Building and Environment 85 (2015) 29–39

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Analysis and experiments on the periodically fluctuating air temperature in a building with earth-air tube ventilation

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ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form
18 November 2014
Accepted 19 November 2014
Available online 28 November 2014

Keywords:
Indoor thermal environment
Fluctuating air temperature
Earth-air tube
Passive cooling
Coupled ventilation system

ABSTRACT

A more thermally comfortable indoor environment with cooler indoor air in summers but warmer air in winters could be achieved by the use of earth-air tube ventilation. The periodically fluctuating behavior of indoor air temperature, which characterizes the indoor thermal environment, is not determined from the earth-air tube system alone but by the coupling of earth-air tube ventilation and the thermal mass contained in a building. A model for the coupling effects of earth-air tube ventilation and building thermal mass on periodically fluctuating air temperature has been previously developed (Yang et al., Energy and Buildings 81: 182–199, 2014). This paper integrates both the yearly and daily fluctuations of air temperature into unified equations. A method for determining the penetration depth of the oscillating tube-air temperature wave in the surrounding soil is proposed to enhance the model accuracy. An experiment was conducted to test the model, and the model predictions show good agreement with the measured data. The roles played by the key engineering parameters with respect to the overall efficiency of the combined system were analyzed. The findings suggest that the effectiveness of an earth-air tube ventilation system cannot be quantified in isolation from the building characteristics. This model is helpful to the optimization of the coupled system.

1. Introduction

Air conditioning and heating have been widely employed for achieving the thermal comfort for building occupants. However, the conventional heating, ventilation, and air conditioning (HVAC) system can use a large amount of energy and increase a building's associated carbon emissions. Numerous alternative techniques, especially sustainable and passive ones, have been explored to reduce energy consumption of buildings. Linden et al. described the principles of displacement ventilation of buildings [1]. Livermore and Woods [2], Yang et al. [3,4], Acred and Hunt [5] and Shi et al. [6] described the use of natural, stack ventilation of buildings. Karava et al. explored mixed-mode cooling strategies in buildings with hybrid ventilation and thermal mass [7]. Ji et al. [8] and Fan et al. [9] investigated the efficiency of shaft ventilation of underground buildings, e.g., tunnels. Another possibility is the adoption of the earth-air tube ventilation system, as also known as earth-to-air heat exchangers (EAHE), ground-coupled heat exchangers, or earth channels. Santamouris et al. reviewed the application of EAHEs in both ordinary buildings and agricultural green houses [10]. Ozgener reviewed both the experimental and analytical studies of EAHEs in Turkey and around the world [11]. A literature research was performed by Peretti et al. in order to analyze the design of EAHEs [12].

An earth-air tube ventilation system uses underground soil as a heat source or sink and air as the medium of heat exchange [13]. Outdoor air is drawn into the earth-air tubes before being supplied to the objective building, rather than being introduced into the building directly (Fig. 1). When air passes through the earth-air tubes, heat is transferred between the soil and ventilation air. Due to the delayed thermal response of soil, the temperature of the soil at a sufficient depth is lower than ambient in summer but higher in winter [14,15]. As a result, the air is pre-cooled by the soil in summer and pre-heated in winter. Furthermore, the earth-air tubes could dampen the amplitude of air temperature fluctuation. This property achieves both a relatively stable temperature and a greater phase shift of supplied air with respect to outdoor air temperature. These benefits have directed researchers and

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http://dx.doi.org/10.1016/j.buildenv.2014.11.019
0360-1323/

Nomenclature

A	fluctuation amplitude of air temperature (K)
ACH	air change rate per hour (h^{-1})
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 ventilation air
E	heat load of building (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_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)
N_p	quantity of earth-air tube
P	fluctuation period (s)
q	volume flow rate of ventilation air (m^3/s)
r	radial coordinate (m)
R	radius of earth-air tube (m)
R_0	penetration radius (m)
R_{tot}	total resistance of earth-air tube per unit of length (m 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)
κ_g	normalized fluctuation amplitude of ground surface 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 tube-air temperature with respect to outdoor air
$\kappa_{sol\text{-}air}$	normalized fluctuation amplitude of sol-air temperature 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
ν_e	normalized fluctuation amplitude of inner surface temperature of external envelope with respect to sol-air temperature
ν_f	normalized fluctuation amplitude of inner surface temperature of external envelope with respect to indoor air temperature
ρ_a	air density (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	fluctuating frequency (s^{-1})

Superscript

—	time-averaged value
~	time-dependant value
⌢	Laplace transformation

Subscript

e	external envelopes
i	indoor air
M	internal thermal mass
n	earth-tube air
o	outdoor air
s	soil
sol-air	sol-air temperature
y; d	values of annual or daily fluctuation period

engineers towards the use of earth-air tube ventilation for passive heating and cooling applications. Previous studies indicated that the earth-air tube system could apply to different climate conditions in regions such as Italy [16], Turkey [11], Malaysia [17] and Kuwait [18].

The effectiveness of an earth-air tube ventilation system is closely related to the air temperature at the tube outlet. Because both the outdoor air and soil temperatures could be harmonic functions of time, the air temperature at the tube outlet can also be represented as a time-harmonic function but probably with different time-averaged temperature, fluctuation amplitude and phase shift. Numerous studies have focused on the calculation of air temperature at earth-air tube outlet and some analytical or numerical models have been derived for it. Darkwa et al. proposed a model to evaluate the energy efficiency of an earth-air tube system [19]. Shukla et al. developed a thermal model for green houses using earth-air tube systems for heating [20]. Kumar et al. used a numerical model to predict the energy conservation potential of EAHEs in a non-air-conditioned building [21]. Krarti et al. developed a simple model to predict the air temperature variation along the earth-air tube [22]. Hollmuller developed an analytical model to characterize the fluctuation of air temperature at the outlet of an