Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

Estimating feasibility of regenerating PCM and Desiccant in room interior wall surfaces using pre-dried air through an external desiccant bed

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Abstract

Buildings account for a significant fraction of energy use. Reduction of energy use in buildings has been the subject of research for quite a while to date. Passive means for comfort provision is one way of energy use reduction in buildings. A passive humidity and temperature control requires regeneration of the participating building envelope materials at some point in order for the buffering to be possible when needed. The present work focuses on investigating the potential for regenerating interior building envelope materials of an office that have been enhanced with a desiccant (for moisture buffering) and a PCM (for temperature buffering). The simulation study reveals that with an appropriate design the regeneration of both PCM and desiccant is possible. In winter, the cooling of the PCM takes place at a faster rate because the outdoor air temperatures are highly subdued during the night. The significantly low temperatures, however, are not favorable for the silica gel regeneration but moisture content of as low as 0.04kg/kg is achieved at the fourth hour of regeneration while beyond this hour the moisture content starts to increase. Temperatures are on a decrease towards minimum as dawn approaches. In summer, it is possible to reach about 0.07kg/kg and at the same time being able to freeze PCM that to dispatch about 470W of cooling power for a 10-hour period.

Keywords: *Regeneration, Phase Change Material, Desiccant, Passive Humidity and Temperature Control*

1. Introduction

Buildings account for a significant percentage of national energy consumption and HVAC systems contribute a significant portion of the buildings' energy demand (Shilei et al., 2007). Research into passive cooling through the application of PCM has received a lot of attention (Shilei et al., 2007, Cabeza et al., 2007, Baetens et al., 2010, 2012, Karim et al., 2014). Key comfort parameters include humidity in addition to the commonly focused on parameter, temperature. While some interior finishes can offer some moisture buffering, it is usually not enough to render the expected comfort. Efforts towards the application of desiccants to interior building envelope materials as a means to enhance the moisture buffering capacity has been limited; one known investigation towards this end is that of Rudd (1994). Potential regeneration for interior surfaces laden with a desiccant at a constant temperature was investigated through spreadsheet simulation (Manyumbu and Martin, 2013). The investigation did not look into the regeneration of the PCM; the assumption was that there is a constant phase change temperature of the PCM always. In the current study, the investigation looks into the feasibility of regenerating both the desiccant as well as PCM.

2. Methods

2.1. The Regeneration Concept

The concept involves a solar channel that has a desiccant bed forming its absorber surface during day-time operation, fig. 1. At night the channel operate as an air dryer, fig. 2, drying ventilation air passing through into the room. While the air is dried in the process, it gets heated up since the process is exothermic (it

doi:10.18086/swc.2015.08.06 Available at http://proceedings.ises.org

release heat of adsorption). The slightly warmer dry air is then responsible for the regeneration of the interior wall surfaces that are laden with a PCM and a desiccant (silica gel).

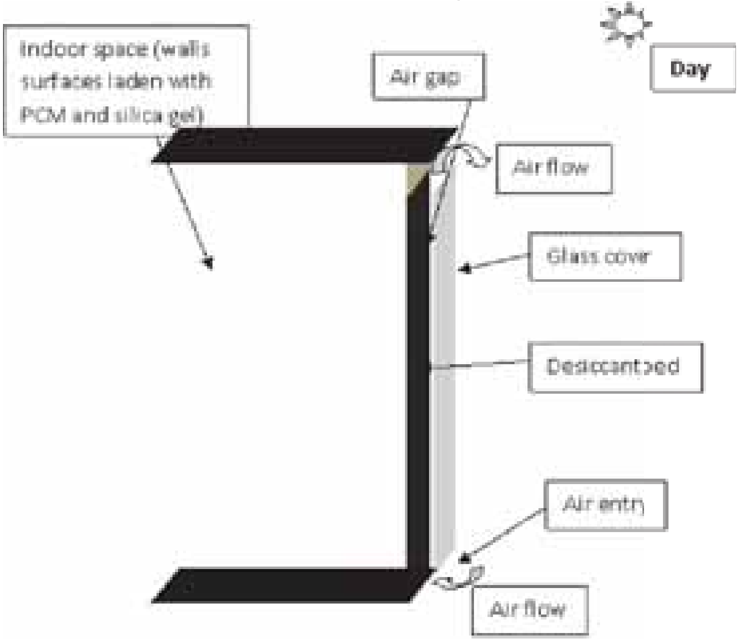

Fig. 1: Proposed Passive Regeneration Strategy for Exterior Desiccant

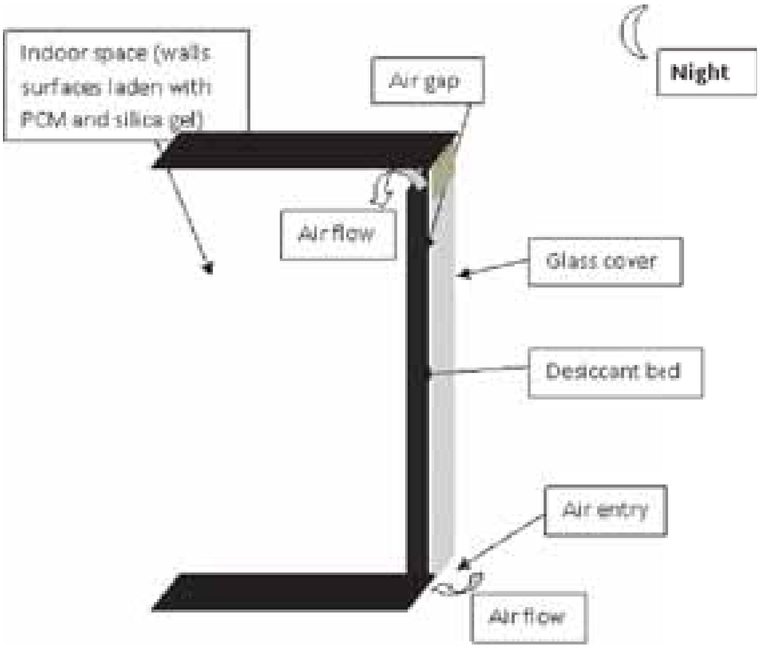

Fig. 2: Proposed Passive Regeneration Strategy for Interior Surfaces

2.2. Passive Ventilation _ Airflow

The air flow rate is based on the simulated results of Manyumbu et al. (2014). A PCM channel is expected to get charged during the day and then provide heating that then result in air flow in the channel at night time. According to Manyumbu et al (2014) the average velocity of air through the channel during charging and discharging is given by eq. 1.

$$u = \left(\frac{C_v g \beta L^2 b Nuk h_g}{24 \mu c_p}\right)\left(\frac{T_{pcm} - T_{in}}{Nuk / b + h_g}\right) \qquad \text{(eq. 1)}$$

A ventilation flow rate of circa 1ach was obtained in the simulations and this is used as input in the current study.

2.3. Mathematical Formulations and Assumptions

Mathematical modeling and spreadsheet simulation are employed in this study. The mathematical modeling is based on the mass and energy principles while applying appropriate boundary and initial conditions. A Quasi-steady state and uniform assumptions are used in modeling the external silica bed processes. Parameters of importance are evaluated, these include exit air temperature and humidity. Energy balance equation for the external silica gel bed system during bed regeneration using solar energy including sorption heat can be generally represented by the following eq. 2.

$$T_f = T_a + \frac{\eta I A_c + Q_s}{2 \dot{m}_a c_p} \qquad \text{(eq. 2)}$$

In eq.1, T_a is the environmental air temperature, η is the efficiency of converting solar radiation to useful thermal regenerating energy, I is the normal solar radiation received by the channel, c_p is specific heat capacity of air and Q_s is the sorption heat of silica gel. During the night, outdoor air temperature is dried as it passes through the channel whose absorber surface is the silica gel bed. Air conditions (temperature and humidity) are obtained based on the following eq. 3 and eq.4.

$$Q_{sorp,t-1} = m_a C_a \left(T_f - T_a\right) + m C_{sg}\left(T_{sg,t} - T_{sg,t-1}\right) \qquad \text{(eq. 3)}$$

$$X_{ao} = \min\left(\left(X_{ai} + \frac{1 \times 10^{-4} m}{\dot{m}_a (1 + X)}\left(X - X_e\right)\right); 0.003732 e^{0.062T}\right) \qquad \text{(eq. 4)}$$

Based on the obtained conditions of the bed and air, the humidity of the exit air is then obtained. The drying power of the silica gel bed depends on the initial dry state and this together with the ambient air conditions determines the extent to which the internal surfaces can be regenerated. Air leaving the bed is expected to be drier and warmer than the night outdoor air, but must still be cool enough to effect PCM regeneration. While elevated temperatures are favorable for the desiccant regeneration, PCM regeneration requires low temperatures. This conflict is somehow compensated by the heat of desorption since the process is endothermic.

2.4. External Bed Regeneration and Air Drying

Regeneration of the external silica gel bed is dependent on the condition of the bed, the conditions of the drying air and the amount of air that is responsible for the drying process. One limiting (or boundary) condition is the combination of the drying capacity of the air and the flow rate. If the air gets saturated it means it cannot absorb any more moisture. The amount of moisture removed from the silica gel bed is the function of moisture uptake by the drying air and its flow rate.

2.5. Internal Surface Regeneration

The condition of the air leaving the external silica gel bed determines the rate and extent of regeneration achievable. While it cannot be disputed that heating air improves its drying capacity, it must be noted that air humidity plays a significant role in the process. If air is saturated it does not matter at what temperature it is, it will not take up moisture. Low-temperature regeneration is possible if the regenerating air is pre-dried to low enough humidity levels. According to Ondier et al. (2010), it is clear that the relative humidity plays a significant role in the moisture exchange process. The temperature affects the rate of drying, but the relative humidity determines the extent of drying at the end of the process determined by the equilibrium moisture content. While saturated vapor pressure of moist air exponentially increase with temperature, Buck (1981), which trend is also followed by the reduction in moist air relative humidity, drying can sufficiently be achieved with relative humidity reduction in low temperature situations. Janssen (2011) concluded that the claim that thermal diffusion has a significant impact on vapor transport in porous media was flawed. According to Dalton's Law, moisture flux at a surface is given by;

$$\dot{m}_w = k\left(X_{sat} - X\right) \qquad \text{(eq. 5)}$$

In eq.5 k is a constant that characterize the moisture exchange, X_{sat} is the saturation (equilibrium) moisture content while X is the moisture content, the difference of the two becomes the driving force. The surface vapor pressure is dependent on the moisture condition of the silica gel. X_{sat} and X are evaluated at the previous and current time steps respectively.

2.5.1. Silica Gel Regeneration

The relative humidity of the air leaving the external silica gel bed determines the rate and extent of silica gel regeneration achievable. The relative humidity is a function of both temperature and the specific humidity. The external silica gel bed dries the air and at the same time raises its temperature as the process is exothermic. The sorption heat generated during air drying will raise the temperature of the bed as well as that of the air being dried. Both drying and temperature increase lower the relative humidity, and this is desirable for the internal silica gel regeneration. However, it needs to be noted that the increase in temperature is not favorable for PCM regeneration. The specific humidity of air leaving the room is estimated based on eq. 6 below.

$$X_{ao} = \max\left(\left(X_{ai} + \frac{6\times10^{-5}m}{\dot{m}_a\left(1+X\right)}\left(X - X_e\right)\right);0.0061X^{0.4329}e^{0.062T}\right) \qquad \text{(eq. 6)}$$

In eq. 6 X_{ao} is the specific humidity of air leaving the room, X_{ai} is the specific humidity of air entering the room, X is the moisture content of silica gel, X_e is the equilibrium moisture content of silica gel, m mass of silica gel, $\dot{m}_a$ mass flow arte of air and is the temperaure of air in the room. Room air temperature is estimated using eq. 7 below assuming the relationship of a vertical surface and the air interaction with it convectionally (Paul and Alzwayi, 2010).

$$T_{room} = T_{PCM} + 0.38\left(T_{ai} - T_{PCM}\right) \qquad \text{(eq. 7)}$$

In eq. 7, T_{room} is room air temperature, T_{PCM} is the PCM laden wall surface temperature and T_{ai} is the temperature of air entering the room from the external silica gel bed.

2.5.2. PCM Regeneration

PCM regeneration is a process of heat removal thereby freezing the PCM. The process, therefore, requires regenerating air that is at a lower temperature than the phase change temperature. The greater the temperature difference between the PCM and the regenerating air the improved the rate of regeneration and the regeneration extend that can then be achieved within the given regeneration period. The increase in air temperature during drying is therefore not desirable for PCM regeneration process. The night outdoor temperatures are highly subdued hence despite the increase of temperature because of the sorption heat during drying, the temperatures are still lower than the phase change temperature of around 26°C. The heat transfer coefficient h at the wall surface is given by eq. 8 below. The heat transfer q is then denoted by the subsequent eq. 9.

$$h = 4.31\Delta T^{0.293} \qquad \text{(eq. 8)}$$

$$q = 4.31\Delta T^{1.293} \qquad \text{(eq. 9)}$$

PCM conduction has been ignored considering that the plaster/PCM mix will result in thermal bridges that are assumed to render the rate of conduction higher than the convective heat transfer rate. According to Amin et al (2009) for PCM of thickness less than 5mm, the heat flow resistance can be considered to be negligible. The heat transfer between the wall is, therefore, dependent on the difference between the wall and room air temperatures.

3. Results and Discussions

The simulations were carried out using a simple spreadsheet program based on the equations presented in the preceding sections. The results presented here are based on channel depth (air gap) of 0.02m, channel height and width of 3m with 5kg of silica gel bed. While there are conflicting requirements in terms of conditions favorable for the regeneration of PCM and desiccant a compromise can be reached that result in desirable regeneration for both. The mass of silica gel in the external bed must be simulated in relation to other conditions such as the initial bed temperature and the desired temperature for the dried air meant for internal surfaces regeneration. The complexity of the processes involved requires a careful analysis in order to predict feasibility. The preliminary predicted regeneration conditions are; silica gel dryness of circa 0.07kg/kg and circa120 kg of PCM frozen if the phase change heat of fusion of 200kJ/kg is assumed. During summer the contribution of the desorption heat towards PCM regeneration is around 11% while in winter it is just 4% when the silica gel has reached the lowest best regeneration level.

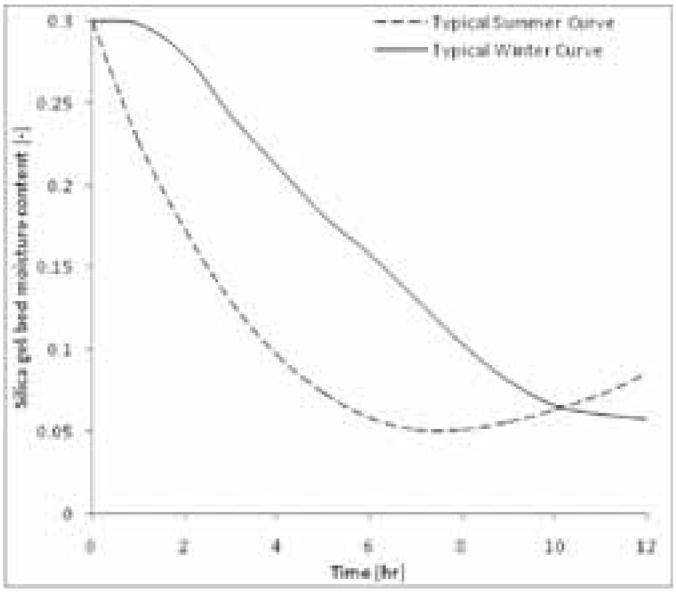

Fig. 3: The extent of external bed regeneration for a west-facing channel (January and June 1999 data)

From fig. 3, it is clear that it is possible to bring down the moisture content of silica gel bed within a solar channel from 0.3kg/kg to about 0.05kg/kg. It must be noted however that during summer, the regenerating process result in an increase of the moisture content of the bed beyond 8hours of regeneration. If the process is allowed to carry on up to 12hours the moisture content of the bed will approach 0.1kg/kg. In winter moisture content of around 0.05kg/kg is reached around the 12th hour of the regeneration process.

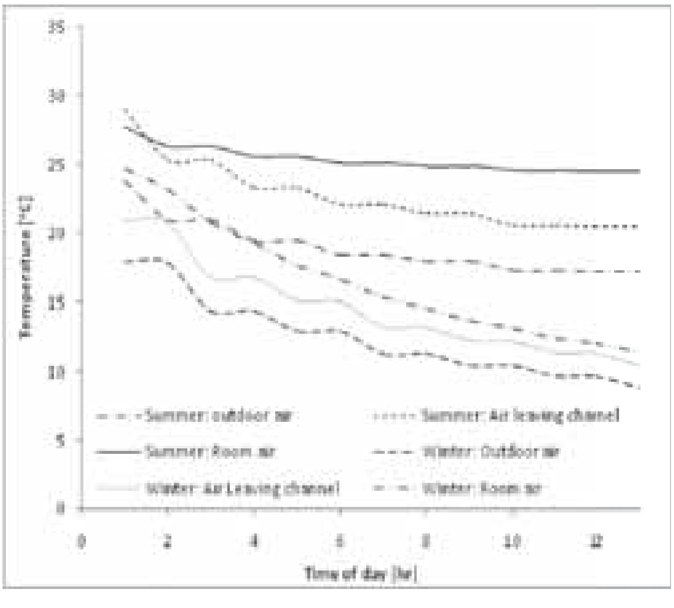

Fig. 4: Air conditions entering and leaving the external silica gel bed (based on January and June 1999 data)

Fig. 4 shows the outdoor temperatures, the simulated temperatures for air leaving the external silica gel bed as well as the room temperatures (estimated from a correlation between PCM surface temperature and natural convective air temperature of Paul and Alzwayi, 2010). The room air temperatures are generally quite low around due to very low outdoor temperatures. Low temperatures coupled with the fact that the drying effect of the external bed becomes less with time, continuing the regenerating process will instead result in an undesirable effect of increasing the moisture content of the interior surfaces. In summer, the effect is less due to generally higher temperatures. It is, therefore, important to have different regenerating time periods for the two seasons.

Fig. 5 below shows the simulated regeneration curves for both silica gel and PCM for the winter season. The moisture content of the silica gel of about 0.08kg/kg is possible. Beyond 6hours of the regeneration process, the moisture content approaches 0.1kg/kg (which is less effective during humidity buffering), hence it becomes advisable to stop the regeneration process since adequate PCM regeneration is already attained. For summer, the regeneration process must go all the stretch to get high PCM regeneration percentage, fig. 6.

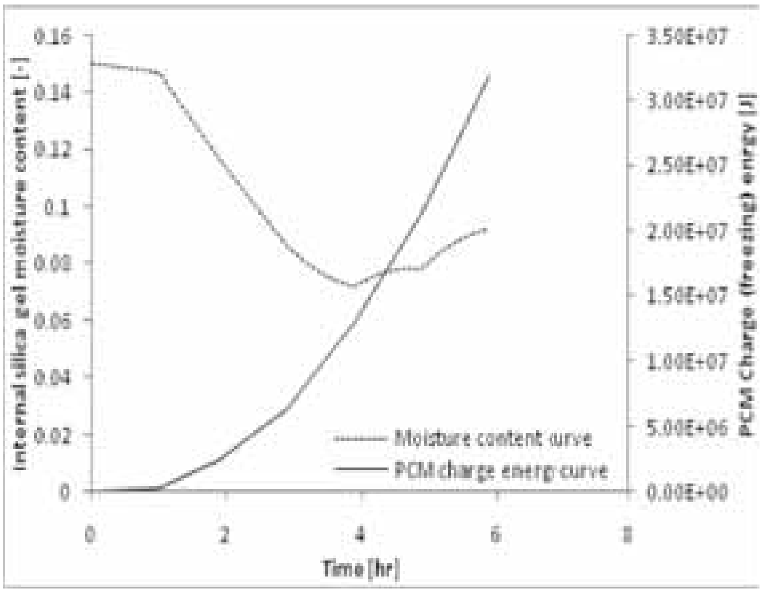

Fig. 5: The extent of internal surfaces regeneration (winter)

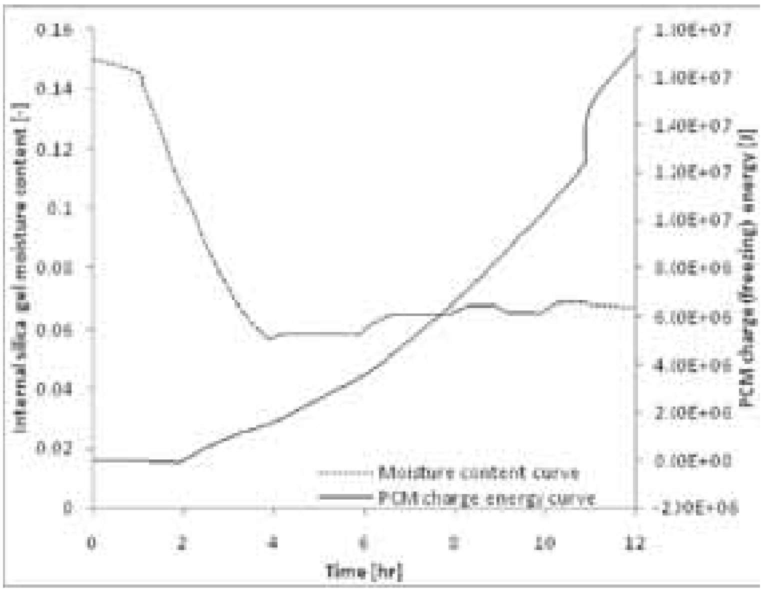

Fig. 6: Internal surface regeneration (summer)

An evaluation of the effectiveness of both the regenerated silica gel and PCM is shown in fig. 7 and fig. 8 below. Fig. 7 is indicating the effectiveness during winter with PCM phase change temperature being set at 27°C with varying mass of silica gel in the interior surfaces. PCM mass is assumed to be matching the available coolness from the regenerating air. A mass of 8kg of silica gel result in the highest performance of humidity buffering effectiveness (considering a 10% relative humidity change) of about 90%, and this correspond to a cooling effectiveness of 122%. This implies that there is possible over cooling of 22%.

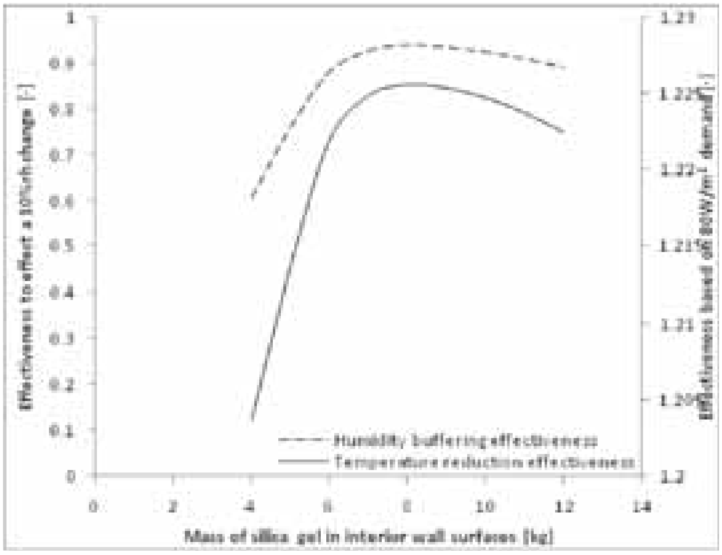

Fig. 7: Variation of the buffering effectiveness with varying silica gel mass within the interior walls for winter season (PCM phase change is set at 27°C), room volume is 27m³

Fig. 8 indicates the estimated humidity and temperature buffering effectiveness of the interior surfaces at varying masses of silica gel within the surfaces for the summer season. Evaluations were carried out at two PCM phase change temperatures of 27°C and 28°C. Improved buffering effectiveness is noted for both humidity and temperature, more so on the later. Elevated PCM phase change temperature results in increased temperature difference and hence improved regeneration. Similarly elevated temperatures have the effect of improving the drying effect of the room air and thus improved regeneration. It is clear that while silica gel regeneration is good, PCM regeneration is somewhat low because of the temperatures of the regenerating air which are fairly high.

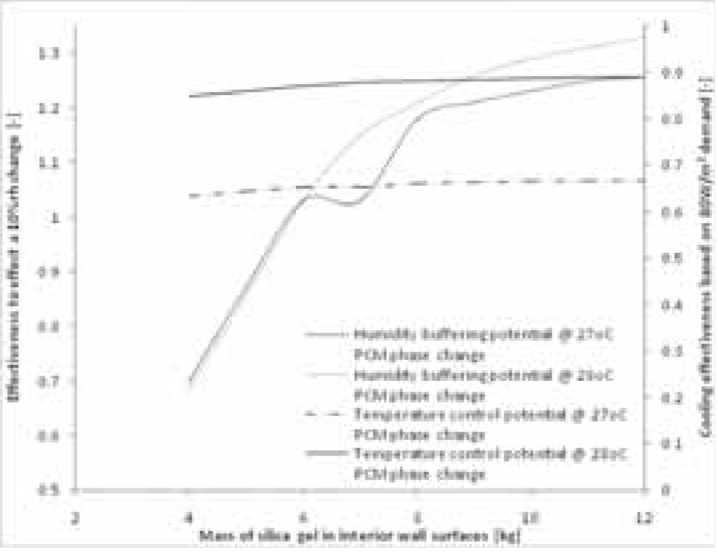

Fig. 8: Variation of the buffering effectiveness with varying silica gel mass within the interior walls for the summer season (PCM phase change is set at 27°C and 28°C), room volume is 27m³

4. Conclusions

The possibility for regenerating both the PCM and Silica Gel for temperature and moisture buffering in an office during daytime occupancy is demonstrated. Using simple mathematical transient models which were implemented in an excel spreadsheet the regeneration of both PCM and Silica Gel in interior wall surfaces could be predicted. Due to high parameter sensitivities and the rudimentary approach applied, it is imperative to conduct an experimental validation in order to firmly establish the feasibility. With further analyses and developments it is possible to have a feasible regeneration strategy that provides adequate humidity and temperature buffering passively for an office space for certain climates.

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