Energy Demand Reduction by PCM Based Plasterboard Application for Passive House in Polish Climatic Conditions

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Abstract

The presented theoretical considerations refer to performance of energy storage unit consisting of phase change material. Integrated to internal wall PCM based plasterboard absorbs solar radiation during daytime and releases the heat at night. The thermal characteristics of the storage unit are described. Analytic model for room, with two nodes consisting of PCM plaster board and internal air, was developed. The basic conservation equations of energy for the storage unit and internal air were provided and analytically solved. The analytical model can be a tool for PCM selection, determination of its amount, and preliminary storage unit performance evaluation. The performance study has been carried out for commercially available PCM added to internal walls and ceiling plasterboards of passive house, functioning in Polish climatic conditions. The PCM also stabilizes the level of internal air temperature during the daytime in summer months reducing cooling demand and improving room comfort both in summer and winter. The examples of PCM based plasterboards were made and experimentally tested during successive charging and discharging processes.

1. The PCM Based Storage Unit

The utilization of renewable energies, solar energy in particular is necessary in case of extremely low energy buildings. The energy possessed from solar irradiation, characterized by periodicity and volatility of parameters, needs to be stored during the day and released during the night. In solar direct gain system the sun is admitted directly into the inhabitant spaces through the conventional window. The solar radiation penetrates building interior and then is being absorbed by internal walls, ceilings, floors or special storage units, which accumulate solar energy. In this work the PCM gypsum board is being considered as such energy storage unit.

The area of the PCM plaster board (as a surface part of internal wall and ceiling – Fig. 1), of volume V_a, is A_a. The storage unit is a composite made up of the gypsum with PCM microcapsules regularly placed inside.

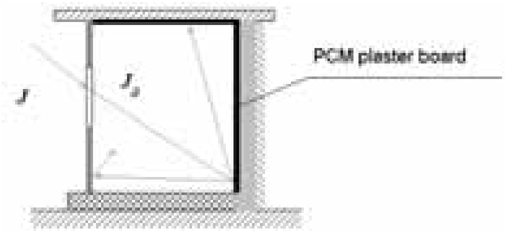

Fig. 1. PCM based storage unit as a surface layer of internal walls and ceiling

Properties of the gypsum as a building material, to which PCM is added, are as follows: the density ρ_g , specific heat c_g. The PCM of volume fraction ratio φ, is characterized by: density ρ_{PCM}, specific heat c_{PCM} equal for solid and liquid phase, and latent heat C_{PCM} . The transitions from solid to liquid and from liquid to solid are occurring at the same and constant temperature T_s. The basic storage unit parameters are density $\rho_a = \varphi\rho_{PCM} + (1-\varphi)\rho_g$ and heat capacity $C_a = V_a[\rho_g(1-\varphi)c_g + \rho_{PCM}\varphi c_{PCM}]$. The superscript *a* refers to the PCM plaster board as the heat storage unit. The forehead surface of storage unit absorbs daily solar radiation $J_a = J\,\tau_o \cdot A_o/A_i$, where *J* denotes daily solar radiation falling on vertical window of aperture area A_o, τ_o – transmittance of the glazing for the incident radiation. The solar irradiation is evenly absorbed by the inside area A_i of the room. Referring to the heat storage unit, where the criterion of small value of Biot number is satisfied ($\mathrm{Bi} = h_i d_a / k_a \le 0{,}15$), where h_i denotes inside film coefficient, d_a storage unit thickness and k_a its thermal conductivity, calculated from formula $k_a = \varphi k_{PCM} + (1-\varphi)k_g$, the temperature of the unit is almost balanced [1]. Such an assumption was adopted in modelling of the PCM plaster board functioning.

2. The Energy Balances of Storage Unit and Internal Air

2.1. The energy balances of storage unit and internal air

The energy E_a balance of the storage unit, resulting from solar radiation and the impact of the air inside the room, assuming adiabatic back surface of the storage unit, is

$$\frac{\mathrm{d}E_a}{\mathrm{d}t} = A_a G_a - h_i A_a (T_a - T_i), \tag{1}$$

where the solar irradiation G_a on storage unit surface is $G_a = J_a / t^D$, where the t^D denotes length of daytime. The internal energy of storage unit, using the Heaviside' a function, is written as

$$E_a = C_a T_a + V_a \rho_{\mathrm{PCM}} C_{\mathrm{PCM}} \varphi \{[\mathrm{H}(t - t_{s1}) - \mathrm{H}(t - t_{s2})]\mu_s(t) + \mathrm{H}(t - t_{s2})\}, \tag{2}$$

where the times t_{s1} and t_{s2} respectively determine the beginning and the end of phase change process, and introduced function $\mu_s(t)$ meets the following conditions: $\left|\mu_s(t)\right|_{t=t_{s1}} = 0$, $\left|\mu_s(t)\right|_{t=t_{s2}} = 1$.

The energy balance of the storage tank is formulated depending on the physical state of the PCM. Three stages of charging process are marked out: (i) increasing temperature of the storage unit from the initial temperature T_a^0 up to the melting temperature T_s, where PCM remains solid (assuming that the temperatures of gypsum and PCM are equal), (ii) the phase change of PCM occurs during the time interval $\Delta t_s = t_{s2} - t_{s1}$, (iii) further increase the PCM plaster board temperature, ranging from temperature T_s - in this stage of the PCM is liquid. The superscripts 1, 2, 3 denote respectively to the stages as above and 0 denotes to the beginning of each stage. The temperatures continuity conditions of the internal air and storage unit, in specified time intervals, are as follows

$$\left|T_{a1}(t)\right|_{t=t_{s1}} = T_s,\ \left|T_{a3}(t)\right|_{t=t_{s2}} = T_s,\ \left|T_{i1}(t)\right|_{t=t_{s1}} = \left|T_{i2}(t)\right|_{t=t_{s1}},\ \left|T_{i2}(t)\right|_{t=t_{s2}} = \left|T_{i3}(t)\right|_{t=t_{s2}}. \tag{3}$$

Depending on the operating conditions and storage unit characteristics, all three or fewer stages as above may occur during charging process. In reverse order there are stages of discharging processes of the storage unit.

Energy balance at room air node is

$$C_i \frac{\mathrm{d}T_i}{\mathrm{d}t} = h_i A_a \left(T_a - T_i\right) + A_b U_b \left(T_e - T_i + R_{b_e} G\right) + G_r A_r + A_o U_o \left(T_e - T_i\right) + \left(1-\eta_w\right)\dot{v}\rho_i c_{p_i}\left(T_e - T_i\right) + \omega_i, \quad ...(4)$$

where $C_i = m_i c_{p_i} = \rho_i V_i c_{p_i}$ is the thermal capacity of the air in the room equipped with storage unit. The superscripts *i, e, o, b* denote respectively to room air, external air, window, and external wall. The successive right-hand terms of the equation are described as follows.

$h_i A_a \left(T_a - T_i\right)$ - energy exchange between storage unit and internal air;

$A_b U_b \left(T_e - T_i + R_{b_e} G\right)$ - energy exchange between internal air and building surroundings of temperature T_e through external wall of area A_b, where U_b is the thermal conductance (heat transfer coefficient) of the external wall, $G = J / t^D$ - daily solar radiation on a vertical surface. $R_{b_e} = 1/h_e$, where h_e denotes outside film coefficient;

$G_r A_r$ - energy absorbed by the room elements other than storage unit, which energy immediately heats the internal air;

$A_o U_o \left(T_e - T_i\right)$ - heat exchanged between internal air and outside through the window of area A_o, where U_o denotes window heat transfer coefficient;

$\left(1-\eta_w\right)\dot{v}\rho_i c_{p_i}\left(T_e - T_i\right)$ - heat ventilation losses, assuming the heat recovery of thermal efficiency η_w, where $\dot{v}$ denotes ventilation air volume flow rate;

ω_i - auxiliary heat flux (assumed equal 0)

2.2. The solution of the air and PCM storage unit energy balances in case of the absence of phase change of PCM

For stage, in which there is no phase change of PCM, the equation (1) is

$$C_a \frac{\mathrm{d}T_a}{\mathrm{d}t} = A_a G_a - h_i A_a \left(T_a - T_i\right) \quad (5)$$

Differentiation of eqn. (4) gives

$C_i \frac{\mathrm{d}^2 T_i}{\mathrm{d}t^2} = h_i A_a \frac{\mathrm{d}T_a}{\mathrm{d}t} - \left[h_i A_a + A_o U_o + A_b U_b + \left(1-\eta_w\right)\dot{v}\rho_i c_{p_i}\right]\frac{\mathrm{d}T_i}{\mathrm{d}t}$, and by inserting to this the equation (5), the differential equation $a\frac{\mathrm{d}^2 T_i}{\mathrm{d}t^2} + b\frac{\mathrm{d}T_i}{\mathrm{d}t} + cT_i = d$ is obtained, relative to the internal air, of initial conditions for the stage (i) $t = 0, T_a = T_a^0, T_i = T_i^0$, where

$$a = \frac{C_a C_i}{\alpha_i A_a},\; b = C_a + C_i + \frac{C_a}{\alpha_i A_a}\left[A_o U_o + A_b U_b + \left(1-\eta_w\right)\dot{v}\rho_i c_{p_i}\right],\; c = A_o U_o + A_b U_b + {}$$
$$+\left(1-\eta_w\right)\dot{v}\rho_i c_{p_i},\; d = A_a G_a + \left[A_b U_b + A_o U_o + \left(1-\eta_w\right)\dot{v}\rho_i c_p\right]T_e + A_b U_b R_{b_e} G + G_r A_r + \omega_i \quad (6)$$

whose solution is $T_i^d = C_1 e^{r_1 t} + C_2 e^{r_2 t} + d/c,$ (7)

where $\Delta = b^2 - 4ac,\ r_1 = \frac{-b-\sqrt{\Delta}}{2a},\ r_2 = \frac{-b+\sqrt{\Delta}}{2a}$. For specified initial conditions the following formulas for constants C_1 and C_2 were obtained.

$$\begin{aligned} C_2 = {} & \frac{r_1}{r_1 - r_2} T_i^0 - \frac{r_1 d}{c(r_1 - r_2)} - \frac{h_i A_a \left(T_a^0 - T_i^0\right) + A_b U_b \left(T_e - T_i^0 + R_{b_e} G\right)}{C_i (r_1 - r_2)} + \\ & - \frac{G_r A_r + A_o U_o \left(T_e - T_i^0\right) + (1-\eta_w) \dot{v} \rho_i c_{p_i} \left(T_e - T_i^0\right) + \omega_i}{C_i (r_1 - r_2)}, \\ C_1 = {} & T_i^0 - d/c - C_2. \end{aligned} \tag{8}$$

The temperature of storage unit, on the base of the equation (5), taking into account (7), is written as

$$\begin{aligned} T_a = {} & \frac{C_i}{h_i A_a}\left(r_1 C_1 e^{r_1 t} + r_2 C_2 e^{r_2 t}\right) + \frac{1}{h_i A_a}\left[h_i A_a + A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho_i c_{p_i}\right] T_i + \\ & - \frac{1}{h_i A_a}\left\{\left[A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho_i c_{p_i}\right] T_e + A_b U_b R_{b_e} G + G_r A_r + \omega_i\right\} \end{aligned} \tag{9}$$

2.3. The energy balances of the internal air and storage unit during phase change of PCM

The energy balance of the internal air, where in the storage unit the phase change of PCM occurs, (in this case $T_a = T_s$) is

$$\begin{aligned} & \frac{\mathrm{d}T_i}{\mathrm{d}t} + \frac{1}{C_i}\left[h_i A_a + A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho c_{p_i}\right] T_i + \\ & - \frac{1}{C_i}\left\{h_i A_a T_s + \left[A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho_i c_{p_i}\right] T_e + A_b U_b R_{b_e} G + G_r A_r + \omega_i\right\} = 0, \end{aligned} \tag{10}$$

whose solution is

$$\begin{aligned} T_i & = T_{i2}^0 - C_3 + C_3 e^{-\frac{h_i A_a + A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho_i c_{p_i}}{C_i} t}, \\ C_3 & = T_{i2}^0 - \frac{h_i A_a T_s + \left[A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho c_{p_i}\right] T_e + A_b U_b R_{b_e} G + G_r A_r + \omega_i}{h_i A_a + A_b U_b + A_o U_o + (1-\eta_w)\dot{v}\rho c_{p_i}}, \end{aligned} \tag{11}$$

where T_{i2}^0 is the internal air temperature at the time t_{s1}, when the temperature of storage unit reaches the value of T_s.

The energy balance of storage unit, based on equations (1) and (2) is

$$\frac{\mathrm{d}\left(\rho_{\mathrm{PCM}} V_{\mathrm{PCM}} C_{\mathrm{PCM}} \mu_s\right)}{\mathrm{d}t} = A_a G_a - h_i A_a \left(T_s - T_i\right) \tag{12}$$

Inserting (11) to (12) and integrating the received equation in the time interval $[t_{s1}, t_{s2}]$, the transcendental equation as follows was obtained, from which the duration of phase change Δt_s is being calculated.

$$\rho_{PCM}V_{PCM}C_{PCM}=\frac{h_iA_aC_3C_i}{\alpha_iA_a+A_bU_b+A_oU_o+(1-\eta_w)\dot{v}\rho_ic_{p_i}}+(A_aG_a-h_iA_aT_s)\Delta t_s+$$
$$+\left\{h_iA_a\frac{h_iA_aT_s+\left[A_bU_b+A_oU_o+(1-\eta_w)\dot{v}\rho_ic_{p_i}\right]T_e+A_bU_bR_{b_e}G+G_rA_r+\omega_i}{h_iA_a+A_bU_b+A_oU_o+(1-\eta_w)\dot{v}\rho_ic_{p_i}}\right\}\Delta t_s+$$
$$-\frac{h_iA_aC_3C_i}{h_iA_a+A_bU_b+A_oU_o+(1-\eta_w)\dot{v}\rho_ic_{p_i}}e^{-\frac{h_iA_a+A_bU_b+A_oU_o+(1-\eta_w)\dot{v}\rho_ic_{p_i}}{C_i}\Delta t_s}. \tag{13}$$

4. Case Study – PCM based plasterboard influence on energy balance of the room

The performance of the PCM based plasterboard in Polish climatic conditions has been theoretically investigated. The PCM plaster board was adapted in the room of building, which meets the passive house standards [2]. The floor area of the room is 30 m^2, the area of window 7.5 m^2. The ventilation volume air rate is 1 m^3/h per 1 m^2 of floor area, and the thermal efficiency of recuperation is 0.75. The total area of the PCM plaster board is 71,6 m^2, thickness d_a=5 mm. The properties of gypsum are c_g=840 J/(kg·K), and ρ_g=1700 kg/m^3, and k_g=0.7 W/(m·K). The calculations were performed for two PCMs. The first one is the Micronal@ DS 5008 X of melting point T_s=23^{o}C and latent heat C_{PCM}=110 kJ/kg. The second is the paraffin RT20 of melting point T_s=22^{o}C and latent heat C_{PCM}=172 kJ/kg [3]. In each case the PCM volume fraction ratio φ=0.5.

The calculations of temperatures of storage tank and internal air, amount of heat stored in PCM plaster board were performed for average daily solar radiation and outside temperature of each months of the year. The results are presented in Tables 1 and 2. The calculation assumes there is no back-up. Gray boxes concern the results for Micronal@5008X, white boxes paraffin RT20. For each day, the air and the storage unit are initially at the same temperature 20^{o}C.

Table 1. The results of calculations for winter months

Month	X	XI	XII	I	II	III
Average daily solar irradiation on vertical surface (J/m^2)	6763	3693	2216	3102	5347	6919
Outside temperature T_e (^{o}C)	8.1	3	-0.6	-3.5	-2.6	1.2
Internal air temperature at the time of phase change beginning T_{i2}^0 (^{o}C)	23.02	22.84	not applica ble$^{*)}$	22.77	22.82	22.92
	22.03	21.86		21.78	21.83	21.94
The time of phase change beginning t_{s1} (h)	1.34	4.25		10.68	2.61	1.50
	0.88	2.73		1.32	1.70	0.99
The length of the time when phase change occurs (h)	10.66	7.75		10.68	9.39	10.50
	11.12	9.27		5.53	10.3	10.13
The percentage of phase change realisation (%)	99	21		1	43	86
	68	17		4	32	55
Energy stored by phase change process (MJ)	19.45	5.859		0.209	9.702	17.17
	18.323	4.677		1.07	8.567	14.777
Internal air temperature at the end of daytime T_i^D (^{o}C)	23.11	22.87	19.6	22.78	22.86	23.01
	22.13	21.88		21.80	21.88	22.02
PCM plaster board temperature at the end of daytime T_a^D (^{o}C)	23	23	19.8	23	23	23
	22	22		22	22	22

$^{*)}$ The temperature of the PCM gypsum plaster does not reach the melting temperature

In the average day of December (Table 1), the temperature of PCM plaster board does not reach the melting temperature level. Solar profits, however, ensure the maintenance of air temperature at about 20°C during all day. In the remaining months of the heating season, the PCM board stores during the day significant amount of energy to be used during the night. There is not necessary to use back-up to heat the room during the day. For summer months the PCM stabilizes sufficiently the internal air inside temperature during the daytime (Table 2). In case of RT20 there is not necessary to limit the solar radiation access to the room. In this case PCM maintain the internal temperature at level 22°C, for Micronal that is 23°C. The amount of heat stored during the average day of October and March is approximately equivalent of daily heat demand of passive house room. In November and February heat stored in PCM plaster is covering over half of the room energy demand. For December and January obviously the back up is necessary.

Table 2. The results of calculations for summer months

Month	IV	V	VI	VII	VIII	IX
Average daily solar irradia-tion on vertical surface (J/m^2)	7675	7979	7496	7568	8169	7750
Outside temperature T_e (°C)	7.8	13.8	17.3	19.1	18.2	13.9
The limitation of solar irradiation penetration$^{*)}$ (%)	0	13	16.5	22	28	24
	0					
Internal air temperature T_{i2}^{0} [°C]	22.88	23	23.07	23.10		
	21.90	22.06	22.13	22.18	22.20	22.19
The time of phase change beginning (h)	1.38	1.3	1.3	1.31		
	0.92	0.72	0.7	0.66	0.61	0.65
The length of the time when phase change occurs (h)	10.62	10.7	10.7	10.69		
	11.08	10.71	11.3	11.34	11.39	11.35
The percentage of phase change realisation (h)	92	100	100	100		
	63	83	86	92	100	94
Internal air temperature at the end of daytime T_a^D (°C)	22.96	23.09	23.16	23.19		
	21.99	22.17	22.25	22.30	22.33	22.31

$^{*)}$ The percentage of solar irradiation that is stopped and not enter the room via windows (e.g. by special curtains)

4. Experimental tests of PCM based plasterboards heating and cooling

The experimental investigations of PCM plasterboard have been conducted. Commercially available PCM product (Micronal DS 5008X) was mixed with gypsum and cement at different PCM volume fractions. The certain number of physicals models were performed (Table 3).

Fig. 2. Microscope photo of PCM capsules and PCM based plasterboards

Table 3. The executed PCM test plaster boards

No.	Construction material	Mass (g)	PCM volume fraction ratio (%)	PCM mass fraction ratio (%)	Test plates sizes (mm x mm x mm)	Volume (dm^3)
1.	Gypsum	3130	59	35	505x505x15	3,83
2.	Gypsum	4420	33	16	505x505x17	4,34
3.	Cement	4934		35	323x323x40	4,17
4.	Gypsum		68	44	test plate very brittle	
5.	gypsum	3097	50	34	323x323x40	4,17
6.	cement	2736	75	47	323x323x40	4,17
7.	cement	3178	67	38	323x323x40	4,17
8.	Cement	2798	80	57	323x323x45	4,69

The executed test boards looked to be too brittle for PCM volume fraction ratio above 50% in case of gypsum and 75% when PCM was mixed with cement.

A number of successive cycles of heating and cooling processes of test plates were performed. Temperatures of front surface and back sides of test plates were monitored during heating and cooling processes of plates in laboratory conditions. The charging process was induced by solar simulator operation, as discharging by natural convection. The temperatures profiles during selected charging and discharging processes of test plate No. 8 are presented below in Fig. 3 and 4.

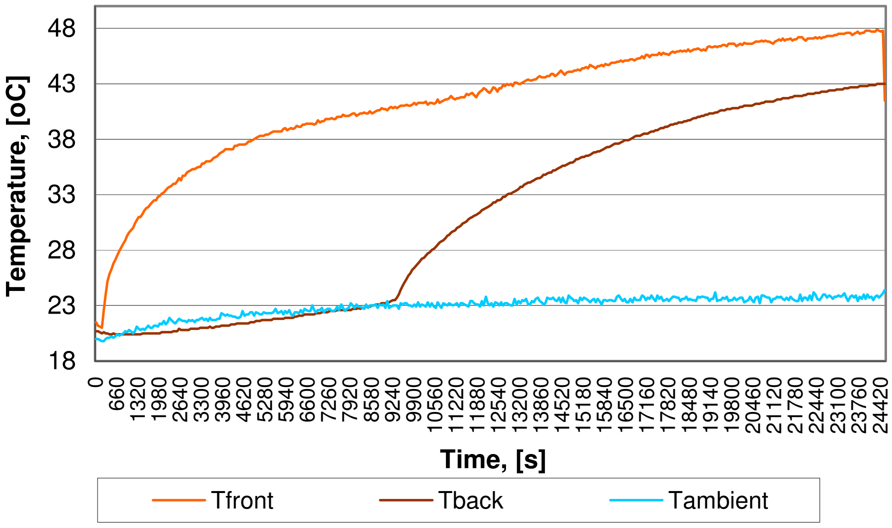

Fig. 3. The profiles of front and back surfaces PCM based palsterboard during charging process

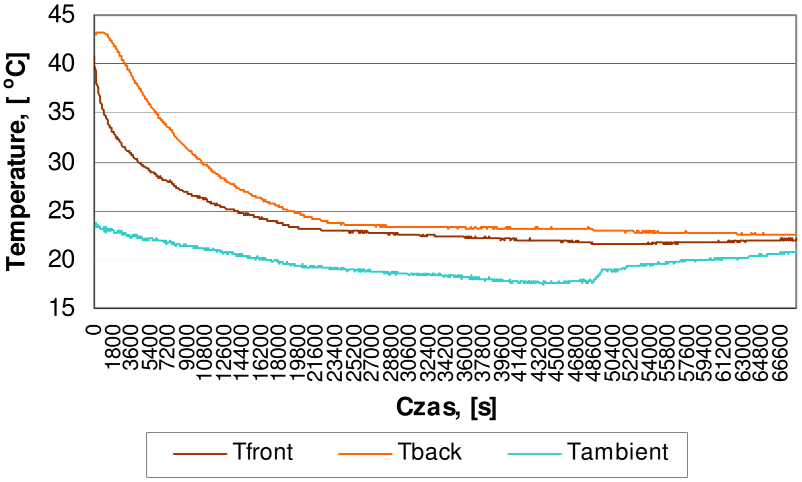

Fig. 4. The profiles of front and back surfaces PCM based plasterboard during discharging process

The temperatures profiles and distribution in PCM based plasterboard are significantly influenced by the PCM material presence.

5. Conclusions

The utilisation of PCM raises the building thermal efficiency. The PCM plaster board accumulates solar gains during the day and releases possessed heat at night and stabilizes the internal temperature at the level of its melting temperature. The stabilization as above occurs evidently during the summer thus reducing the cool demand. The amount of PCM should be carefully set to achieve the maximum effect. The analytical model can be a tool for PCM selection and preliminary storage unit performance evaluation. The presented calculations were performed for the extremely low energy building where the daily accumulation of possessed solar energy has significant effect for conventional energy demand reduction. Also the cooling demand is being reduced by PCM (of characteristics as assumed) adoption.

Acknowlegments

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