [KJ/(m³*K)] |
| \( c_c \rho_c \) | 1900 [KJ/(m³*K)] |
| \( \rho_s \) | 1000 [kg/m³] |
| \( c_s \rho_s \) | 1.2 [KJ/(m³*K)] |
| \( \lambda_s \) | 2.9 [W/(m*K)] |
| \( \lambda_c \) | 1.5 [W/(m*K)] |
| \( r \) | 0.0035 [kg/m³h(kg/kg.D.A.)] |
| \( r \) | 2470 [KJ/kg] |
| Linear Eq. Summer: | 6155.9 [kg/m³(kg/kg.D.A.)] |
| \( \kappa \) Winter: | 4848.3 [kg/m³(kg/kg.D.A.)] |
| Linear Eq. Winter: | Year: 11761.4 [kg/m³(kg/kg.D.A.)] |
| \( \nu \) | 5.59 [kg/m³°C] |
| \( \kappa \) Winter: | 1.14 [kg/m³°C] |
| Linear Eq. Summer: | Year: 6.58 [kg/m³°C] |
| \( c' \) | 0.15 [m³/m³] |
| \( \alpha \) | 9.3 [W/(m²*K)] |
| \( \alpha \) | 6.2+4.2*v [W/(m²*K)] |
| \( \alpha \) | \( \alpha / C_\alpha [kg/m³h(kg/kg.D.A.)] \) |
kg.D.A, respectively. Calculated value is somewhat smaller than measured value, but calculated results almost agree with measured values.

From these results, it is confirmed that the proposed theoretical model based on hygroscopic humidity is valid to predict moisture behavior of the system.

**Linear calculation using constant value of \( \kappa \) and \( \nu \)**

As mentioned above, it is necessary to use a nonlinear calculation considering the change of \( \kappa \) and \( \nu \) to predict moisture behavior of the system, because these are generally dependent on temperature and humidity. However, nonlinear calculation taking into account coupled heat and moisture transfer in earth tube requires a huge computational task, calculating time, memory, and so on. Therefore, if it were possible to calculate them as constant values, it would be very useful as a design tool. In this system, needless to say that the annual mean change of air temperature and humidity in the earth tube is smaller than that of the ambient. So the possibilities to apply linear calculation using three types of constant value of \( \kappa \) and \( \nu \) are investigated.

It is compared with three cases proposed as follows.
(1) Linear calculation by use of an annual mean value of outdoor air temperature (case1).
(2) Linear calculation by use of a seasonal mean value of outdoor air temperature in summer and winter, respectively (case2).
(3) Linear calculation by use of a mean value of case1 and case2 (case3).
(4) Nonlinear calculation using the boundary adsorption isotherm curve (case4 reference).

Figure 8 and 9 show comparisons of humidity ratio and relative humidity by nonlinear calculation (case4) and linear calculations (case1–case3) in summer and winter, respectively. The temperature results by linear calculations are omitted in this paper because the results are in good agreement with the nonlinear calculation result. The daily mean differences between humidity ratio and relative humidity variations of case1 and those of case4 during a summer day are 0.2g/kgD.A. and 1.4%. Calculated results of case2 and case3 during a summer day are almost equal and the differences with those of case4 are less than 0.1g/kgD.A. and 0.8% during a summer day.

The daily mean differences between humidity ratio and relative humidity variations of case1 and those of case4 during a winter day are 0.2g/kgD.A. and 3.3%. The daily mean differences between humidity ratio and relative humidity variations of case2 and those of case4 during a winter day are 0.15g/kgD.A. and 2.2%. Case3 is in good agreement with case4 during a winter day, the difference with case4 of humidity ratio and relative humidity was less than 0.035g/kgD.A. and 0.49%.

From these results, linear calculation by use of \( \kappa \) and \( \nu \) of case3 is applied to examine the reducing effect of fresh air latent heat load by the earth system.
Reducing effect of a fresh air load in usual weather condition region

In this section, the reducing effect of fresh air latent heat load in summer under the usual weather condition is examined quantitatively. The weather data used for the simulation is Tokyo standard weather data in JAPAN supported in the HASP. The calculated condition is the same value shown in Table 1.

Figure 10 and 11 show the amount and the peak of fresh air latent load in summer respectively. As shown in Figure 10, although the length of tube increased, there was almost no change of the amount of fresh air latent heat load in summer. The amount of fresh air latent heat load reduction at 100m was 2.2 GJ, and it means cutting down 1.9% of fresh air latent load in summer. On the other hand, as shown in Figure 11, as the length of the tube wall increases, the reduction effect of peak load is relatively large. The amount of fresh air latent heat load reduction at peak at 100m was 28.8 MJ/h, and it means cutting down 15% of fresh air latent load.

From these results, under usual weather condition, it was confirmed that there is very small reducing effect of the amount of fresh air latent heat load in summer, but the system is useful to reducing a fresh air latent load at peak.

Reducing effect of a fresh air load in high humidity weather condition region

The mean relative humidity of Tokyo using as usual weather condition in summer is 76.7%, however, there are not few regions of high humidity during summer in Japan. Therefore, the reducing effect of fresh air latent heat load in the region with high humidity during summer is investigated. The weather data used for the simulation is Tokyo standard weather data and the mean relative humidity in summer was only raised to 85%.

Figure 12 shows the amount of fresh air latent heat load in summer. As the length of the tube increases, fresh air heat load is reduced. The amount of a fresh air latent heat load reduction in summer at 100m was 17.8 GJ, and it means cutting down 10% of fresh air latent load in summer.
summer. Figure 13 shows the peak of fresh air latent heat load in summer. As the length of the tube using as earth tube increases, a fresh air latent heat load is reduced. The amount of fresh air latent heat load reduction at peak at 100m was 66.6MJ/h, it means cutting down 24% of fresh air latent load at peak.

From these results, for the supposed region with very high humidity during summer, it was confirmed that earth tube is useful system for reduction of a fresh air latent heat load. The result as the air velocity in earth tube changed is omitted in this paper because the same result as mentioned above was obtained.

Conclusion
To examine the reducing effect of fresh air latent heat load by the earth tube system, 2-dimensional model using coupled heat and moisture in a hygroscopic region is proposed.
1. The measured air temperatures and humidity of earth tube in actual building were compared with calculated results using a simplified numerical model. In conclusion, they were in good agreement.
2. To simplify calculation, the possibility to apply linear calculation using constant values of $\kappa$ and $\nu$ was investigated. The linear calculation using the mean value of seasonal value and annual value of $\kappa$ and $\nu$ in summer and winter was applied to examine the reducing effect of fresh air latent heat load by earth system.
3. When the ground-water table position in the place where it is installed is considerably deep (ex. top of the hill and so on.), the reducing effect of a fresh air latent heat load under usual weather condition and high humidity weather condition in summer was examined.
4. Under usual weather condition, it was confirmed that there is little reducing effect of the amount of fresh air latent heat load in summer, but the system is useful to reducing a fresh air latent load at peak in summer.
5. For the supposed region with very high humidity during summer, it was confirmed that earth tube is not only useful system for reducing the amount of fresh air latent heat load in summer, but also effective as a reducing system for fresh air latent heat load at peak.

Nomenclature
- $c$: specific heat [J/m$^2$K]
- $c'$: porosity [m$^2$/m$^2$]
- $H$: height of pit [m]
- $P$: standard atmospheric pressure [Pa]
- $P_{sv}$: saturation water vapour pressure [Pa]
- $r$: latent heat of vaporization [J/kg]
- $T$: temperature [°C]
- $t$: time [s]
- $V$: air velocity [m/sec.]
- $X$: humidity ratio [kg/kg D.A.]
- $x$, $y$: length, depth [m]
- $\alpha$: heat transfer coefficient [W/m$^2$K]
- $\alpha_i$: heat transfer coefficient of indoor [W/m$^2$K]
- $\alpha'$: vapour transfer coefficient [kg/m$^2$h(kg/kg.D.A.)]
- $\rho$: moisture content [m$^3$/m$^3$]
- $\kappa$: thermal conductivity [W/mK]
- $\kappa'$: water vapour conductivity [kg/mh(kg/kg.D.A.)]
- $\rho_s$: specific weight of material [kg/m$^3$]
- $\rho_a$: density of air [kg/m$^3$]
- $\rho_w$: density of water [kg/m$^3$]
- $\sigma$: relative humidity [%]

*Subscript
- $a$: air
- $c$: concrete
- $cu$, $cd$: upper, lower concrete surface in the double slab space
- $s$: soil

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