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Theoretical assessment of the combined effects of building thermal mass and earth–air-tube ventilation on the indoor thermal environment

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ABSTRACT

Both earth-tube systems and building thermal mass have the potential to provide desired performance levels for both indoor thermal comfort and energy saving; however, their coupling effects need to be further investigated. A model for evaluation of the combined effects of earth-tube ventilation systems and building thermal mass is proposed. Both the time-averaged indoor air temperatures and periodic temperature fluctuations are given as explicit formulas. Unlike the time lag induced by the separate use of building thermal mass, which is no longer than 6 h, the combination with an earth-tube system could extend the time lag of indoor air temperature in an annual fluctuation period by tens of days and that of a daily period by a couple of hours. It is noticeable that the building thermal mass has significant impact on the effectiveness of earth-tube systems; therefore, a small heat transfer coefficient of external envelopes helps increase the annual time lag of indoor air temperature. Using a proper combination of building thermal mass and earth tubes, indoor thermal comfort can be achieved for a building located in a region with both hot summers and cold winters without any additional cooling or heating load.

1. Introduction

Achieving indoor thermal comfort using less energy has been an important issue and also a great challenge for our society. Nowadays, several passive measures are used to substitute for or to complement traditional heating, ventilating and air-conditioning (HVAC) systems [1–5]. An appropriate coupling of the thermal mass and ventilation has the potential to improve indoor thermal environment [6–9]. The thermal mass contained in a building is classified into two categories [8]: the indoor thermal mass, which is not exposed to ambient air, e.g., furniture and internal concrete partitions, and the external thermal mass, e.g., external walls and roofs, that is exposed both to the ambient and indoor air. The working principle of the thermal mass is absorbing heat from indoor air when the temperature of thermal mass is lower than the indoor air temperature and releasing heat to indoor air when the its temperature is higher than the indoor air temperature. As the outdoor air temperature varies periodically, the indoor air temperature follows periodical changes, as well, but with both different phase shift and fluctuation amplitude from the outdoor air temperature. Yam et al. [7] and Zhou et al. [8] developed theoretical models about the fluctuation of indoor air temperature in a passively ventilated building integrated with thermal mass. The indoor air temperature fluctuations were correlated with two parameters, i.e., the time constant, $\tau = MC_M/\rho_a C_a q$, and the dimensionless convective heat transfer number, $\lambda = h_2 S_M/\rho_a C_a q$ [7,8]. Yam et al. [7] assumed that the building envelope is perfectly insulated and showed that the maximum time lag of indoor air temperature is 6 h. Zhou et al. [8] incorporated the effects of external envelopes but neglected the temperature difference between the internal thermal mass and the indoor air. The above studies indicate that the separate use of building thermal can achieve a time lag of a couple of hours.

The underground thermal mass can also be used in passive ventilation. Ventilation through earth–air tubes, currently also known as earth to air heat exchangers (EAHEs), is a prevalent technology [1]. The soil temperature at a sufficient depth is lower than the outside air

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Nomenclature

A	fluctuation amplitude of air temperature (K)
b_w	thickness of external envelopes (m)
C_a	specific heat of air (J/kg K)
C_M	specific heat of internal thermal mass (J/kg K)
D	dimensionless residence time of ventilated air
E	indoor heat release rate (W)
h_1	heat transfer coefficient at the earth–air-tube walls (W/m^2 K)
h_2	heat transfer coefficient at the surface of internal thermal mass (W/m^2 K)
h_4	heat transfer coefficient at the inner surface of external envelopes (W/m^2 K)
h_5	heat transfer coefficient at the outer surface of external envelopes (W/m^2 K)
I	solar irradiance (W/m^2)
I_n	first kind of modified Bessel functions of order n
K	overall heat transfer coefficient of earth–air-tube (W/m K)
k_a	thermal conductivity of air (W/m K)
K_e	effective heat transfer coefficient of external envelopes (W/m^2 K)
K_n	second kind of modified Bessel functions of order n
M	mass of internal thermal mass (kg)
$\dot{m}_a$	mass flow rate of ventilation air (kg/s)
N_p	quantity of earth–air-tube
P	fluctuation period (s)
q	volume flow rate of ventilation air (m^3/s)
r	the radius coordinate (m)
R	radius of earth–air-tube (m)
R_0	radius of soil annulus surrounding air-tube (m)
R_{tot}	total resistance of earth–air-tube per unit of length (m K/W)
R_w	total thermal resistance of external envelopes (m^2 K/W)
S	surface area (m)
T	temperature (K)
V_a	air velocity in the earth–air-tube (m/s)
V_i	internal volume of building (m^3)
x	length of earth–air-tube (m)
z	burial depth of earth–air-tube (m)

Greek symbols

α_s	thermal diffusivity of the soil (m^2/s)
θ_n	phase shift of air temperature of air-tube with respect to outdoor air (rad)
V_e	damping factor of inner surface temperature of external envelope with respect to sol–air temperature
V_f	damping factor of inner surface temperature of external envelope with respect to indoor air temperature
$\kappa_{sol-air}$	normalized fluctuation amplitude of sol-air temperature with respect to the outdoor air temperature
κ_i	normalized fluctuation amplitude of indoor air temperature with respect to outdoor air
κ_n	normalized fluctuation amplitude of air temperature of air-tube with respect to outdoor air
λ	dimensionless convective heat transfer number of internal thermal mass
λ_e	thermal conductivity of external envelopes (W/m K)
λ_s	thermal conductivity of soil (W/m K)
λ_w	dimensionless convective heat transfer number of external thermal mass
λ'_w	dimensionless effective heat transfer number of external thermal mass
ρ_a	density of air (kg/m^3)
ρ_e	absorption coefficient of outer surface of external envelopes
τ	time constant of ventilation system (s)
φ_e	phase shift of inner surface temperature of external envelope with respect to sol–air temperature (rad)
φ_f	phase shift of inner surface temperature of external envelope with respect to indoor air temperature (rad)
φ_g	phase shift of ground surface temperature with respect to the outdoor air temperature (rad)
φ_i	phase shift of indoor air temperature with respect to outdoor air (rad)
φ_s	phase shift of soil temperature with respect to outdoor air (rad)
ω	frequency of outdoor temperature variation (s^{-1})

Superscript

$-$	time-averaged value
$\sim$	time-dependant value
$\frown$	Laplace transformation