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Cooling load reduction by using thermal mass and night ventilation

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ABSTRACT

We provide a quantitative understanding of the relationship between thermal mass and cooling load, i.e. the effect of thermal mass on energy consumption of air-conditioning in office buildings. A simple office-building model with air-conditioning at daytime and free cooling at nighttime is analyzed in detail to quantify the hourly and overall variation of cooling load of air-conditioning. As an important parameter, an increase of time constant can effectively reduce the cooling load, by as much as more than 60% when the time constant is more than 400 h. However, when the time constant is larger than 1000 h, a further increase may slightly increase the cooling load, as a too large time constant may also postpone the heat release of thermal mass until the daytime. For the most effective reduction of cooling load, the interior and exterior convective heat transfer numbers need to be matched.

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1. Introduction

Buildings consume more than 30% of the primary energy worldwide. In China, buildings account for 23% in 2003 of the total energy use and is expected to increase to 30% by 2010 [1]. 65% of the building energy consumption in 2003 in China was due to heating, ventilation and air-conditioning [1]. Hence, improving building energy efficiency has become one of the critical issues for overall national energy strategy in China.

The use of thermal mass in a building can reduce peak heating or cooling load, and subsequently building energy consumption, in particular when it is integrated with night ventilation. Thermal mass is defined as the thermal materials that can absorb heat, store it and release it later. Thermal mass includes building envelope, furniture, internal walls, etc. Thermal storage capacity of building mass is one of the factors describing the building thermal performance [2]. In naturally ventilated buildings, thermal mass is effective for reducing the air temperature fluctuation [3].

Many studies investigated the relationship between thermal mass and indoor air temperature, and the effect of thermal mass and night ventilation on cooling load; as reviewed by Balaras [4]. 16 different simplified models for estimating the cooling load of a building, considering the building's thermal mass, were summarized and compared in Ref. [4]. Parameters describing the effects of thermal mass include the effective heat storage capacity [5,6], diurnal heat capacity [7], thermal effectiveness parameter [8], admittance factor [9], and total thermal time constant [10]. The effective layer thickness of external walls [11] and the surface area of thermal storage [12,13] also significantly affect the thermal mass performance.

Existing studies showed that the reduction in cooling load by using thermal mass vary between 18 and 50% [8,14–16]. But these studies were mostly based on the laboratory monitoring or field experiments, without systematic theoretical studies. Hence this paper aims to provide a detailed theoretical analysis on the relationship between use of thermal mass and reduction of cooling load. Through a simple building model, all parameters affecting the thermal mass performance are quantitatively evaluated and analyzed.

2. A simple building model

Here only the warm climates are considered, while the results and analysis can also be easily extended to the cold climates. Fig. 1 shows a simple office-building model with daytime air-conditioning and night ventilation. The air temperature distribution in the building is uniform. Both internal and external thermal storage materials are modeled as a thermal mass wall. All building envelope except the thermal mass wall is perfectly insulated. As shown later, the location of thermal mass relative to insulation and effect of insulation may be analyzed by changing the interior and exterior convective heat transfer numbers. Thermal radiation between room surfaces is ignored. All heat gain (including solar heat gain) and heat generation in the building is lumped into one heat source term, i.e. E at daytime and no indoor heat gain is considered at nighttime. The temperature distribution in the

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Nomenclature

A_i	interior surface area of thermal mass (m^2)
A_o	exterior surface area of thermal mass (m^2)
c_m	heat capacity of the thermal mass (J/kg K)
c_p	heat capacity of air (J/kg K)
E	heat generation rate (W)
g	acceleration of gravity (m/s^2)
h_i	interior convective heat transfer coefficient (W/m^2 K)
h_o	exterior convective heat transfer coefficient (W/m^2 K)
M	mass of the thermal mass (kg)
q_v	night ventilation rate (m^3/s)
Q_{cl}	cooling load (W)
t	time (s)
T_E	temperature rise due to internal heat gain (K)
T_i	indoor air temperature (K)
T_m	thermal mass temperature (K)
T_o	outdoor air temperature (K)
T_{set}	indoor air setting temperature at daytime (K)
$\tilde{T}_o$	mean outdoor temperature (K)
$\Delta\tilde{T}_o$	amplitude of outdoor air temperature fluctuation (K)

Greek symbols

β	phase shift (s)
λ_i	interior convective heat transfer number
λ_o	exterior convective heat transfer number
ξ	cooling load ratio
ξ_t	total cooling load ratio
ρ	air density (kg/m^3)
τ	time constant (s)
ω	frequency of outdoor temperature variation (1/s)

thermal mass is also assumed to be uniform, i.e. T_m. This means that the thermal conduction process within the materials is much faster than thermal convection at surface. At daytime, the indoor air temperature is kept constant, i.e. T_{set}; see Fig. 1a. At nighttime, the ventilation rate, q_v, is constant; see Fig. 1b.

2.1. Daytime

The heat balance equations for thermal mass and room air are

$$Mc_m\frac{\partial T_m}{\partial t} + h_oA_o(T_m - T_o) + h_iA_i(T_m - T_i) = 0 \tag{1}$$

$$Q_{cl} + h_iA_i(T_m - T_i) + E = 0 \tag{2}$$

where Q_{cl} is the heat removed by air-conditioning equipment, i.e. the cooling load.

We assume that the outdoor temperature can be expressed by Fourier analysis as the sum of sinusoidal components of periods 24, 12, 8, 6 h, etc. We consider the main sinusoidal component of period 24 h.

$$T_o = \tilde{T}_o + \Delta\tilde{T}_o \sin(\omega t) \tag{3}$$

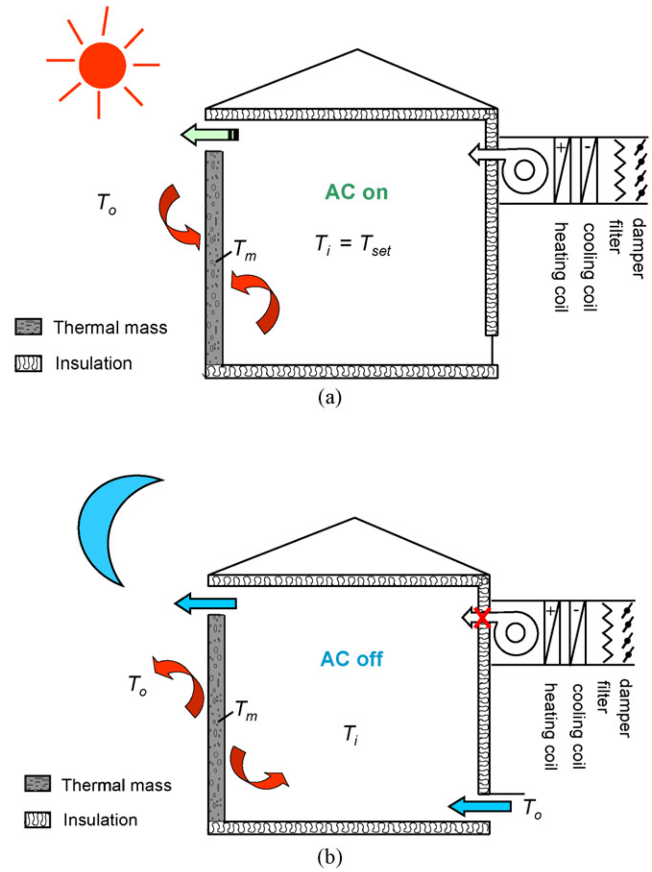

Fig. 1. A simple one-zone building model with periodic outdoor air temperature variation when: (a) daytime, the air-conditioning (AC) system is on and the indoor air temperature is kept constant and (b) nighttime, AC is off and the building is ventilated at a constant ventilation rate.

where $\Delta\tilde{T}_o$ and $\tilde{T}_o$ are independent of time and $\Delta\tilde{T}_o \geq 0$; ω is the frequency of the outdoor temperature fluctuation with a value of $2\pi/24\ h^{-1}$.

Substituting Eq. (3) into Eq. (1), we get

$$\omega\tau\frac{\partial T_m}{\partial(\omega t)} + (\lambda_o + \lambda_i)T_m = \lambda_o\tilde{T}_o + \lambda_iT_i + \lambda_o\Delta\tilde{T}_o\sin(\omega t) \tag{4}$$

where $\tau = Mc_m/\rho c_p q_v$ is the time constant based on a reference ventilation rate q_v, which is chosen to be the night ventilation flow rate. $\lambda_o = h_oA_o/\rho c_p q_v$ is the non-dimensional exterior convective heat transfer number, and $\lambda_i = h_iA_i/\rho c_p q_v$ the interior convective heat transfer number.

Two convective heat transfer numbers λ_i and λ_o measure the relative strength of interior and exterior convective heat transfer at the thermal mass surfaces. A small thermal resistance (large interior or exterior convective heat transfer number) represents the interior or exterior convective heat transfer is very effective compared to the flow mixing in the room. In such situations, the thermal mass is considered to be in thermal equilibrium with the room air or outdoor.

The general solution of Eq. (4) is

$$T_m(\omega t) = \frac{\lambda_o}{\lambda_o + \lambda_i}\tilde{T}_o + \frac{\lambda_i}{\lambda_o + \lambda_i}T_{set} + \frac{\lambda_o\Delta\tilde{T}_o}{\sqrt{(\lambda_o + \lambda_i)^2 + \omega^2\tau^2}}\sin(\omega t - \beta_1) + C_1\,e^{-((\lambda_o+\lambda_i)/\omega\tau)\omega t} \tag{5}$$

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