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Coupling of thermal mass and natural ventilation in buildings

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Abstract

The coupling of thermal mass and natural ventilation is important to passive building design. Thermal mass can be classified as external thermal mass and internal thermal mass. Due to great diurnal variation of ambient air temperature and solar radiation intensity, heat transfer through building envelopes, which is called external thermal mass, is a complex and unsteady process. Indoor furniture are internal thermal mass, affecting the indoor air temperature through the process of absorbing and releasing heat. In this paper, a heat balance model coupling the external and internal thermal mass, natural ventilation rate and indoor air temperature for naturally ventilated building is developed. In this model, the inner surface temperature of building envelopes is obtained based on the harmonic response method. The effect of external and internal thermal mass on indoor air temperature for six external walls is discussed of different configurations including lightweight and heavy structures with and without external/internal insulation. Based on this model, a simple tool is developed to estimate the indoor air temperature for certain external and internal thermal mass and to determine the internal thermal mass needed to maintain required indoor air temperature for certain external wall for naturally ventilated building.

Keywords: Thermal mass; Natural ventilation; Indoor air temperature; Harmonic response method

1. Introduction

Natural ventilation integrated with thermal mass is a passive cooling system that can be used to adjust the indoor environment to ensure indoor thermal comfort and maintain acceptable indoor air quality (IAQ). Ventilation can be used for three completely different purposes in a building: improving IAQ, providing cooling for people and cooling the thermal mass of the building [1]. The working principle of the last one is very simple—the thermal mass, including external and internal thermal mass, stores heat during a warm period and releases it at a later cool time during the day [2]. At the same time, good IAQ is usually a direct product of using natural ventilation systems as the outdoor air may dilute indoor pollutants. So the technology of coupling natural ventilation and thermal mass may be used to lower the capital, operational, and maintenance costs to obtain sustainability of building, as well as to improve its IAQ.

Previous researchers investigated much about night ventilation, one of the most important natural ventilation methods. The key parameters related to the efficiency of night ventilation can be divided into three groups, namely the climatic parameters, the building parameters and the technical parameters [3]. The outdoor air temperature, which includes mean daily temperature and diurnal temperature range, is the climatic potential index [3,4]. The building parameters include the building type, envelope openings such as windows and doors, building material, building structure, etc. Thermal mass, which is a function of building parameters, can increase the efficiency of night ventilation, since the inertia of the building increases with the increase of thermal mass. The effect of night ventilation can be observed in the next day's indoor temperature profiles, with a lower and delayed peak indoor air temperature [5]. The technical parameters include the operation period of the building and its ventilation system. All other natural ventilation methods have similar principles as night ventilation. Among all above parameters, this paper will investigate the factor of thermal mass and its impact on natural ventilation.

Based on its location, thermal mass of buildings can be divided into two basic types, i.e. the external thermal mass and

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Nomenclature

A	area of the inner surface of external wall (m^2)
A_i	amplitude of fluctuation of indoor air temperature (°C)
A_o	amplitude of fluctuation of outdoor air temperature (°C)
$A_{sol\text{-}air}$	amplitude of fluctuation of sol-air temperature (°C)
C	heat capacity of material (J/kg °C)
C_a	heat capacity of air (J/kg °C)
C_m	heat capacity of the internal thermal mass (J/kg °C)
D	index of thermal inertia
E	effective total heat power (W)
f_i	decrement factor of indoor air temperature
K	thermal conductivity of material (W/m K)
M	mass of internal thermal mass (kg)
q	ventilation flow rate (m^3/s)
R	total heat resistance of external wall (m^2 K/W)
R_0	heat resistance of external wall (m^2 K/W)
S	coefficient of thermal storage (W/(m^2 K))
t	time (h)
T_E	air temperature rise due to the inner steady state heat source (°C)
T_i	indoor air temperature (°C)
T_o	outdoor air temperature (°C)
$T_{sol\text{-}air}$	sol-air temperature (°C)
T_W	temperature of inner surface of external wall (°C)
$\bar{T}_i$	mean indoor air temperature (°C)
$\bar{T}_o$	mean outdoor air temperature (°C)
$\bar{T}_{sol-air}$	mean sol-air temperature (°C)
$\bar{T}_W$	mean inner surface temperature of external wall (°C)

Greek letters

α_i	total heat transfer coefficient of inner surface (W/m^2 K)
α_o	total heat transfer coefficient of external surface (W/m^2 K)
λ	heat transfer number
ν_e	damping factor of inner surface temperature respect to sol-air temperature
ν_f	damping factor of inner surface temperature respect to indoor air temperature
ν_i	damping factor of indoor air temperature respect to outdoor air temperature
ξ_e	time lag of inner surface temperature respect to sol-air temperature (h)
ξ_f	time lag of inner surface temperature respect to indoor air temperature (h)
ξ_i	time lag of indoor air temperature respect to outdoor air temperature (h)
ρ	density of material (kg/m^3)
ρ_a	density of air (kg/m^3)
τ	time constant (h)
φ_e	phase shift of inner surface temperature respect to sol-air temperature
φ_f	phase shift of inner surface temperature respect to indoor air temperature
φ_i	phase shift of indoor air temperature respect to outdoor air temperature
$\varphi_{sol\text{-}air}$	phase shift of sol-air temperature respect to outdoor air temperature
ω	frequency of outdoor temperature variation (h^{-1})

Subscripts

i	indoor air
o	outdoor air
sol-air	solar and outdoor air
W	inner surface of external wall

the internal thermal mass [2]. They have different impacts on natural ventilation.

The external thermal mass exposes directly both to the ambient and indoor air. General speaking, the external envelopes such as external walls and roofs belong to this category. They connect the outdoor environment and the indoor environment. The internal thermal mass, such as furniture and internal concrete partitions, does not expose directly to the ambient air but only to the indoor environment.

The heat transfer process of building envelopes can be a very complex phenomenon, involving convection, conduction and radiation. At the same time, the outdoor air temperature and solar radiation intensity change significantly during day and night. The indoor air temperature also varies with time in naturally ventilated buildings. In order to analyze the heat transfer of building envelopes, different methods were developed, such as harmonic response method, response factor method and Z transfer function method, etc. [6]. The harmonic response method is suitable for calculating heat transfer with periodically changing external air temperature. Through the harmonic response method, the decrement factor and the time lag of wall can be obtained. Therefore, it is widely used in thermal engineering calculation, design and analysis in heating, ventilation and air conditioning engineering [7,8].

Because that external wall is usually multi-layer structure, heat resistance, heat capacity and thickness of each layer affect the dynamic thermal behavior of wall [9,10]. Most of previous researchers focused on the impact of building envelopes on the heating/cooling loads of buildings assuming the indoor air temperature is constant [11,12]. Even though a building is naturally ventilated in summer, its mean indoor air temperature is considered as a constant, to be only 1.5 °C higher than the outdoor air temperature [13]. However, when a building is naturally ventilated, the indoor air temperature also varies periodically because of the impact of outdoor air temperature and ventilation rate [2], therefore it cannot be considered as a constant as in analyzing air-conditioned buildings. In 2002, Kossecka analyzed the impact of external wall and insulation location on the heating/cooling load for six typical wall configurations [14]. In 2006, Zhang numerically analyzed the ideal thermophysical properties for free-cooling/heating buildings, which are closely related to the outdoor climate condition, internal heat source intensity, building configuration and ventilation mode, etc. [15]. These studies did not consider the indoor air temperature as a constant. However, they focused on the external thermal mass, without considering internal thermal mass. At the same time, the methods they proposed to analyze thermal mass are too complex to be used by architects and engineers.

In 1991, van der Maas and Roulet [16] developed a simple dynamic model coupling airflow, heat transfer and a thermal model for the wall, numerical method was used to solve the coupled equations. Based on this model, Yam et al. [2] considered the nonlinear coupling between thermal mass and natural ventilation, developed a naturally ventilated building model with adiabatic envelope. They analyzed the effect of internal thermal mass on indoor air temperature. In 2006, they presented a simple design formula for architects and engineers which involves only three design related parameters, i.e., the time constant of the system, the dimensionless convective heat transfer number and the Fourier time constant [17]. This method allows the fast determination of the amount of thermal mass as well as key design parameters when the phase shift of indoor air temperature and the attenuation of the indoor air temperature fluctuation are specified. But their models assumed adiabatic walls, or the building envelope is assumed to be perfectly insulated.

This paper proposed a model to estimate the impact of external and internal thermal mass on the indoor air temperature of naturally ventilated buildings. The parameters developed by Yam et al. [2], including the time constant of the system, the dimensionless convective heat transfer number and temperature increase induced by internal heat source are adopted to analyze the effect of thermal mass. The inner surface temperature of external wall is calculated with harmonic response method. Based on this model, a simple tool which can be used by architects and engineers is developed to estimate the indoor air temperature for certain building parameters including external and internal thermal mass, and to determine the amount of the internal thermal mass needed to meet a certain temperature variation range requirement for determined building parameters including external thermal mass, both for naturally ventilated building.

2. Analysis

The following assumptions are made to analyze the effect of thermal mass on indoor air temperature for a single room with windows (Fig. 1):

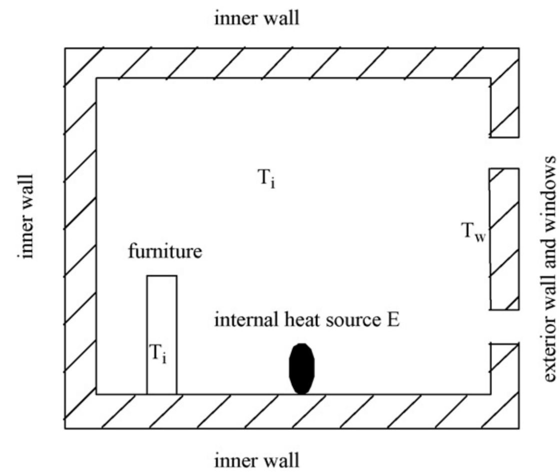

Fig. 1. A simple building model with natural ventilation.

(1) The air temperature of outdoor air (T_o) and the solar-air temperature ($T_{sol\text{-}air}$) are a harmonic function of time with angular frequency ω and amplitudes A_o and $A_{sol\text{-}air}$. $\bar{T}_o$ and $\bar{T}_{sol\text{-}air}$ are the average temperature of the outdoor air temperature and the solar-air temperature. A period of 24 h is considered so that $\omega = 2\pi/24\ \text{h}^{-1}$. The phase shift of solar-air temperature is $\varphi_{sol\text{-}air}$. The outdoor air temperature and solar-air temperature can be written as:

$$T_o = \bar{T}_o + A_o \cos(\omega t) \qquad (1)$$

$$T_{sol\text{-}air} = \bar{T}_{sol\text{-}air} + A_{sol\text{-}air} \cos(\omega t - \varphi_{sol\text{-}air}) \qquad (2)$$

(2) The air temperature distribution in the building is uniform and can be described by T_i, with an angular frequency ω and amplitude A_i:

$$T_i = \bar{T}_i + A_i \cos[\omega t - \varphi_i] = \bar{T}_i + A_i \cos[\omega(t - \xi_i)] \qquad (3)$$

where $\bar{T}_i$ is the average indoor air temperature; φ_i is the phase shift and ξ_i is the time lag.

(3) The temperature distribution of the internal thermal mass is assumed to be uniform and equal to the indoor air temperature. This means that the thermal diffusion process is much faster than the convective heat transfer at thermal mass surface. This assumption allows us to calculate the heat exchange between external thermal mass and internal thermal mass, the radiation between these two bodies can be described by a total heat transfer coefficient.

(4) The ventilation flow rate is constant. The natural ventilation can be induced by mechanical effect, stack effect or wind effect. When a building is mechanically ventilated or wind driven by a constant velocity, the ventilation rate can be obtained easily and can be assumed as a constant. But for stack-driven natural ventilation, the ventilation flow rate depends on the temperature difference between indoor and outdoor air, while the indoor air temperature is a function of the ventilation flow rate. In this way, ventilation flow rate and indoor air temperature are coupled in a nonlinear manner. Yam et al. [2] found that the ventilation flow rate changes periodically for stack-driven natural ventilation, but with very small variation, so we consider it as a constant and equal to the mean ventilation rate which can be calculated by a mean outdoor air temperature.

(5) All heat gain and heat generation in the building can be represented by a lumped heat source term, E. The radiation heat exchange between heat source and other surfaces is

ignored. The direct solar heat gain through openings is ignored.

Based on above assumptions, the heat balance equation for the internal thermal mass can be written as follows:

$$\rho_a C_a q(T_o - T_i) + \alpha_i A(T_w - T_i) + E = MC_m \frac{dT_i}{dt} \quad (4)$$

The first term on the left side of Eq. (4) is the heat supplied by ventilation, the second term is the heat supplied by external wall and the third term is the power of the internal heat source generated in the room. The right term of the equation denotes the internal energy increases of the internal thermal mass.

According to the harmonic response method, the temperature of the inner surface of external wall can be described by solar-air temperature and indoor air temperature [7,8]:

$$T_W = \bar{T}_W + \frac{A_{\text{sol-air}}}{\nu_e}\cos[\omega t - \varphi_{\text{sol-air}} - \phi_e] + \frac{A_i}{\nu_f}\cos[\omega t - \varphi_i - \varphi_f] \quad (5)$$

On the right hand of Eq. (5), the first term is the average inner surface temperature which can be easily calculated. The second term is the fluctuation of the inner surface temperature caused by the variation of solar-air temperature under constant indoor air temperature condition. The third term is the fluctuation of the inner surface temperature induced by the variation of indoor air temperature under constant outdoor air temperature condition. For certain material and configuration of the external walls, ν_e, φ_e, ν_f, and φ_f are damping factors and phase shift with respect to outdoor air temperature and indoor air temperature, respectively. The value of these four parameters can be found from the design handbook for certain external wall and can also be calculated from the wall thickness, inside and outside total heat transfer coefficients (α_i, α_o), heat resistance (R_0), coefficient of thermal storage (S) and thermal inertia (D).

Considering steady state, the inner surface temperature of external wall can be written as:

$$\bar{T}_W = \bar{T}_i + \frac{\bar{T}_{\text{sol-air}} - \bar{T}_i}{\alpha_i R} \quad (6)$$

where R is the total thermal resistance and can be calculated by:

$$R = \frac{1}{\alpha_o} + R_0 + \frac{1}{\alpha_i} \quad (7)$$

Combining Eqs. (1)–(6), the average indoor air temperature $\bar{T}_i$, the decrement factor f_i which is the reciprocal of damping factor ν_i and the time lag of the indoor air temperature with respect to out door air temperature can be obtained and expressed by Eqs. (8)–(10), respectively

$$\bar{T}_i = \frac{\bar{T}_o + T_E + (\lambda/R\alpha_i)\bar{T}_{\text{sol-air}}}{1 + (\lambda/R\alpha_i)} \quad (8)$$

$$f_i = \frac{1}{\nu_i} = \frac{A_i}{A_o} = \sqrt{\frac{c^2 + d^2}{a^2 + b^2}} \quad (9)$$

$$\xi_i = \frac{1}{\omega}\arctan\left(\frac{bc - ad}{ac + bd}\right) \quad (10)$$

where

$$a = 1 + \lambda - \frac{\lambda}{\nu_f}\cos(\varphi_f),$$

$$b = \frac{\lambda}{\nu_f}\sin(\varphi_f) + \tau\omega,$$

$$c = -1 - \frac{\lambda}{\nu_e}\frac{A_{\text{sol-air}}}{A_o}\cos(\varphi_{\text{sol-air}} + \varphi_e),$$

$$d = \frac{\lambda}{\nu_o}\frac{A_{\text{sol-air}}}{A_o}\sin(\varphi_{\text{sol-air}} + \varphi_e) \quad \text{and}$$

$$\lambda = \frac{\alpha_i A}{\rho_a C_a q}, \tau = \frac{MC_m}{\rho_a C_a q}, T_E = \frac{E}{\rho_a C_a q}. \quad (11)$$

Three parameters, λ, τ *and* T_E, suggested by Yam et al. [2] are adopted but used in slightly different manner for λ. The convective heat transfer number λ is the dimensionless heat transfer number which measures the relative strength of heat transfer at the inner surface of *external* thermal mass compared with the heat transfer by ventilation air flow entering the room, instead of that of the *internal* thermal mass as in Yam et al. [2]. τ is the time constant of the system and have the dimension of time (h), which represents the impact factor of internal thermal mass on the variation of indoor air temperature. T_E is temperature increase induced by internal heat source.

3. Results and discussion

It can be observed from Eq. (8) that the mean indoor air temperature increases with the increase of average outdoor air temperature, the mean sol-air temperature and the power of heat source inside the building. The mean indoor air temperature equals to the mean outdoor air temperature when there is no heat source in the building and the solar radiation is negligible.

Eq. (8) can be rewritten as follows:

$$\bar{T}_i = \frac{\bar{T}_o + T_E + (\lambda/R\alpha_i)\bar{T}_{\text{sol-air}}}{1 + (\lambda/R\alpha_i)} = \bar{T}_{\text{sol-air}} + \frac{T_E + \bar{T}_o - \bar{T}_{\text{sol-air}}}{1 + (\lambda/R\alpha_i)} \quad (12)$$

It can be observed from Eq. (12) that:

(1) If $T_E + \bar{T}_o > \bar{T}_{\text{sol-air}}$, then $\bar{T}_i > \bar{T}_{\text{sol-air}}$. $\bar{T}_i$ decreases with the increase of λ and the decrease of R.
(2) If $T_E + \bar{T}_o = \bar{T}_{\text{sol-air}}$, then$\bar{T}_i = \bar{T}_{\text{sol-air}}$. The mean indoor air temperature is equal to the mean solar air temperature and independent of other parameters.
(3) If $T_E + \bar{T}_o < \bar{T}_{\text{sol-air}}$, then $\bar{T}_i < \bar{T}_{\text{sol-air}}$. $\bar{T}_i$ increases with the increase of λ and the decrease of R.

Because of the impact of solar radiation, the mean sol-air temperature in summer is much higher than the average outdoor

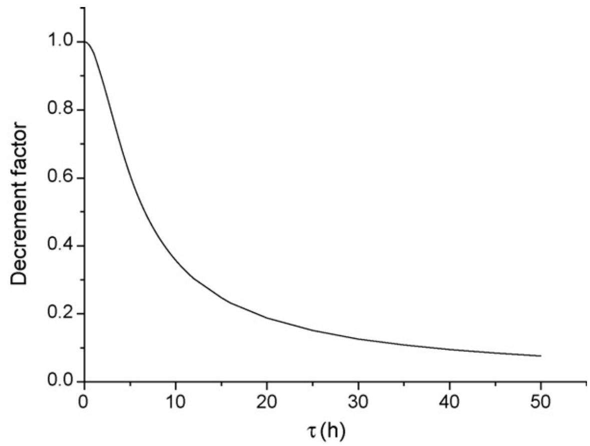

Fig. 2. The decrement factor as a function of the time constant for perfectly adiabatic walls.

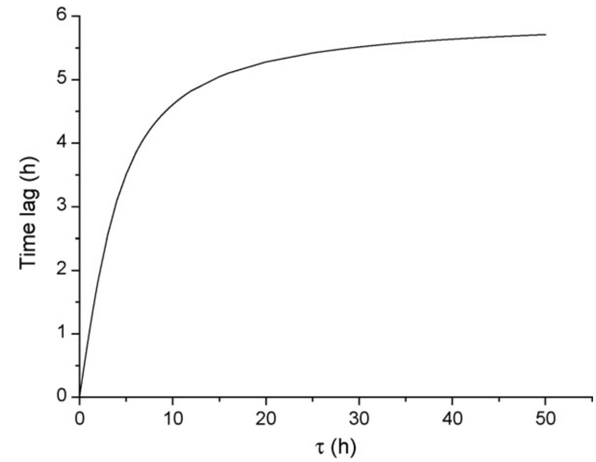

Fig. 3. The time lag as a function of the time constant for perfectly adiabatic walls.

air temperature and often beyond the upper limit of human thermal comfort zone. Thus, only when the internal heat source of a building satisfies $T_E < \bar{T}_{\text{sol-air}} - \bar{T}_o$, natural ventilation can be considered as suitable for cooling building in summer.

It can also be observed from Eqs. (8)–(10) that the internal thermal mass has impact on the fluctuation and the time lag but not on the mean value of indoor air temperature. In addition, periodical internal heat source but not constant in building is common practice. When we consider the periodical internal heat source, we can also found that the average power affects the average indoor air temperature and its change affects the variation of indoor air temperature. When the amplitude of heat source increases, the decrement factor of indoor air temperature increases and its time lag respect to outdoor air temperature decreases.

3.1. Perfectly adiabatic walls

The case of perfectly adiabatic walls means that no heat transfer occurs between the indoor air and inside surface of the envelope. Therefore, α_i equals to zero, so that $\lambda = \alpha_i A / \rho_a C_a q = 0$. So the solution described by Eqs. (8)–(10) can be rewritten as follows:

$$\bar{T}_i = \bar{T}_o + T_E \quad (13)$$

$$f_i = \frac{1}{\sqrt{1 + \tau^2 \omega^2}} \quad (14)$$

$$\xi_i = \frac{1}{\omega} \arctan(\omega \tau) \quad (15)$$

The solution is identical to that obtained by Yam et al. [2]. Under this circumstance, only the internal thermal mass affects the fluctuation and the phase shift of the indoor air temperature. The relationship between them and the time constant is shown in Figs. 2 and 3.

It can be observed from Eq. (14) that the magnitude of the indoor air temperature fluctuation is always smaller than that of the outdoor air temperature by a value of $1/\sqrt{1 + \tau^2 \omega^2}$. It can be concluded from Figs. 2 and 3 that the decrement factor decreases and the time lag increases when the time constant increases. But when the time constant is larger than 20, the change of decrement factor and time lag is very small. This suggests that when the time constant is larger than 20, the method that adjusting indoor air temperature by increasing internal thermal mass is not effective. At the same time, the temperature of indoor air has nothing to do with solar radiation because that the insulation blocks the heat transfer to the inside of the building.

3.2. Realistic external walls

3.2.1. The effect of internal thermal mass

The external walls are not adiabatic in real buildings. In this section, six types of commonly used external wall with different configurations and materials are chosen to analyze the impact of external thermal mass on the thermal performance of building. The external walls are composed of foam concrete or reinforced concrete, and insulated by polystyrene. The configurations of the six types of external walls, numbered from 1 to 6, are summarized in Table 1 and their material properties are shown in Table 2.

Table 1
Description of six different external walls

No.	Wall description	Material
1	Lightweight wall with internal insulation	Stucco–foam concrete–polystyrene
2	Lightweight wall with external insulation	Polystyrene–foam concrete–stucco
3	Heavy wall with internal insulation	Stucco–reinforced concrete–polystyrene
4	Heavy wall with external insulation	Polystyrene–reinforced concrete–stucco
5	Lightweight wall (uninsulated)	Stucco–foam concrete–stucco
6	Heavy wall (uninsulated)	Stucco–reinforced concrete–stucco

Table 2
Thermophysical properties of each wall material

Material description	Thickness (mm)	K (W/m K)	ρ (kg/m^3)	C kJ/(kg K)	S (24 h) (W/(m^2 K)	D
Polystyrene	30	0.042	30	1.38	0.35	0.25
Foam concrete	200	0.19	500	1.05	2.81	2.96
Stucco	20	0.81	1600	1.05	10.07	0.25
Reinforced concrete	200	1.74	2500	0.92	17.2	1.98

External wall of No. 4 in Table 1 is selected to analyze the effect of internal thermal mass on building with natural ventilation. This type of wall is composed of reinforced concrete with polystyrene insulated on the outer surface and with stucco rendered on the internal surface. It is supposed that a building with this external wall on its west outside is located in Changsha, a central southern city of China. The average outdoor air temperature in summer of Changsha is 32.7 °C, with a temperature amplitude of 5.2 °C. The average solar air temperature is 36.7 °C with a temperature amplitude of 18.1 °C. The time lag of the solar air temperature with respect to the maximum of outdoor air temperature is 0.72 h [7]. For naturally ventilated building in summer, the commonly heat transfer coefficient of inner surface is 8.29 W/m^2 K and the outside heat transfer coefficient is 22 W/m^2 K [18]. Based on the harmonic response method, the values of ν_e, φ_e, ν_f, and φ_f for this wall can be calculated as 42.799,6.668, 2.535 and 0.0331, respectively. Substitute these values to Eqs. (9)–(10), the relationship among the indoor air temperature, the time constant and the heat transfer number can be obtained and shown in Figs. 4 and 5.

It can be observed from Figs. 4 and 5 that the decrement factor and the time lag for external wall No.4 vary with time constant in a similar way as for the adiabatic wall. When λ is small, the effect of internal thermal mass on the indoor air temperature is more obvious. The fluctuation of the indoor air temperature decreases and the time lag increases with the increase of time constant. The variation amplitude decreases when τ is larger than 20. But when λ becomes as large as 100, the effect of the internal thermal mass is also negligible. In this case, the decrement factor and the time lag of the indoor air temperature become constant, with values of 0.1 and 7 h, respectively. These values will differ for different types of external wall.

When the time constant approaches zero, the effect of internal thermal mass is negligible so that the decrement factor and the time lag are determined entirely by heat transfer number of the external wall. When the heat transfer number λ increases, the fluctuation of the indoor air temperature decreases, but the time lag increases.

3.2.2. Effect of configuration of external walls

Six different external walls are chosen (Table 1) to investigate the effect of configuration of external wall on natural ventilation and indoor air temperature. The weather data, location and the orientation are the same as in Section 3.2.1. T_E is set to zero and τ, λ are set to 1.

The results are shown in Table 3. Where columns 2–4 give the values of ν_e, ξ_e, ν_f and ξ_f. The last three columns represent the indoor air temperature which is shown in Fig. 6.

It can be observed from Table 3 that the fluctuation of indoor air temperature is smaller and the time lag is smaller for walls with external insulation than those with internal insulation. It indicates that the external insulation can maintain more steady indoor temperature while the internal insulation can postpone the time when peak indoor temperature appears. When externally insulated or without insulation, a heavy weight wall can result in smaller temperature fluctuation and longer time lag than a light weight wall. When internally insulated, the difference of temperature fluctuation between heavy and light weight wall is negligible.

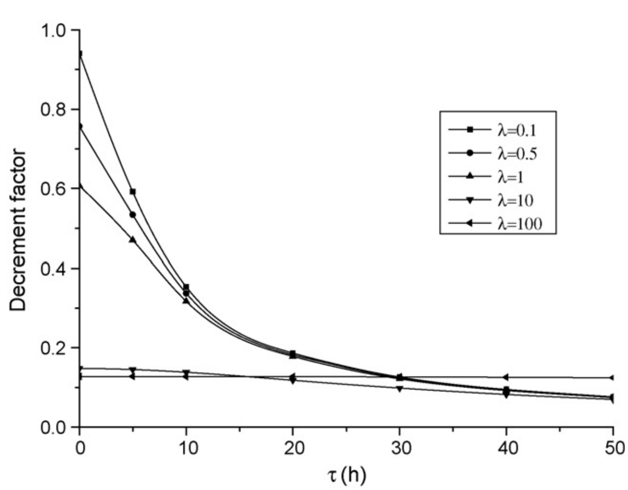

Fig. 4. The decrement factor as a function of the time constant and heat transfer number for external wall No. 4.

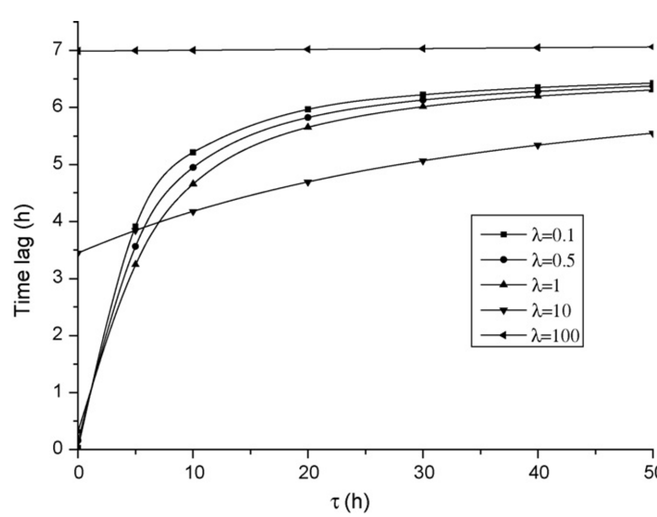

Fig. 5. The time lag as a function of the time constant and heat transfer number for external wall No.4.

Table 3
Average indoor air temperature and decrement factor and time lag for different external wall

No. of external wall	ν_e	ξ_e	ν_f	ξ_f	$\bar{T}_i$	f_i	ξ_i
1	43.119	9.294	1.060	0.00505	32.9	0.855	1.189
2	52.607	9.302	1.519	0.0193	32.9	0.690	0.932
3	28.536	6.658	1.0991	0.00664	33.1	0.859	1.546
4	42.799	6.668	2.535	0.0331	33.1	0.599	0.990
5	21.974	9.305	1.519	0.0192	33	0.633	1.199
6	7.058	6.681	2.535	0.0331	33.8	0.580	3.317

Moreover, the degree of thermal comfort in a naturally ventilated room can usually be indicated by the highest indoor air temperature [19]. The average indoor air temperatures using the six external walls are listed in Table 3. It can be seen that the peak indoor air temperature of the heavy wall with external insulation (No. 4) is the lowest among the six walls. Fig. 6 shows comparison of the outdoor air temperature and the indoor air temperature profile for different external walls. It can be concluded from Table 3 and Fig. 6 that in summer, in order to reduce the peak indoor air temperature and the wave of indoor air temperature for naturally ventilated rooms in Changsha, the heavy wall with external insulation would be the best choice.

3.3. The simple design and evaluate tool

Based on this model, a simple tool is developed to estimate the indoor air temperature for certain external and internal thermal mass and to determine the amount of internal thermal mass needed to maintain required indoor temperature for certain external wall for naturally ventilated building.

The determination of internal thermal mass includes following steps. First, the ventilation rate of the building is estimated. Secondly, the damping factor and time lag of the external wall are calculated. Thirdly, the above data are substituted into Eqs. (8)–(10), together with the weather data. Finally the relationship among indoor air temperature, heat transfer number and time constant can be obtained. With the dimensionless heat transfer number and the highest indoor air temperature, the time constant can be obtained so that the amount of internal thermal mass needed can be determined.

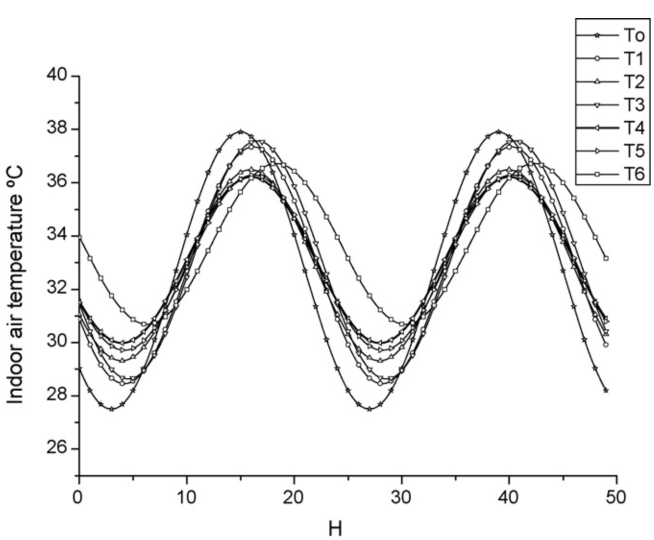

Fig. 6. The indoor air temperature with six different external walls comparing to outdoor air temperature (To is the outdoor air temperature, T1, T2, T3, T4, T5 and T6 are the indoor air temperature for external wall of Nos. 1–6, respectively).

Similarly, the indoor air temperature of a naturally ventilated building can be estimated when external and internal thermal masses are known. The process is illustrated in the following example.

Let us consider a single room with dimension of 3 m (long) × 3 m (wide) × 3 m (high). The room has a constant ventilation flow rate of 3 air changes per hour (ACH) and a 100 W internal heat source. It has only one west external wall and other walls are insulated well. The external wall and the weather data are the same as in Section 3.2.1.

Suppose that there is some furniture inside the building which is all made up of sheet wood. The volume of wood is estimated as 1 m^3 so that the volume of air in building is 26 m^3. The internal thermal mass is the sum of wood and air. The density of wood and air is 600 kg/m^3 and 1.2 kg/m^3, respectively. The heat capacity of wood and air is 2.5 1kJ/(kg K) and 1.005 kJ/(kg K), respectively. Then the values of τ, λ and T_E can be calculated:

$$\tau\,(\mathrm{h}) = \frac{(MC)_{\mathrm{air}} + (MC)_{\mathrm{furniture}}}{\rho_a C_a q} = \frac{26 \times 1.2 \times 1.005 + 1 \times 600 \times 2.51}{1.2 \times 1.005 \times 27 \times 3} = 15.45 \tag{16}$$

$$\lambda = \frac{\alpha_i A}{\rho_a C_a q} = \frac{8.29 \times 3 \times 3 \times 3600}{1.2 \times 1.005 \times 1000 \times 27 \times 3} = 2.75 \tag{17}$$

$$T_E\,(^\circ\mathrm{C}) = \frac{E}{\rho_a C_a q} = \frac{100 \times 3600}{1.2 \times 1.005 \times 1000 \times 27 \times 3} = 3.69 \tag{18}$$

Substitute these values, the weather data, the phase shift and the time lag of external wall to Eqs. (8)–(10), we can obtain that the decrement factor is 0.19 and the time lag is 4.74 h, the average of indoor air temperature is 36.46 °C.

4. Conclusion

In this paper, a simple model coupling thermal mass and natural ventilation is developed, the impact of internal thermal mass and the external thermal mass on the indoor air temperature is analyzed for adiabatic wall and six realistic actual external walls with different configurations.

When the external wall is perfectly insulated, the average indoor air temperature equals to the sum of the average outdoor air temperature and the temperature increases induced by the internal heat source. The internal thermal mass affects the decrement factor and the time lag of indoor air temperature. The fluctuation of indoor air temperature decreases and the maximum time defers with the increase of the amount of internal thermal mass, but the effect becomes negligible when the time constant of the system is over 20 h.

For the realistic external wall, the average indoor air temperature is determined by the average outdoor air temperature, the total heat transfer coefficient, the temperature increases induced by the internal heat source, the average sol-air temperature, thermal resistance and the dimensionless heat transfer coefficient of the inner surface of external wall. Only when steady state air temperature increases induced by the internal heat source is smaller than the difference between average outdoor air temperature and average sol-air temperature, the average indoor air temperature can be smaller than the average solar air temperature, so that the natural ventilation system can be considered in summer.

When heat transfer number is small, the effect of internal thermal mass is similar to the adiabatic condition. But when heat transfer number is larger than 100, the decrement factor and the time lag remain unchanged and have no distinct relationship with the amount of the internal thermal mass.

Six different external walls are compared. When the material components are the same, the use of external insulation can achieve smaller fluctuation of indoor air temperature than internal insulation. The use of heavy wall with external insulation is predicted to have the lowest amplitude of indoor air temperature among the six different external walls. So the heavy wall with external insulation is suitable for naturally-ventilated buildings.

A simple tool is developed on the basis of the model to serve architects and engineers to estimate the indoor air temperature and design the amount of thermal mass needed. The method can be used for natural ventilated buildings with concentrated and small size heat source, thin furniture, one external wall while other walls are insulated well or are surrounded by other natural ventilated rooms. Method can be extended for a building with more external walls.

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