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Combination of Phase Change Materials with Ceiling Cooling Panels in Office Environments

Rita Farkas[#1], Zoltán Andrássy[#2]

[#]*Budapest University of Technology and Economics, Faculty of Mechanical Engineering, 3 Műegyetem rkp. Budapest, Hungary*

[1]f.rita33@gmail.com

[2]zolee92@gmail.com

Abstract

In the international routine, phase change materials (PCM) are mainly used for decreasing the energy usage of buildings. In our paper we investigated a ceiling cooling system operated with phase change materials in an office environment. We analyzed the PCM, the ceiling cooling system and their combination with ANSYS simulations. The aim of CFD simulations was to determine the cooling performance of the panel and to investigate the improvement potentials using PCMs.

We made a Matlab program which can calculate the uptime of the refrigerator and its EER in the function of the PCM properties and thickness, the volume and shape of office, the inner heat generation rate, and the ambient temperature. We investigated the process of phase change, the heat fluxes, the effect of radiation, and the temperature of walls and cooling water. In the simulations we determined the optimal melting and solidification points, and the thickness of the optimal phase change materials in different room types to maximize the reduction in annual energy usage. Finally, to validate our results we built a small scale adiabatic room in the department's laboratory.

As a result we could determine the optimal PCM properties, which can maximize the energy reduction of the office building. According to our calculations, simulations and measurements we can state that the usage of phase change materials in office environment can reduce the annual cooling energy usage of the building by 10-20%, depending on the operation conditions.

Keywords - phase change material, thermal energy storage, surface cooling system, energy efficiency

1. Introduction

In our paper we would like to present a new solution for a comfort problem in Hungary. As the inner heat generation rate is huge in offices, the cooling energy usage of these buildings is very high, in some cases there is a need for cooling in winter period as well.

We investigated a ceiling cooling system to fulfil the inner heat comfort criteria and combined it with phase change materials (PCM) to improve its properties. The inner temperature fluctuation of the investigated office has caused regulation problems, which could be reduced with thermal energy storage. The combined system can reduce energy usage of the office building, as the operation of the system could be improved by energy storage. The efficiency can be improved with the better operation due to

PCMs, as the system can avoid working in inadequate operation points, when the efficiency of the system is low [1], [2], [3].

Figure 1 The examined ceiling cooling system [4]

With surface cooling systems due to the low temperature of surfaces and the even distribution of temperature the heat transmission with radiation can grant pleasant inner heat comfort.

Phase change materials (PCM) are materials used for storing heat energy. To do that these materials use latent heat in the storing process, so PCMs store heat with higher density and release it, when it is necessary.

The most commonly used material for thermal energy storing purposes is water. Let's see a quick example why an average PCM is better than water. Changing the temperature of 1 m^3 water by 10 °C, cca. 42 MJ/m^3 energy could be stored. With an average PCM (latent heat capacity: 200-250 kJ/kg, density: 800 kg/m^3) just with the use of its latent heat capacity, so without changing its temperature 160-200 MJ/m^3 thermal energy could be stored. This results in smaller storage volumes.

Phase change materials has many advantages and disadvantages as well as it can be seen below.

Advantages:

- high density thermal energy storing capabilities,
- can lower heat oscillation,
- wide range of melting temperatures,
- simple storage,
- cheap (in material).

Disadvantages:

- thermodynamic properties are function of time and temperature,
- low heat conductivity,
- density change when changing phase,
- degradation after many cycles,
- supercooling,
- phase segregation,
- could be reactive, corrosive, flammable.

2. Methods

2.1 Experimental setup

Many articles deal with similar problems [5]-[9], in our case we combined an active ceiling cooling system with PCMs and we investigated the performance reduction effect of the freezing of the PCM and the performance increasing effect of the PCM, when it melts.

For the investigation of the processes in practice we built an experimental system. It is a well insulated (12 mm polystyrene) 1x0,8x0,7 meter adiabatic box including the ceiling cooling panel and PCM on the top and a 105 W light bulb. The size of the box is calculated according to the surface area to volume ratio, using the small sample model. With the light bulb the inner heat generation can be modelled. We placed 8 temperature sensors inside the box to measure the distribution of the temperature and the temperature of the PCM. The adiabatic box can be seen on *Figure 2* and *Figure 3*.

Figure 2 Adiabatic box

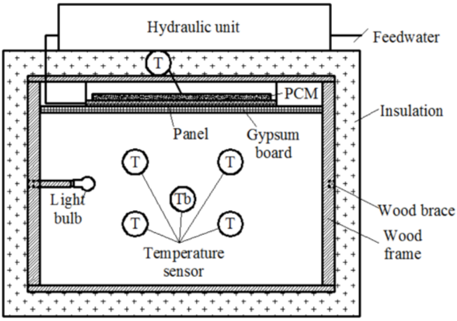

Figure 3 Section drawing of the adiabatic box

We used two types of PCMs in our research: BioPCmat M27 and savE® HS 22. Due to lack of material properties, we had to determine the heat capacity, the density and the heat conductivity of materials with measurements. The used methods can be seen on *Table 1*.

Table 1 Methods used for determining the material properties

Measured property	Method	Uncertainty
Heat capacity	DSC	0,1%
Phase change temperature	DSC	0,1 °C
Density	Volume displacement method	5 kg/m^3
Heat conductivity	C Therm TCI	1%

The results of the measurements can be seen in *Table 2*. Column four contains the average properties of savE® materials, which was used for optimization issues. BioPCM was not appropriate for our system, and the melting temperature of savE® HS 22 was not suitable for cooling purposes. In the end we used this material for measurements but we changed the operating conditions of the system. That is why the experimental system is insulated well.

Table 2 Properties of the used PCMs

	BioPCM	savE®HS22	avg. savE®PCM
Solidification temperature [°C]	19	22	
Melting temperature [°C]	23	25	
Latent heat of melting [kJ/kg]	160,7	185,0	185,0
Specific heat in solid phase [kJ/kg K]	2,37	2,50	2,40
Specific heat in liquid phase [kJ/kg K]	3,34	3,06	3,0
Density in solid phase [kg/m^3]	850	1840	1600
Density in liquid phase [kg/m^3]	840	1540	1500
Heat conductivity in solid phase [W/m K]	0,18	0,54	0,60
Heat conductivity in liquid phase [W/m K]	0,18	1,09	1,0

2.2 Thermodynamic model

The problem could be modelled separately in four subsystems, could be solved separately and joined through other boundary conditions. The four subsystems we divided the whole setup are:

- phase change material,
- ceiling cooling system,
- heat radiation inside the examined room,
- heat generation and heat loss of the examined room.

Due to page constraints we only present the essential parts of the model.

When modelling PCMs the following essential divisions should be considered:

- the hysteresis phenomena,
- the heat resistance is the function of liquid fraction,
- phase change,
- physical properties changing as the function of temperature and phase.

The most important parts of the ceiling cooling subsystem are:

- the temperature of flowing water in pipes,
- the heat conduction of the fins of the panel,
- average heat performance.

To model the heat radiation effect, the walls, the ceiling and the floor should be divided into elementary areas. Between every two areas heat radiation occurs as the function of temperature difference and angle/view factor. With more areas, more precise results can be obtained.

To model heat generation and heat loss we used different profiles for inner heat gain (*Figure 4*) and ambient temperature (*Figure 5*) as function of time during a day.

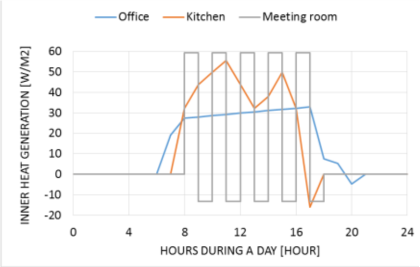

Figure 4 Inner heat generation

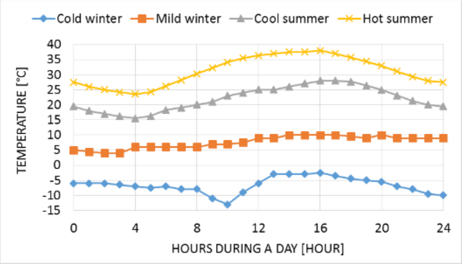

Figure 5 Ambient temperature

2.3 CFD model

To examine the system on a smaller scale and to validate the thermodynamic model we made a CFD model. Heat transfer inside the structure, the liquid-solid transition of the PCM, the turbulent flow of the air room, the Bouyancy effect near the border of air and gypsum board, the inner heat gain of the room and contact resistances were taken into account.

The geometry can be seen on *Figure 6*. From top to bottom it consists of the PCM layer placed onto the surface cooling panel, under a gypsum board can be seen and at the bottom the air of the simulated room. The mesh can be seen on *Figure 7*, a fine mesh is needed to model the heat transfer and the difficult geometry properly. After mesh independence study we optimized the applied models in ANSYS FLUENT. We used Realizable k-epsilon turbulence model with enhanced wall function and full Bouyancy effect. With the CFD simulation we could define some values that could not be defined with the measurement and the thermodynamic model. For example we could model the surface heat transfer coefficient inside the PCM and on the border of the air and the gypsum layer.

Due to symmetry reasons the size of the CFD model is 0,1x0,333x0,5m. The simulation contains the following factors:

- heat transfer between water and cooling pipes are neglected,
- heat conductivity inside the cooling pipes and steel profile,
- heat transfer between the steel profile and PCM,
- heat conductivity inside the PCM, heat storing of PCM, phase changing of PCM,
- fin effect of the profile,
- heat conductivity inside the gypsum board,
- heat transfer between the gypsum board and the air of the room.

The simulation was focused on the modelling of solidification/melting, and the heat transfer between the gypsum layer and the air of the room. Many different turbulence models were tested, the best results occurred with Realizable k-epsilon turbulence model according to measurement data.

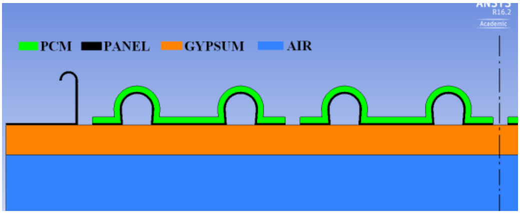

Figure 6 Geometry of CFD model

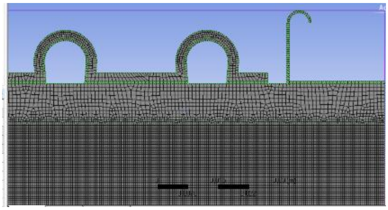

Figure 7 Mesh of CFD model

3. Results

There are several possibilities to improve energy effectiveness with PCMs:

- reduction of the time of cooling,
- avoidance of partial loads,
- better operation of the refrigeration system means a growth in effectiveness (EER),
- reduction of the mass flow of cooling water,
- cooling with ambient air at night.

Figure 8 presents the cooling time (operating time of cooling system) reduction in the function of PCM thickness. The operating time of the cooling system is reduced due to energy storing, as the system can avoid partial loads. This means that the system only operates in its designed operating point with better energy efficiency.

As the PCM layer thickness grows, cooling time reduction grows as well, but if thickness is greater than 2,5 mm the reduction effect decreases due to the increasing heat resistance of the PCM. The specific cooling time reduction depends on the mass of the material. It can be seen, that the 0,5 mm thickness shows the best result. It is a technical maximum, but an economic calculation should be added to find the economical optimum and decide whether it is a worthy possibility.

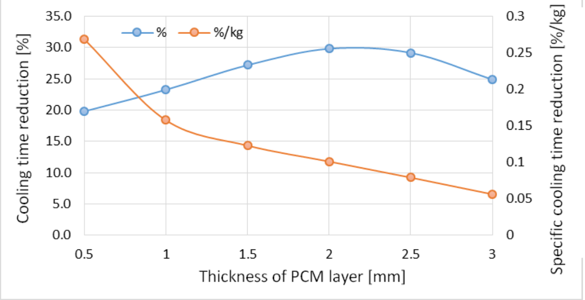

Figure 8 Cooling time reduction in the function of PCM thickness

Figure 9 shows the EER increase of the cooling system in case of different room types, on hot and cool summer days. The increase in the effectiveness of the cooling system can reach 15-18%. As the EER is proportional to the electricity usage of the compressor of the cooling system, it is a direct way to reduce the electricity usage of the system.

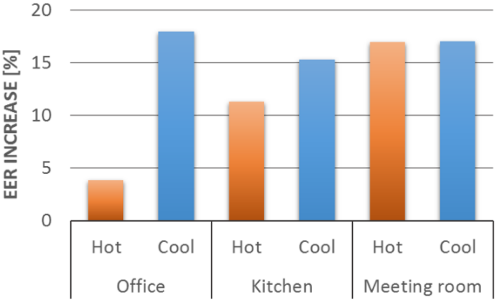

Figure 9 ERR increase in different room types

Due to the high latent heat capacity and density energy storage of PCMs the system can work effectively with free cooling, with lower temperature night air ventilation. If the PCM can change phase completely, the inner temperature of the office will not rise above the upper level of the comfort temperature for at least 4-5 hours.

The results of the CFD simulation can be seen on *Figure 10* and *Figure 11*. When there is no PCM in the system, the surface temperature is not even but with PCM its distribution is lower. As the cooling performance is proportional to the surface temperature, the system containing PCM has bigger cooling performance due to the evenly low ceiling temperature. .

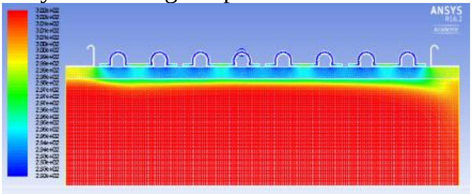

Figure 10 Temperature without PCM

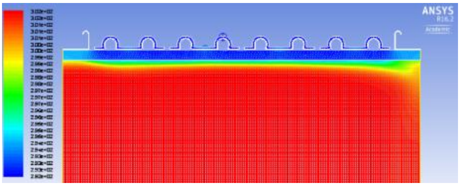

Figure 11 Temperature with PCM

The design value of the performance of the cooling system is 74 W/m^2 with 2 °C difference between the temperature of the inlet and outlet water temperature and 0,07 kg/s mass flow (in one cooling circuit). With low temperature PCM, the mass flow could be reduced with the same cooling performance. The temperature difference will not grow, as the PCM can locally cool the water in the pipes.

With the use of PCM the average heat performance of the panel can be 85 W/m^2 during cooling system operation. *Figure 12* shows the performance of the PCM when the cooling system is not running as the function of the temperature difference of the PCM and the inside air temperature of the room. The PCM itself can produce 30-40 W/m^2 cooling performance.

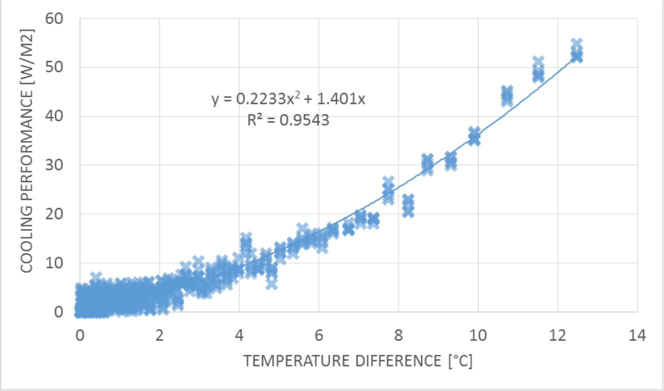

Figure 12 Temperature profile of the cooling panel

Figure 13 shows the temperature of the PCM as the function of time. It compares the result of the CFD simulation and the measured data. CFD1 shows the temperature between two cooling pipes and CFD2 is the temperature of a monitor point above a cooling pipe. The measurement data is an averaged temperature, with the data of 4 monitor points, so the CFD data has to be averaged as well. The results of the CFD are nearly the same as the measurement results; the average relative error is 1,2%.

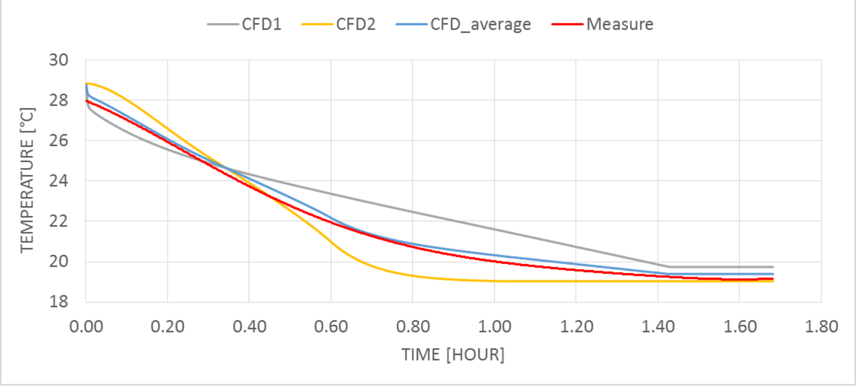

Figure 13 Temperature of the PCM in the function of time

Figure 14 shows the average temperature of the office, PCM and cooling water during a hot summer day. The cooling system starts its operation at 6 am to freeze the PCM by8 am. Then the cooling system turns off, thus only the PCM cools the room while it melts. Before the temperature reaches the upper limit of desired operative temperature (24±1,0 °C) the cooling system turns on to lower the temperature of the room and to freeze the PCM again. The cooling performance is lower, as part of the cooling energy goes to the PCM. After two freezing and melting cycles the day is over and cooling is not needed.

The comfort criteria is not met in the morning, as the inside of the room is undercooled. The problem becomes less significant if the air temperature is studied, as the heat capacity of the air is negligible, so with the huge inner heat generation the air temperature reaches the minimum limit of the temperature quickly.

Energy could be saved if the cooling system operates from 6 am to 8 am, with higher EER, instead of from 8 am to 12 am. The energy production could be rearranged to increase the effectiveness of the system.

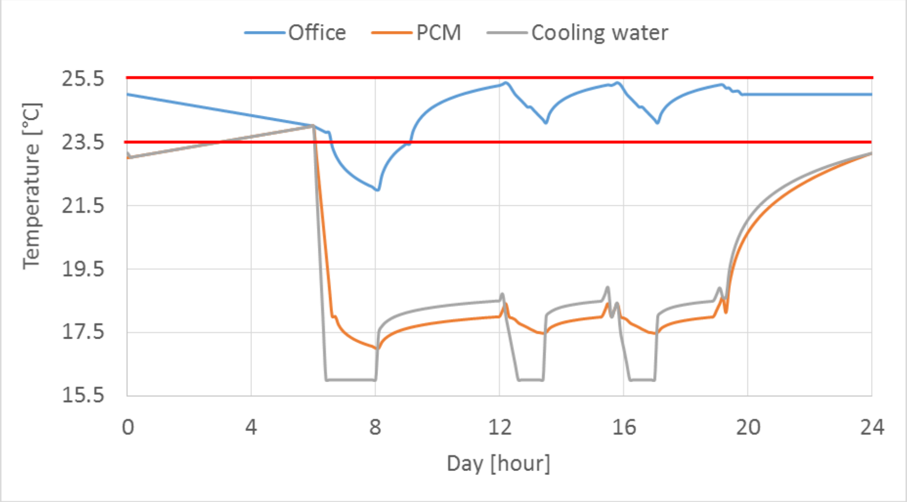

Figure 14 Office inner average operative temperature, average temperature of PCM and cooling water during a hot summer day for the office type room

With simulations for different days and with the frequency distribution of temperature the annual energy saving can be estimated. It can be 10-20% depending on the operation conditions. In the future a yearly simulation should be carried out with the validated thermal model for the precise result.

4. Conclusions

In our work we combined a ceiling cooling system with phase change material. We investigated their combination with a thermodynamic model, with a CFD simulation and with an experimental system. The combined system holds several energy saving potential, the overall amount of energy saving can be 10-20% depending on the operation conditions. The cooling performance of the system can be higher than the design value and the PCM, without the cooling water, can absorb 30-40 W/m^2 energy as the function of temperature difference. The system has many challenges and an economic calculation has to be done to decide that is it reasonable or not.

References

[1] Rita Farkas, Zoltán Andrássy: Using of PCMs in wall structures, Scientific Student Conference, Budapest, Hungary, 11. November 2014.
[2] M.Ravikumar, Dr. Pss. Srinivasan: Phase change material as a thermal energy material for cooling of building, Journal of Theoretical and Applied Information Technology, (2005-2007) 503-511.
[3] Kálmán Árokszállási: Hőtárolás-a jövő technológiája (Heat energy storing, the technology of future), Roxa Kft. 2008.
[4] http://www.ngbsh.hu/
[5] Lidia Navarro, Alvaro de Gracia, Albert Castell, Luisa F. Cabeza: Experimental evaluation of a concrete core slab with phase change materials for cooling purposes, Energy and Buildings, (2016) in press
[6] Jiawei Lei, Jinglei Yang, En-Hua Yang: Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore, Applied Energy, 162 (2016) 207-217.
[7] M.R. Anisur, M.A. Kibria, M.H. Mahfuz, R. Saidur, I.H.S.C. Metselaar: Cooling of air using heptadecane phase change material in shell and tube arrangement: Analytical and experimental study, Energy and Buildings, 85 (2014) 98-106.
[8] Ebrahim Solgi, Rima Fayaz, Behrouz Mohammad Kari: Cooling load reduction in office buildings of hot-arid climate, combining phase change materials and night purge ventilation, Renewable Energy, 85 (2016) 725-731.
[9] Francesco Guarino, Sonia Longo, Maurizio Cellura, Marina Mistretta, Vincenzo La Rocca: Phase Change Materials Applications to Optimize Cooling Performance of Buildings in the Mediterranean Area: A Parametric Analysis, Energy Procedia, 78 (2015) 1708–1713.