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Coupling of earth-to-air heat exchangers and buoyancy for energy-efficient ventilation of buildings considering dynamic thermal behavior and cooling/heating capacity

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ABSTRACT

Energy-efficient technologies such as earth-to-air heat exchangers (EAHEs) and buoyancy-driven natural ventilation (BV) are employed for space conditioning. However, a fan is required in conventional EAHEs for air circulation, and BV normally serves as a passive cooling measure in temperate transitional seasons. This paper proposes the coupling of EAHEs and the buoyancy generated inside a building to achieve passive and autonomous ventilation without requiring any mechanical system. A model is developed to investigate the effects of the coupled system, with a primary focus on the dynamics of the airflow temperature, flow rate, and cooling/heating capacity provision. The model results are in good agreement with those of the computational fluid dynamics simulation. The model is applied in a hypothetical building located in a hot-summer/cold-winter region (Chongqing, China). The proposed coupled scheme is superior to the BV in hot and cold seasons. The indoor air temperature, ventilation flow rate, and cooling/heating capacity are found to fluctuate asynchronously. The cooling capacity is 56.3 kWh for the hottest day, and the heating capacity is 111.1 kWh for the coldest day. The maximum cooling or heating capacity is nearly achieved at the hottest or coldest times with the help of ventilation flow rate fluctuation.

1. Introduction

To maintain a comfortable indoor thermal environment, active heating, ventilation, and air conditioning (HVAC) devices are usually employed in buildings. The energy consumed by HVAC devices accounts for approximately 30–50% of the total energy consumption of the building [1,2]. Electricity is the main source of energy consumed by HVAC, and its generation process consumes a significant amount of fossil fuels and causes environmental pollution [3–5]. To decrease the energy consumed by HVAC devices, many passive technologies have been developed in recent years, such as natural ventilation [6–12], solar energy [5,13], geothermal energy [5,14,15], and wind energy [16].

Earth-to-air heat exchangers (EAHEs), a passive measure, have received a significant amount of attention worldwide [5,14,15,17–26]. Studies have explained the heat transfer occurring in the pipes of an EAHE. Hollmuller [18] analyzed the temporal variation in the air temperature of a circular EAHE pipe in the case with a constant airflow rate and sinusoidal-type temperature input. Hollmuller and Lachal [19] provided climate-independent design guidelines for dampening the temperature fluctuation and analyzed the advantages and limitations. However, the yearly or daily variation in the soil temperature was not directly included in the analysis. Because the temperature of a shallow soil layer fluctuates in an annual climatic period [20], Yang et al. proposed an analytical approach to evaluate the performance of EAHEs subjected to a periodically fluctuating ambient air temperature and fluctuating soil temperature [21]. They incorporated the concept of an “excess fluctuating temperature” to consider the variation in the soil temperature around the pipes due to the interaction between the temperature wave transmitted from the ground surface and that emitted from the EAHE pipes. The model results indicate that an EAHE pipe could decrease the air temperature by 7 °C and produce a cooling capacity of 3000 W on a summer day. Bansal et al. [22] developed a transient and implicit model based on

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Nomenclature

A	temperature fluctuation amplitude (K)
A_b	opening area of the bottom inlet (m^2)
A_n	fluctuation amplitude of EAHE pipe outlet temperature (K)
A_q	fluctuation amplitude of the ventilation flow rate (m^3/s)
$A_{s,z}$	fluctuation amplitude of soil temperature at the depth of z (K)
A_t	opening area of the upper outlet (m^2)
A^*	effective opening vent area (m^2)
C_a	specific heat capacity of air (J/(kg·K))
C_d	discharge coefficient
C_M	specific heat capacity of the internal thermal mass (J/(kg·K))
C_s	specific heat capacity of the soil (J/(kg·K))
d	diameter of the EAHE pipe (m)
D	dimensionless air exchange time for the interior space
E	effective heat input (W)
F	combination of modified Bessel functions
g	acceleration due to gravity (m/s^2)
h	height difference between two openings (m)
h_1	convective heat-transfer coefficient of the inner surface of the EAHE pipe (W/(m^2·K))
h_2	convective heat-transfer coefficient of the surface of the internal thermal mass (W/(m^2·K))
i	the imaginary unit
K_e	effective heat transfer coefficient of the building surface (W/(m^2·K))
L	length of the EAHE pipe (m)
M	mass of the internal thermal mass (kg)
Nu	Nusselt number
P	fluctuation period (s)
Pr	Prandtl number
q	ventilation flow rate (m^3/s)
r	radius of the internal thermal mass (m)
Q	heating or cooling capacity (W)
Q_d	characteristic geometric parameter (m^6/s^2)
Re	Reynolds number
R	radius of the EAHE pipe (m)
S_e	area of the building surface (m^2)
S_M	area of the internal thermal mass surface (m^2)
T	temperature (K)
$T_n(x)$	EAHE pipe air temperature as a function of distance x (K)
T_n	air temperature at the EAHE pipe outlet (K)
T_R	inner surface temperature of the EAHE pipe (K)
$T_{s,z}$	soil temperature at the depth of z (K)
t	time (s)
u	bulk flow velocity (m/s)
V_i	volume of the building (m^3)
x	position along the length of the EAHE pipe (m)

Greek symbols

α_s	thermal diffusivity of the soil (m^2/s)
θ	dimensionless heat input of the building
λ	dimensionless convective heat transfer number of the internal thermal mass
λ'	friction factor
λ_a	thermal conductivity of air (W/(m·K))
λ_s	thermal conductivity of the soil (W/(m·K))
λ_M	thermal conductivity of the thermal mass (W/(m·K))
λ'_w	dimensionless effective heat transfer number of the building envelopes
μ	dynamic viscosity coefficient of air ((N·s)/m^2)
ν	kinematic viscosity coefficient of air (m^2/s)
ρ_a	air density (kg/m^3)
τ	dimensionless time constant for measuring the thermal storage capability of the internal thermal mass
ϕ_i	phase shift of the indoor air temperature with respect to the outdoor air temperature (rad)
ϕ_M	phase shift of the internal thermal mass temperature with respect to the outdoor air (rad)
ϕ_n	phase shift of the outlet air temperature of the EAHE with respect to the outdoor air temperature (rad)
ϕ_q	phase shift of the ventilation flow rate with respect to the outdoor air temperature (rad)
$\phi_{s,z}$	phase shift of the soil temperature with respect to the outdoor air temperature (rad)
ω	fluctuation frequency (s^{-1})

Superscripts

$-$	time-averaged term
$\sim$	fluctuation term

Subscripts

g	ground surface
ini	initial condition
i	indoor air
M	internal thermal mass
n	EAHE outlet air
o	outdoor air
s	soil
w	external wall
$y; d$	values of the annual or daily fluctuation periods
z	depth
$t; b$	top opening or bottom opening

computational fluid dynamics (CFD) to predict the heating capacity of EAHEs. They demonstrated that the increase in the temperature of a pipe system with a length of 23.42 m is in the range of 4.1–4.8 °C for flow velocities in the range of 2–5 m/s on a winter day. Al-Aimi et al. [23] developed a model to predict the outlet air temperature and cooling potential of EAHEs for a hot and arid climate. They showed that EAHEs could yield a reduction in the peak cooling load of 1700 W and reduce the cooling energy demand by 30% over the summer season. Khabbaz et al. [24] performed investigations on EAHEs installed on a residential building in a hot semiarid climate. Their TRNSYS simulations show that the air temperature could be decreased by 19.5 and 18.3 °C for one and three pipes, respectively, using EAHEs [24].

The airflow circulation is crucial for both enhancing the heat exchange in underground EAHE pipes and delivering the heating or cooling capacities produced by the EAHEs to the interiors of a building. Currently, mechanical driving systems are largely used to circulate the flow for EAHEs. However, the mechanical driving system used for air circulation consumes electricity, and the operation of electrical machinery could release excrescent heat to the