International Journal of Heat and Mass Transfer 96 (2016) 218–230

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Fluctuation of natural ventilation induced by nonlinear coupling between buoyancy and thermal mass

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ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form 5 January 2016
Accepted 6 January 2016
Available online 25 January 2016

Keywords:
Thermal mass
Natural ventilation
Buoyancy
Anharmonic oscillation
High-frequency fluctuation
Nonlinear effects

ABSTRACT

The coupling between thermal mass and buoyancy-driven natural ventilation has great potential for passive regulation of indoor thermal environment. The nonlinearity associated with the use of this coupled mode has attracted great attention. Theoretical models have been developed for decoupling indoor air temperature and ventilation flow rate for buildings exposed to harmonically fluctuating external thermal environments. However, the solutions in existing models are implicit and only the main fluctuation frequency of indoor environmental parameters is accounted for. This paper focuses on multi-frequency fluctuation behaviors induced by the coupling between thermal mass and buoyancy-driven natural ventilation. A mathematical approach is undertaken to decouple the indoor air temperature and ventilation flow rate, and explicit solutions are obtained for both the phase shift and fluctuation amplitude of the indoor air temperature and ventilation flow rate at various frequencies. Experiments are performed to validate the theoretical analysis. Both analytical and experimental results show that coupling between thermal mass and buoyancy inside a building can lead to multi-frequency (or anharmonic) fluctuation of natural ventilation. The phase shifts of the high-order indoor air temperature fluctuation terms (with respect to the 1st-order outdoor air temperature fluctuation term) can exceed $\pi/2$.

1. Introduction

The energy consumption of buildings is responsible for about 30–45% of global energy demand, of which most is used for maintaining thermally comfortable indoor environments, i.e., space heating or cooling (i.e., air-conditioning) of buildings. In China, space heating or cooling energy consumption accounts for about 19% of the national total energy consumption of the country [1]. In the UK, 40% of the country's energy consumption and carbon emissions come from buildings [2]. The desire to achieve satisfactory performance levels in both indoor thermal environments and energy conservation drives people to seek passive measures and technologies. Buoyancy-driven natural ventilation is widely used for passive cooling of buildings and improving occupants' satisfaction with the indoor environment [3]. The principle of buoyancy-driven natural ventilation is to remove contaminated air, excess heat, humidity, and unwanted substances from interior spaces by using the hydrostatic pressure produced by the temperature difference between the internal and external air, thus achieving indoor environments at comfortable temperature and humidity levels [4]. Flow characteristics induced by natural ventilation and its effects on the indoor thermal environment have attracted great attention [5,6]. However, passive cooling by natural ventilation is only applicable when the outdoor climate is temperate [7].

An alternative low-energy solution is to utilize the thermal storage effects of a building's structure to regulate indoor thermal environments [8–10]. The diurnal temperature variation of structural thermal mass generally lags behind that of environmental air temperature, with the result that the temperature difference between the exposed structure of a building and the incoming air facilitates heat exchange between them. The exposed building structure functioning in this manner is termed thermal mass, and a thermal mass without a route for heat transmission to the environment is termed an internal thermal mass [11]. Both the components of a building (e.g., concrete floor slabs exposed to indoor air) and the furniture contained inside can play the role of the internal thermal mass, which stores heat when incoming air is warmer than the thermal mass and releases heat when the incoming air becomes cooler. The use of thermal mass can both dampen the fluctuation of indoor air temperature and produce a time lag with

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.01.017
0017-9310/

Nomenclature

A_b	area of the bottom inlet vent (m^2)
A_i	indoor air temperature fluctuation amplitude (K)
A_M	thermal mass temperature fluctuation amplitude (K)
A_q	ventilation flow rate fluctuation amplitude (m^3/s)
A_t	area of the top outlet vent (m^2)
A_0	outdoor air temperature fluctuation amplitude (K)
A^*	effective vent area of both the inlet and outlet vents (m^2)
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)
C_d	discharge coefficient
d	diameter of steel ball (m)
D	dimensionless air exchange time for the interior space
E	effective heat input (W)
g	acceleration of gravity (m/s^2)
h	height between the top and bottom openings (m)
h_1	heat transfer coefficient at the inner surfaces of envelopes (W/m^2 K)
h_2	heat transfer coefficient at the surface of steel balls (W/m^2 K)
i	the imaginary unit
K_e	effective heat transfer coefficient at the building envelopes (W/m^2 K)
M	mass of internal thermal mass (kg)
n	infinite natural number
Nu	Nusselt number
N	truncated position of the Fourier series
P	fluctuation period (s)
Pr	Prandtl number
q	ventilation flow rate (m^3/s)
Q_d	a characteristic geometric parameter (m^6/s^2)
Re	Reynolds number
S_e	surface area of building envelopes (m^2)
S_M	surface area of internal thermal mass (m^2)
T_i	indoor air temperature (K)
T_M	internal thermal mass temperature (K)
T_0	outdoor air temperature (K)
t	time (s)
u	bulk flow velocity inside a building (m/s)
V_i	volume of interior space of a building (m^3)

Greek symbols

α_w	thermal diffusivity of building envelopes (m^2/s)
δ	periodic thermal penetration depth for a plate (m)
θ	dimensionless temperature difference between indoor and outdoor air
λ	dimensionless convective heat transfer number of internal thermal mass
λ_a	thermal conductivity of air (W/m K)
λ'_w	dimensionless effective heat transfer number of building envelopes
μ	air viscosity (N s/m^2)
ν	kinematic viscosity coefficient of air (m^2/s)
ρ_a	air density (kg/m^3)
τ	dimensionless time constant to measure thermal storage capability of internal thermal mass
$\varphi_{i,j}$	phase shift of indoor air temperature with respect to outdoor air temperature at the jth-order fluctuation frequency (rad)
$\varphi_{M,j}$	phase shift of internal thermal mass temperature with respect to outdoor air temperature at the jth-order fluctuation frequency (rad)
$\varphi_{q,j}$	phase shift of ventilation flow rate with respect to outdoor air temperature at the jth-order fluctuation frequency (rad)
ω	the main angular frequency of a fluctuation cycle, $\omega = 2\pi/P$, (s^{-1})

Superscript

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

respect to the variation in ambient air temperature [10]. Therefore, in relatively hot weather, thermal mass material can be cooled by incoming air at night and then used as a heat sink to reduce the peak cooling loads in the daytime. Night ventilation is based on this principle. Alternatively, in cooler weather the heat stored in the thermal mass during the daytime, which may be enhanced by solar gains, is released into interior spaces in the late afternoon and can partly satisfy heating needs. Both the phase shift and fluctuation amplitude of indoor air temperature are related closely to the effectiveness of using thermal mass and thus are of primary interest. Previous works focused mainly on the response of buildings with a constant ventilation flow rate and harmonic variation of environmental temperature, e.g., Mathews [12]. Yam et al. [10] proposed three parameters that control a dynamical system coupled with ventilation and thermal mass. The theoretical analysis of Yam et al. indicated that the maximum phase lag of the interior air temperature with respect to the outside air is $\pi/2$. Yang et al. [13,14] proposed a methodology for decomposing the heat balance equations into time-averaged components and fluctuating components, and explicit expressions describing the periodic variation of indoor air temperature were obtained. For an insulated building with a forced constant ventilation flow rate, the variation in indoor air temperature obtained by Yang et al. agrees well with that of Yam et al. The model proposed by Yang et al. can also incorporate thermal storage effects of earth-to-air heat exchangers and external thermal mass.

Buoyancy-driven natural ventilation can be coupled with thermal mass. For thermally massive buildings, this could be more commonplace for natural ventilation. As shown in Fig. 1, in this coupled mode buoyancy acts as the driving force for both mass and heat exchange between the interior air and the external environment; the thermal mass could be partially or totally responsible for regulating indoor air temperature variation. This coupled ventilation strategy could have greater applicability in case of outdoor climate variation than natural ventilation without thermal mass coupling. However, other difficulties in dealing with the coupling of buoyancy-driven ventilation and thermal mass may arise. The reason is that buoyancy-driven natural ventilation and thermal mass are coupled in a nonlinear manner, as indicated by Yam et al. [10]. This leads to the fact that both the indoor air temperature and ventilation flow rate vary periodically but asynchronously. In Yam et al., if the environmental air temperatures were set to be harmonically varying (i.e., fluctuating at a single frequency), approximately harmonic variations in indoor air temperature were found from numerical solutions. Furthermore, Yam et al. indicated that the phase shift between the indoor and outdoor air temperatures varies between 0 and 6 h; however, the phase shift of ventilation flow rate varies between 6 and 12 h. Hol-