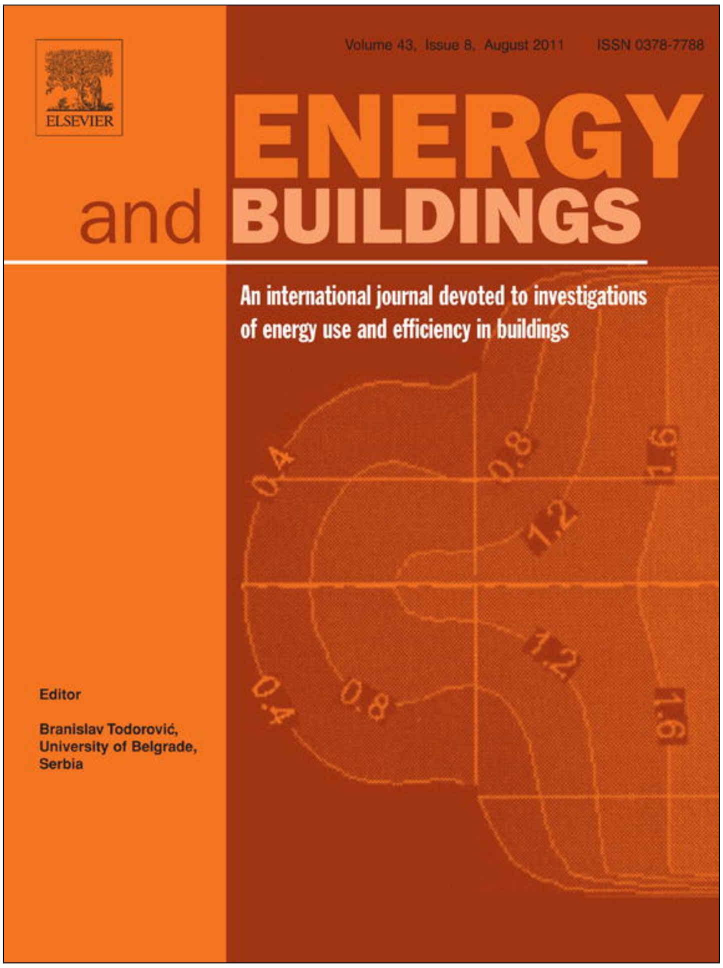
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Effects of wallboard design parameters on the thermal storage in buildings

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ABSTRACT

The phase change material (PCM) could be added to the wallboard to increase the thermal mass to decrease in indoor temperature fluctuation and improve thermal comfort. In this study, experimentally validated simulation was performed to investigate the effects of various parameters of PCM including the nominal average phase change temperature, its range, the convective heat transfer coefficients and the wallboard thickness on the thermal storage performance of the wallboard such as the thermal energy storage and the time shift.

It was found that the average phase change temperature should be close to the average room temperature to maximize the thermal heat storage in the wallboards. The phase change temperature should be narrow to maximize the thermal heat storage in the PCM wallboards. The thermal heat storage increased with the convective heat transfer coefficient, and the optimal average phase change temperature to maximize the storage shifted a bit to a higher temperature with it. The time shift was found to decrease with the convective heat transfer coefficient and the phase change temperature range.

1. Introduction

The wallboards are installed to separate the in- and out-door thermal environments to reduce the in-door temperature swing, so that their thermal properties greatly affect the building energy efficiency. The buildings with thick walls of large heat capacity are known to be comfort to live in due to the small in-door temperature change. There have been researches to improve the building energy efficiency by including phase change material instead of thickening the walls to save the cost of heating and air conditioning.

There are many review articles reporting the applications of the phase change materials (PCM) to the building heating and air conditioning (For example, Farid et al., 2004; Khudhair and Farid, 2004; Sharma et al., 2009). Peippo et al. (1991) investigated the use of PCMs for short-term heat storage in passive solar applications and concluded that the heat storage became optimal when the phase change temperature is 1–3 K above the average room temperature. Feustel and Stetiu (1997) investigated both experimentally and numerically the usage of thermal mass in buildings to reduce the peak-power demand, downsize the cooling systems, and/or switch to low-energy cooling sources. Neeper (2000) investigated theoretically the effects of the phase change temperature range, the heat transfer coefficient and the amount of the PCM material included in the wallboard on the thermal storage. He concluded that the energy stored during a daily cycle depends on the melt temperature of the PCM, the temperature range over which melt occurs, and the latent capacity per unit area of wallboard. He also reported the maximum diurnal energy storage occurs at a value of the PCM melt temperature that is close to the average room temperature in most circumstances in contrast to the results of Peippo et al. (1991) and the energy storage decreases if the phase change transition occurs over a range of temperatures. Zalba et al. (2003) reported the benefits of using the enthalpy method in simulation model for the energy equations in dealing with the melting and solidification, and presented the application examples. Lamberg et al. (2004) compared the application of the enthalpy method and the effective heat capacity method for the energy equation, and they reported both the methods yielded good estimation where the effective heat capacity method gave a little bit better results for the cases of narrow phase change temperature range. Zhang et al. (2008) presented a revised simulation model considering the finite latent heat of PCM by supplementing the Neeper's model and performed the numerical analysis on the effects of the latent heat, melting temperature, and thermal conductivity on the thermal storage in the PCM wallboards.

In this study, experimentally validated simulation is performed to investigate the effects of various parameters of PCM including the nominal average phase change temperature, its range, the convective heat transfer coefficients and the wallboard thickness on the thermal storage performance of the wallboard such as the thermal energy storage and the time shift.

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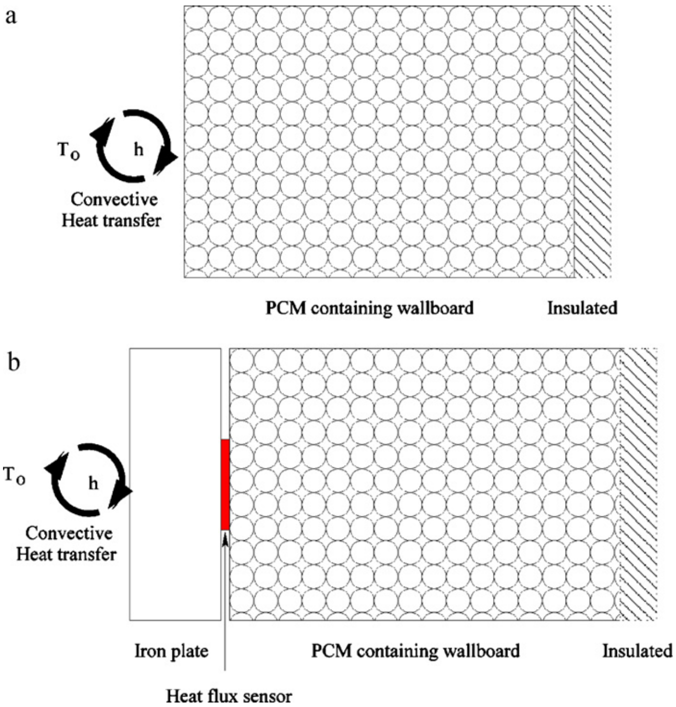

Fig. 1. Schematics of the wall configurations used for validation and model studies.

2. Theory and experimental set-up

2.1. Governing equations

Eq. (1) shows the one-dimensional unsteady energy equation used in the simulation, and the relation between the enthalpy and the specific heat is shown in Eq. (2) where the latent heat during the phase change of the PCM is taken care of in it.

$$\rho C_p(T)\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} \tag{1}$$

$$C_p(T) = \frac{dh}{dt} \tag{2}$$

The specific heat change during the phase change of the PCM was simulated as a piecewise linear function over the equally divided quadrants and assumed to be symmetric about the average phase temperature. The maximum value of it was calculated assuming that the specific heat is a quadratic function. The specific heat values at the first and third quadrants were determined to match the latent energy during the phase change. The governing equations were solved implicitly using FLUENT 6.3, a commercial computational fluid dynamics code, with the time step of 300 s. All simulation data were obtained from the results for the fifth day from the start.

2.2. Boundary conditions

Fig. 1(a) and (b) represents the test cases considered. It was assumed that the wallboard is one-dimensional, exposed to convective heat transfer on one side and insulated on the other side. The room temperature history is preset and assumed not to be affected by the wall temperature change. The room temperature history $T_R(t)$ is given as

$$T_R(t) = 299 + 2.4\cos(\omega t + 2.4725) + 1.265(2\omega t - 1.3037) + 0.4126\cos(3\omega t + 1.2236) \tag{3}$$

where ω is 7.2722×10^{-5} (Neeper, 2000) for the case of Fig. 1(a). The convective heat transfer coefficient h varied between 3, 6 and 12 W/m^{2}K, which sets the heat flux between the room and the wallboard together with the temperature difference between them. The indoor convection could be established by either natural or mixed convection mode depending on the strength of the forced flow. In case of simple natural convection, the Nusselt number is given as a function of the Rayleigh number as in Eq. (4) whereas it is given as an empirical formula as shown in Eq. (5) for the mixed convection cases.

$$Nu_{\mathrm{natural}} = C\,Ra^n \tag{4}$$

$$Nu_{\mathrm{mixed}} = (Nu^n \pm Nu^n)^{1/n} \tag{5}$$

where Nu, C, n, Ra, natural and forced mean the Nusselt number, a constant, a constant for the exponent, Rayleigh number, natural convection, and forced convection, respectively. Here the Nusselt (Nu) and Rayleigh (Ra) numbers are defined as $Nu(=hk/L)$ and $Ra(=\beta\Delta TgL^3/\nu\alpha)$ where h, k, L, β, g, ν and α are heat transfer coefficient, thermal conductivity of air, characteristic length, thermal expansion coefficient of air, gravitational acceleration (=9.81 m/s^2), kinematic viscosity and the thermal diffusivity of air, respectively.

For gases, the heat transfer coefficient ranges between 2 and 25 W/m^{2}K for the free convection cases (Cengel, 1997). In addition to the convective heat transfer, the impact of the radiation heat transfer should be included in the heat transfer coefficient, i.e., combined heat transfer coefficient. Researchers have used the values between 1 and 10 (typically 6–9) W/m^{2}K as the combined heat transfer coefficient for the walls, e.g., 5.67 and 8.3 W/m^{2}K in Neeper (2000), 8.7 W/m^{2}K in Zhang et al. (2008), and 7.7 W/m^{2}K in TRNSYS 16 manual (2007). The room temperature changed linearly between the stepwise changes in Fig. 1(b). The heat transfer in this case was set to be 12 W/m^{2}K, which is not surprising considering the fact that the fan is always on in the test room to control the room temperature.

2.3. Experimental setup

In this study, a commercial PCM wallboard (Knauf, Germany) containing encapsulated organic phase change material was used. The latent heat and the apparent specific heat of the PCM wallboard were measured using the differential scanning calorimeter (DSC-Q1000, TA Instrument, UK) for the temperature range between 243 and 343 K under the condition of temperature rise rate 10 K/min. The thermal properties of the PCM wallboard were found to be slightly different from the specification from the manufacturer. The nominal phase change temperature, where the apparent heat capacity reached the maximum, and the latent energy related to the phase change were found to be 297 K and 246 kJ/m^2, which were informed to be 299 K and 330 kJ/m^2 in the specifications. The phase change occurred for the temperature range over 10 K, whereas more than 80% of the latent energy was concentrated within $\pm$2 K range from the nominal phase change temperature. The deviations of the melting temperature and the latent heat between the specifications and the measurement might be attributed to the hysteresis due to the instability occurring after repetition of certain number of phase changing processes – delay in phase change and different fusion temperature dependence (Nikolic & Ristic, 1992) (see Table 1).

A heat flux meter is fabricated by winding a thermocouple 16 times around a 1 mm thick silicon rubber plate of 100 mm $\times$ 100 mm area to enhance the sensitivity of the heat flux meter. The heat flux meter was calibrated against the joule heating heat flux from the nichrome wires. A linear relation is obtained from a regression analysis of the relation between the heat flux and the induced voltage difference.

The assembly of a 6 mm iron plate, the heat flux meter, the 15 mm thick PCM wallboard and 200 mm isopink insulation layer

Table 1
Thermal properties of the PCM wallboard.

Property	Value
Base material	Gypsum
Nominal phase change temperature	299 K
Latent heat	28.7 kJ/kg
Specific heat	1.2 kJ/kgK
Dimension (height × width × thickness)	600 mm × 400 mm × 15 mm
Thermal conductivity	0.134 W/mK

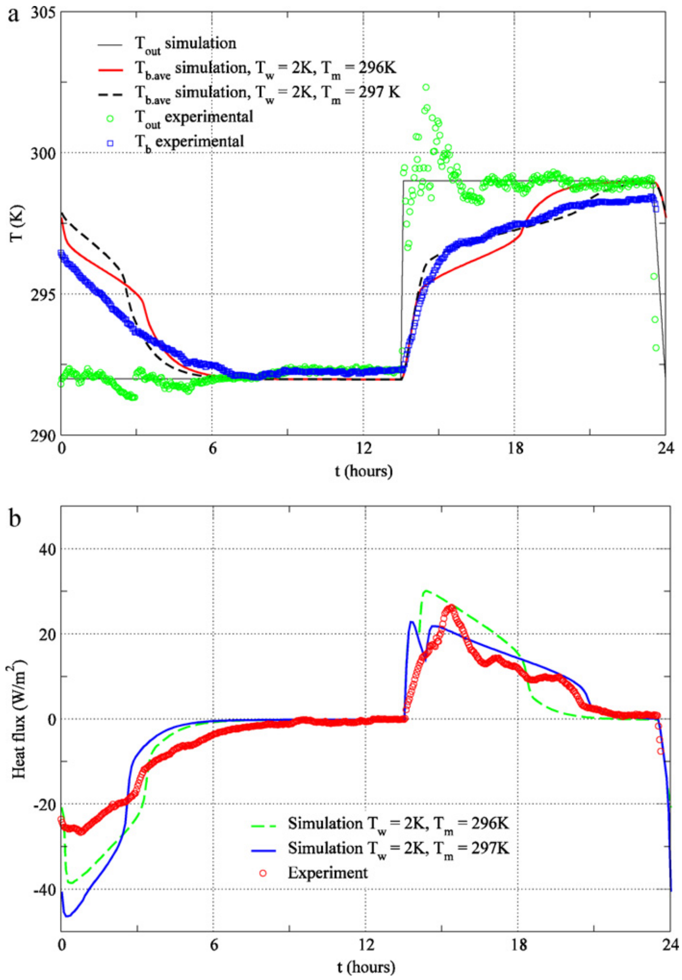

Fig. 2. Comparison of the heat flux and temperature histories between the results obtained from measurements and simulations.

(Byucksan, South Korea) in Fig. 1(b) was placed in a room where the room temperature was manipulated using a number of convective heaters and an air-conditioner. The room temperature was controlled by a PID temperature controller and an electric power controller. The temperatures were sampled at three different locations on each layer and the averaged values were used. To ensure the insulation, the layers of a PCM wallboard, a silicon rubber and an iron plate were placed on the back side of the isopink insulation layer as a mirror image.

3. Results and discussion

3.1. Model validation

The simulation model was validated with the experimental measurements of the wallboard temperature and heat flux for the model case shown in Fig. 1(b). Fig. 2 shows the comparison between

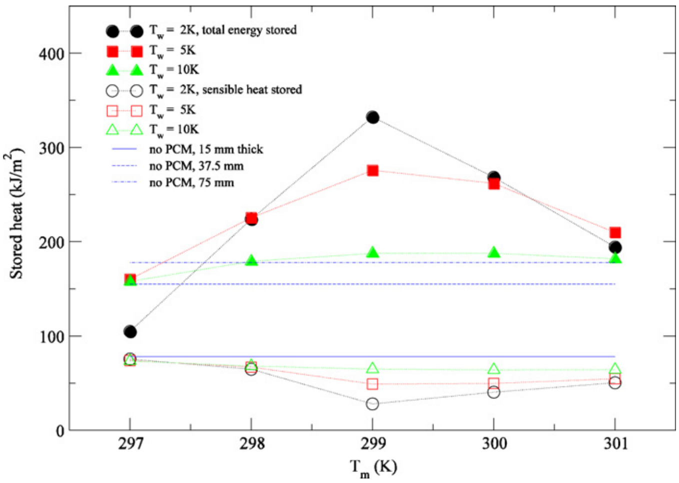

Fig. 3. The effects of the average phase change temperature and its duration on the stored energy (h = 6 W/m^{2}K).

the measurements and the simulation results. It was observed that the room temperature overshoot at the temperature step-up which was followed by small oscillations. The temperature on the wallboard rose with the room temperature step-up and the rate of the temperature rise decreased as the wallboard temperature went through the phase change temperature range. The simulation results captured well the characteristics of the temperature history from the measurements as shown in Fig. 2(a). The heat flux histories of the measurements and the simulation result are compared in Fig. 2(b). The measured heat flux history shows a delayed peak after the temperature step-up, which cannot be observed if the iron plate is not placed ahead of the heat flux meter. A small heat flux peak just after the temperature step-up is observed, which is followed by a delayed peak. The width of the region from the simulation results, where the heat flux is affected by the phase change, is comparable to that of the measured data. From the validation study, it was concluded that the simulation model was physically sound and the parameter studies could be performed using the model.

3.2. Thermal energy storage in the PCM board

The phase change temperature and the latent energy of the wallboard used in the experiments were described in Section 2.3. The phase change was observed to occur over a 10 K of the temperature range, while the latent heat was concentrated within ±2 K range from the nominal phase change temperature. Only the nominal phase change temperature and the related latent heat were given as the specifications of the wallboard, which were slightly different from the measurements. The phase change temperature of the polymers is related to their chain length, which might be controlled by the degree of the polymerization during the PCM production process. The results in Figs. 3 and 4 are obtained from the analytical simulation study, and represent the effects of the variations in the phase change temperature and its range on the thermal energy storage performance and the fraction of the latent energy storage used. The total stored energy in the wallboard was calculated by integrating the heat flux entering into the wallboard through its surface in a day when the heat balance between the incoming and outgoing heat fluxes are met. The sensible heat used could be calculated in the same way where the change of the sensible heat in time, i.e., the product between the wallboard mass, the specific heat and the average temperature change, was integrated. The latent heat used was estimated by subtracting the sensible heat calculated from the total stored energy. The results show that the stored energy in the PCM wallboard reaches maximum when the average room

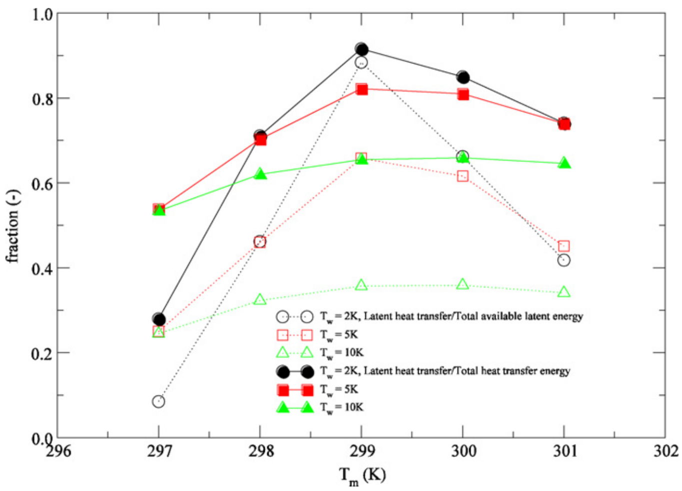

Fig. 4. Comparison of the fraction of used latent heat out of the total available latent heat in the PCM panel and that in the total heat transferred ($h = 6\,\mathrm{W/m^2K}$).

temperature is the same as the PCM phase changing temperature. The stored sensible energy decreases, while the thermal energy is stored more in the form of the latent energy as the phase changing temperature approaches the mean room temperature (see Fig. 4). In contrast, the stored energies are independent of the temperature for the wallboards without PCM. The energy storage performances of the 15 mm thick PCM wallboards outperform that of the 75 mm thick wallboards without PCM if the phase changing temperature is close enough to the average room temperature.

The figures also present the effects of the phase change temperature range T_W on the stored thermal energy. The stored energy increases with the decrease of the phase change temperature range as the average room temperature goes closer to the average room temperature. In contrast, as the phase change temperature deviates from the average room temperature the stored energy decreases more rapidly for the cases of narrower phase change temperature range, so that the stored energy for the cases of $T_W = 2\,\mathrm{K}$ becomes smaller than that of $T_W = 10\,\mathrm{K}$ when the temperature difference between the average phase changing temperature of the PCM and the average room temperature exceeds 2 K. It could be concluded that the thermal storage performance of the PCM wallboards could be optimized by matching the average phase change temperature and the average room temperature and narrowing the phase changing temperature range. However, to comply with the wide swing of the average room temperature, the PCM boards of wide phase change temperature range could be a better solution.

Fig. 5 shows the effect of the convective heat transfer coefficient h on the thermal energy storage in the PCM boards. It was found that the thermal energy storage in the board increases with the increase of it. The average phase change temperature at which the stored energy peaks shifts to a bit higher temperature with the increase of the coefficient.

3.3. Time shift effect

While the room temperature changes, there could be a time lag between the wallboard and room temperatures owing to the heat capacity of the wallboards. The time lag between the temperature peaks in the room and the board is defined as the time shift (see Fig. 6). Large time lag is preferable to save the energy for the heating and air conditioning.

Fig. 7 represents the effects of the nominal phase change temperature, phase change temperature range and heat transfer coefficient on the time shift. The time shift becomes maximum when the nominal phase change temperature approaches the aver-

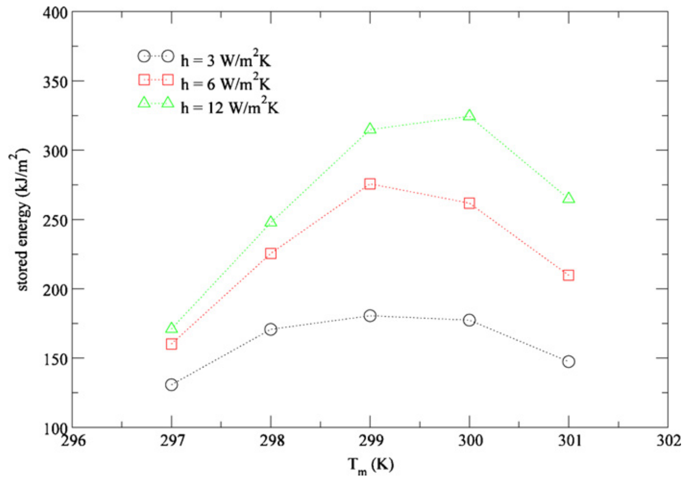

Fig. 5. Effects of heat transfer coefficient h on the stored latent heat energy in the PCM board ($T_W = 5\,\mathrm{K}$).

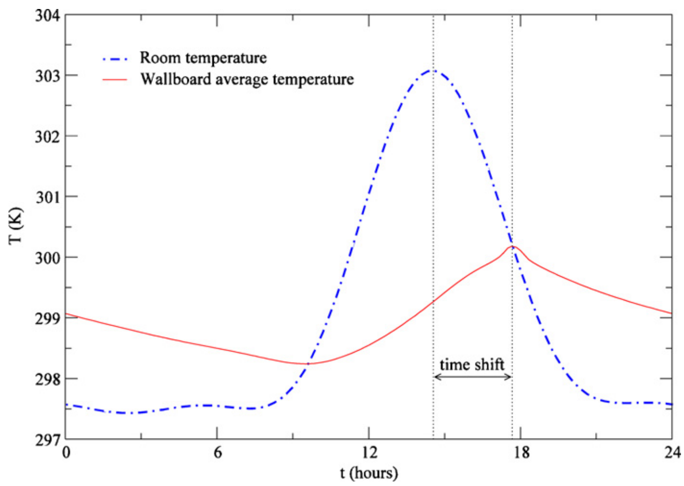

Fig. 6. The definition of the time shift.

age room temperature for the cases of $h = 3$ and $6\,\mathrm{W/m^2k}$, while it reaches the maximum value at slightly higher temperature than the average room temperature for the cases of $h = 12\,\mathrm{W/m^2K}$. This could attribute to the fact that the stored energy becomes max-

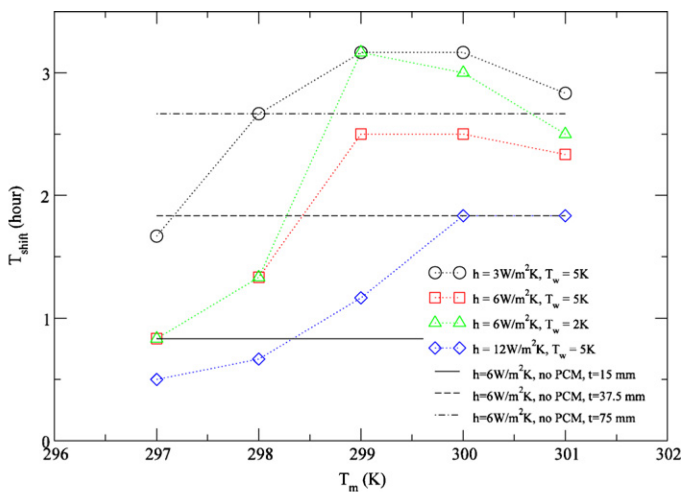

Fig. 7. Effects of heat transfer coefficient and phase change duration on the time shift.

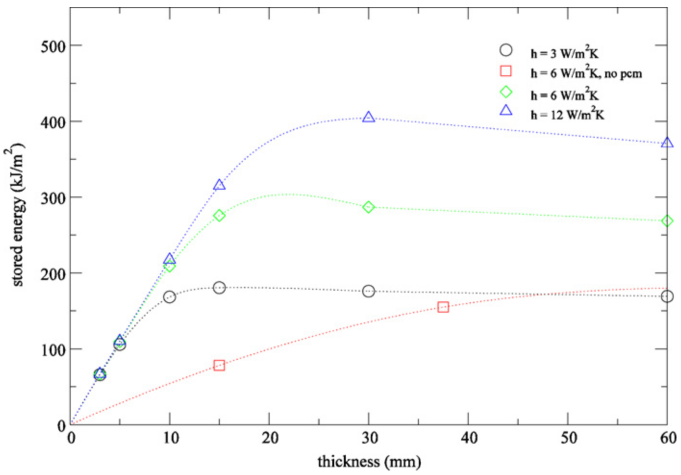

Fig. 8. Effects of the heat transfer coefficient on the stored energy in the PCM boards.

imum at T_m = 300 K as shown in Fig. 5. In contrast to the stored thermal energy, the time shift is found to decrease with the heat transfer coefficient due to the increase of the heat transfer between the room and the wallboards. The time shift of 15 mm thick PCM wallboards is found to be comparable with that of the 75 mm thick wallboard without PCM for the cases of h = 6 W/m^{2}k. The time shift is found to decrease with the phase change temperature range.

The stored thermal energy and the time shift are found to have their maximum at slightly higher nominal phase change temperatures than the average room temperature especially for the case of high heat transfer coefficients, which was observed and reported by Peippo et al. (1991).

3.4. Determination of the PCM board thickness

The effects of the wallboard thickness on the thermal energy storage are presented in Fig. 8. As was observed in Section 3.2 the thermal energy storage increases with the heat transfer coefficient. For the cases of a given heat transfer coefficient, there is an optimum wallboard thickness to maximize the thermal energy storage; it increases to the maximum value with the wallboard thickness before a critical value, then it decreases slightly. The critical thickness was found to increase with the heat transfer coefficient. For the wallboard without PCM, the critical thickness is much thicker than those with PCM. The impact of the thickness increase on the thermal energy storage decreases with the board thickness.

4. Conclusions

The followings are the conclusions drawn from the current study.

- The effects of the PCM inclusion in a wallboard could be successfully modeled by using apparent heat capacity formulation to simulate the impact of the latent heat during the phase change.
- It was found that the average phase change temperature should be close to the average room temperature to maximize the thermal heat storage in the wallboards. The phase change temperature should be narrow to maximize the thermal heat storage in the PCM wallboards. In contrast it is preferable to have a wide phase change temperature range to comply with wide range of the average room temperature seasonal variation.
- The thermal heat storage increased with the convective heat transfer coefficient, and the optimal average phase change temperature to maximize the storage shifted a bit to a higher temperature with it.
- The time shift was found to decrease with the convective heat transfer coefficient and the phase change temperature range. The optimal average phase change temperature to yield the maximum time shift increased with the convective heat transfer coefficient.
- The board thickness of 15 mm seems to be a proper selection from the fact that the thermal energy storage reaches maximum for the case of h = 3 W/m^{2}K.

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