Energy and Buildings 118 (2016) 214–225

Contents lists available at ScienceDirect

Energy and Buildings

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

Numerical simulation of thermal mass enhanced envelopes for office buildings in subtropical climate zones

Andrey A. Chernousov*, Ben Y.B. Chan

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 23 February 2016
Accepted 28 February 2016
Available online 4 March 2016

Keywords:
Smart building envelope
Thermal performance
Phase change material
Energy efficiency
PCM optimization

ABSTRACT

The morning power overloading for office cooling is often the aftereffect of not using air conditioning on hot summer nights. Integration of phase change material (PCM) into the office building envelope can be a solution, but, prior to usage, the PCM layer has to be optimized to deal with a number of alternating boundary conditions. The diurnal alternation of the heat load level facing the building envelope is very critical in predicting PCM behavior and cooling energy consumption in a real PCM integrated office building in Hong Kong.

EnergyPlus numerical simulation of a PCM layer with specific properties and encased in between two layers of a building envelope was adopted to assess PCM efficiency in relation to its placement, thickness and orientation to the sun, causing moderate and elevated heat loads. The optimized PCM envelope with windows was simulated as a part of a realistic office building model to estimate the air conditioning power balancing on the hottest days and during the entire hot season.

The results show that the considered PCM layer should be placed at the inner building envelope part, i.e., close to the office interior. The optimization stage revealed the negative effect of the excessive PCM thermal mass bringing indoor overheating in certain combinations of diurnal heat loads. This is an outcome of not using air conditioning at nights and on Sundays. In the realistic office building model, the negative PCM effect diminishes, though the PCM reduces the morning peak power by up to about 5%. The PCM impact is clearly shown in the comprehensive results for the entire cooling season, where effective smoothing of the AC power demand is indicated. The PCM usage, however, considerably prolongs the AC operation in a narrow power mode (200–244 kW) that can aid the chiller selection.

The study demonstrates that the morning peak power can be effectively managed via the PCM optimized building envelope in subtropical climate zones. For an office building, a combined window and building envelope with PCM can be an excellent alternative to fully glazed curtain walls.

1. Introduction

Lightweight and energy efficient sandwich constructions, such as building envelope systems, have drawn much attention in the design of high-rise buildings [1,2]. Today, developments are driven by a competitive market dictating more sophisticated solutions that are lighter, of larger area, thinner, safer and smarter. Therefore, increasingly, more envelope manufacturers are resorting to new sandwich laminates based on fiber reinforced polymers (FRP) rather than the much heavier metallic or cement laminates [3,4]. In order to enhance thermal mass, a phase change material can be introduced into the building envelope [5]. The phase change material, compensating for the inadequate thermal mass of the basic panel, is used to maintain a desired indoor temperature with reduced air conditioning effort. The PCM is charged or discharged during material melting or crystallization, respectively.

A phase change material is commonly placed as a layer at a particular position in the building envelope to provide better efficacy in hot summer conditions. Several good examples include a PCM presence at the interior [6–8], exterior [9–11] or inside the envelope [10–12]. It was suggested that the PCM thermal mass does not play a significant role in lightweight building envelopes with a relatively high thermal resistance [4,8]. That is, the studying of large-scale (3 × 3 m and above) and compact systems (40 mm thick and below) reinforced with FRP is very promising. In the general case, the encased smart layer is equivalent to a PCM thermal mass operating between two envelope layers of certain thermal resistance and thermal mass. Such a problem was touched upon in [12],

* Corresponding author.
E-mail address: chernous@ust.hk (A.A. Chernousov).

http://dx.doi.org/10.1016/j.enbuild.2016.02.054
0378-7788/

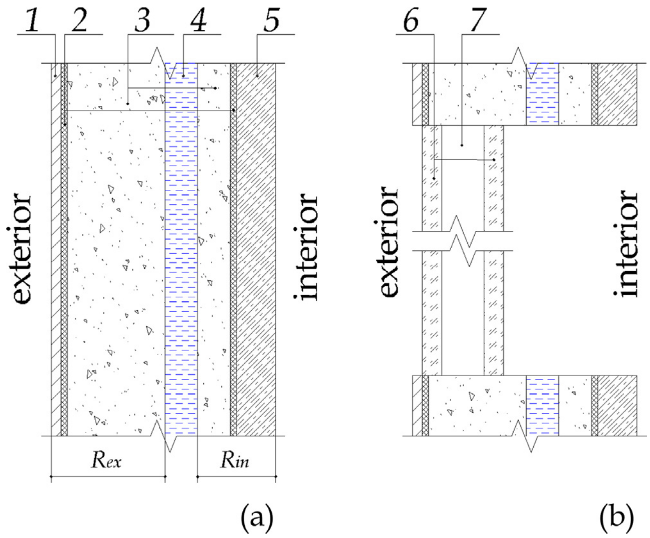

Fig. 1. The layout of the building envelope system (a) without and (b) with a double glass window. Positions: (1) Aluminum alloy, (2) Fiber reinforced polymer, (3) Foam insulation, (4) Phase change material, (5) Gypsum plaster, (6) Glass pane, (7) Air gap.

where the appropriate PCM position for day-and-night cooling was shifted outwards from the interior because the PCM requires charging (melting), which can only occur due to outdoor fluctuations in the air temperature, irradiation level, wind speed, etc. However, 24 h cooling for a smart office building is still not affordable in subtropical megacities. In Hong Kong offices, for example, cooling energy consumption usually lasts from 8:30 to 21:00. In the remaining period of time, offices are ventilated by outdoor air [13]. Despite the quite effective approach of night ventilated PCM-based systems, it can provoke room warming during hot summer nights [14]. On the other hand, the absence of night ventilation leads to heat energy accumulation over hot days in the internal PCM layer and, consequently, higher power consumption [15]. There is also uncertainty about the relatively thick PCM layers fencing an office space. For complete discharging or congealing of PCM from its liquid state, night ventilation can turn out to be insufficient. That is, the PCM application can be inefficient and even detrimental in certain weather conditions.

It is also important to study the building envelope orientation to the sun because this creates a variable heat load, from low to elevated, at the metallic face of the building envelope [6,7]. Extending earlier studies, the efficiency effects of a substantial thermal mass of a PCM layer surrounded by 2 layers with changeable thermal resistance and thermal mass were separately determined for distinct envelope orientations to the sun track, within the hot season in Hong Kong. Subsequently, the optimized cases were adapted for a typical office building (5 storey section) with both windowless and glazed building envelopes in order to carry out more authentic modeling and to estimate the PCM advantages.

2. Methodology

2.1. Smart building envelope system and material properties

In this study, the building envelope designed by Cheung's research team [4,12], was studied. This windowless envelope consists of a polymeric foam core laminated by exterior and interior composite layers (Fig. 1a). The exterior layer is composed of an aluminum facing, which is 3 mm thick, reinforced by 2 mm of fiber reinforced polymer FRP. The interior composite is a combination of 2 mm of FRP and a finished layer of 12 mm gypsum plaster. Commercially available polyisocyanurate foam PIR (Australian Urethane & Styrene Pty., Ltd.) and organic PCM-RT (Rubitherm Shijiazhuang PCMs Co., Ltd.) were chosen for the core (t_C = 40 mm) and smart PCM layer (t_{PCM} = 5, 10 and 20 mm), respectively. In a real design, the PIR foam plate is completely isolated from external impacts (moisture, insects, etc.) by the FRP laminate, providing a long-life protection in subtropical regions. It is also valid for the PCM encased in the PIR, and has unlimited lifetime and chemical inertness to polyisocyanurate. In the building envelope modeling, all the constituent layers are arranged parallel to each other, and the smart layer of a phase change material can have any particular location within the confined faces of the insulation core (Fig. 1a). As seen from Fig. 1a, the envelope structure is split by the PCM layer into two layers of different thermal properties. So, the PCM is separated from the exterior by the relative thermal resistance (Eq. (1)) and the relative thermal mass (Eq. (2)):

$$R_{rel} = R_{ex}/(R_{ex} + R_{in}) \quad (1)$$

$$C_{rel} = C_{ex}/(C_{ex} + C_{in}) \quad (2)$$

where ex and in refer to the exterior and the interior envelope parts, respectively.

The building envelope can be combined with energy efficient window systems. Fig. 1b illustrates a simplified model of the envelope/window combination for the numerical simulations.

Table 1 gives the material properties for the constituent layers used as input in the modeling. The layer thickness t was measured by a digital caliper (Neiko 01409A, $\Delta t/t \sim \pm 0.1\%$). The hot wire method (QTM-500, KYM Co., Ltd.) and the DSC method of ASTM E1269 (Q1000, TA Instruments) were respectively used for thermal conductivity k and specific heat capacity c measurement. The material density d was determined as the ratio of the mass to volume of the measured material. The thermal resistance R and thermal mass C of the individual layers are calculated from Eqs. (3) and (4), respectively.

$$R = t/k \quad (3)$$

$$C = c \times t \times d \quad (4)$$

The major contribution to the total thermal resistance belongs to the polymeric foam core. The R value of the 5–20 mm thick PCM has a significant effect on the total envelope resistance, ranging from 1.9 to 7.8%. In addition, a 5, 10 or a 20 mm PCM layer enhances the envelope to thermal mass by amounts of 32, 41 and 58 kJ/(K m^2), respectively. That is, a 20 mm PCM layer embodies the building envelope with a thermal mass equivalence of around 30 mm of heavy concrete wall.

It should be noted that the PCM includes the latent heat that is released and absorbed due to the phase transition. To account for this effect, the specific heat capacity function c(T) of the PCM is converted by integration into an enthalpy change dependence parameter $\Delta H(T)$. The $\Delta H(T)$ dependence given in Fig. 2 was obtained via the dynamic DSC method (Q1000, TA Instruments) at a constant heating rate of 1 K/min on a 1 mg sample [4]. The referred melting curve represents a typical enthalpy-temperature dependency for organic PCMs, and can be used for the modeling simplification. In particular conditions, the PCM can melt incompletely, bringing partial energy accumulation and lower energy efficiency (Fig. 3).

Assuming that a molten fraction is an invertible function of temperature [16], the PCM molten volume V_{liq} can be estimated by:

$$V_{liq} = \Delta H_T / \Delta H \quad (5)$$

where ΔH_T is the enthalpy change by a temperature rise to T and ΔH is the total enthalpy change over the phase change temperature range.

The major charging (melting) of the PCM occurs within an interval of 4 °C (28–32 °C), with an absorbed energy of 160 J/g. The entire