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Initial development of a combined PCM and TABS solution for heat storage and cooling

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KEYWORDS: *Phase change material, thermally activated building system, thermal mass, dynamic heat storage capacity, cooling.*

SUMMARY:

This paper investigates heat storage and cooling concept that utilizes both phase change material (PCM) and a thermal active building system (TABS) implemented in a hollow core concrete deck element.

PCMs are promising materials for improving the heat storage capacity of a building due to their significant thermal energy storage capabilities. The TABS has a potential for increasing the exploitation of the thermal mass of the building, which is rarely exposed for heat transfer. The main objective of this study is to optimize the location and amount of PCM in a hollow core deck in order to optimize heat storage capacity. A series of simulations were conducted using the COMSOL program to obtain knowledge regarding the dynamic heat storage capacity of the investigated hollow core deck element as a function of the amount and location of PCM. Furthermore, the dynamic heat storage capacity of a passive deck element and the possible cooling power of the thermally activated deck element were predicted and then compared. Finally, results obtained from precise numerical simulations in COMSOL Multiphysics were compared with results calculated in the whole building simulation software BSim. Initial results indicate that the best location of the PCM in the hollow core concrete deck element is close to the surface that is facing to the room. Moreover, the heat transfer coefficient on the surface of the deck has a very significant impact on the heat storage capacity of the concrete deck element.

1. Introduction

The study presented in this paper demonstrates a new technology that can be competitive compared to existing cooling by air-conditioning in buildings. The technology combines phase change material (PCM) and thermal activated building system (TABS) that are integrated in the element of prefabricated concrete hollow core deck. This technology has a potential to decrease energy use for cooling and heating in buildings and thus reduce CO₂ emission to the atmosphere. Moreover, the concept presented in this paper considers flattening demand for cooling and shifting peak energy use from day time to night time. Furthermore, measurements conducted in the real buildings with integrated TABS indicated that this technology can provide and sustain acceptable indoor thermal environment (De Carli 2002).

The properties of PCM that allow it to store large amount of heat have been known for many years. However, successful PCM implementation into building constructions did not start until the development of the microencapsulated PCMs. The microencapsulated PCMs have spherical shape of only a few micrometers, and they can be incorporated into various broadly used building materials. The capsule shell prevents direct contact between the incorporated paraffin wax/PCM and matrix material, for example, concrete. When paraffin is bounded by the shell, it can melt and solidify almost

isothermally and thereby charge and discharge heat without any destructive impact on the material matrix. Isothermal processes occur only in the close range around the specific melting temperature of the PCM. For building purposes melting point temperature is usually chosen within the average thermal comfort temperature range for an occupied space (Kuznik 2009).

On one hand, there is a substantial amount of research which focuses on PCM application in the refurbished light weight buildings and light weight constructions in order to increase thermal mass of the building (Kuznik 2009a) and (Schossig 2005). On the other hand, only a few studies have been made on implementation of PCM into concrete (Hunger 2009).

Parallel to PCM development has been conducted works on TABS technology. The TABS concept started in the 1990s in Switzerland and involved an idea of activation of the thermal mass of concrete slabs that are located between each storey in the building. As a consequence, when circulating hot or cold water in the slabs, building can be respectively heated up or cooled down. TABS were investigated in many theoretical studies and were implemented in a number of full scale projects for example presented in (Meierhans 2005). Additionally, laboratory tests and theoretical studies have indicated that this technology can be energy efficient and has a significant potential to reduce operational costs for the cooling/heating of buildings and provide appreciated indoor thermal comfort (Lehmann 2007).

The purpose of study that is presented in the paper is to investigate the most advantages design of concrete hollow core slab with regards to optimal location and amount of the PCM. The optimal location and amount of PCM should result in increased thermal mass and at the same time optimal utilization of thermal mass capacity. Moreover, focus is also put on, how to establish possible heat storage and cooling power performance of the deck element within realistic dynamic thermal condition in the building. Due to the fact that PCM is expensive and its addition to the concrete element not necessarily has to improve thermal storage capacity of the hollow core deck element, it has to be precisely investigated, how, how much and where it should be integrated in the deck element to achieve feasible and price competitive product.

First, in this paper is presented development of concept for integrated PCM and TABS in the element of prefabricated hollow core slab. Secondly, developed concept is transferred to the COMSOL Multihysics program, where various scenarios for variation of geometrical and thermal properties and boundary condition parameters are calculated. Obtained results reveal which parameters are of most importance to utilize thermal mass of the slab and where PCM shall be located. What is more, diurnal dynamic heat storage capacity for the passive approach of the deck is compared with diurnal cooling effect in case when the deck is activated according to miscellaneous time schedules. Finally, results obtained from the precise finite element simulations in COMSOL Multihysics are used to validate module for calculation of heat storage capacity and module for implementation of PCM in a whole building simulation program (BSim).

2. Materials and methods

2.1 Development of specification of PCM and TABS-deck element

In this study, the development and design of PCM and TABS concrete deck element was based on existing and already commercially introduced product, which is called ThermoMax, see Fig. 1. Yet ThermoMax is produced as deck made of only concrete, in other words without PCM.

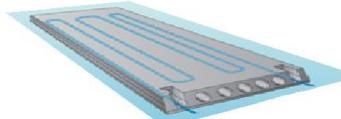


Fig. 1. ThermoMax: Prefabricated concrete ceiling deck element with integrated water pipes.

2.2 Thermal properties of combined PCM and concrete material

In order to be able to calculate dynamic heat storage capacity of any material, three parameters have to be known. These parameters are: density- ρ , heat conductivity- λ and specific heat capacity- C_p .

Normal concrete has its well known and defined thermal properties. Thermal properties of different PCMs are known or can relatively easily be defined with use of differential scanning calorimetry, see Table 1. However, if concrete and PCM is combined into one material, then physical and thermal properties have to be specially defined for each of combination ratios. In this investigation, density for combined concrete and PCM is calculated according to simple Eq. 1.

$$\rho = (P_PCM) * \rho_{pcm} + (100 - P_PCM) * \rho_{concrete} \quad (1)$$

Where: P_PCM - is weight percentage of added PCM [%]
 ρ_{pcm} - is PCM density [kg/m^3]
 $\rho_{concrete}$ - is concrete density [kg/m^3]

Heat conductivity of combined concrete and PCM is calculated according to methodology for calculation of heat conductivity for inhomogeneous materials, which is presented in DS 418 (Calculation of heat loss from buildings.) After simplification, methodology adapts the same form as Eq. 1, but density is replaced by respectively heat conductivity of PCM and concrete.

TABLE 1. Thermal properties of concrete and PCM.

	Density [kg/m^3]	Conductivity [W/mK]	Specific heat capacity [J/kgK]
PCM	98	0,14	-
Concrete	2300	1,8	1000

Calculation of specific heat capacity for combined concrete and PCM is based on the results obtained from (DSC) for pure PCM. Due to the fact that PCM specific heat capacity varies with its temperature, analogically the same can be assumed for combined concrete and PCM material.

In Fig. 4, are presented calculated heat capacities for different weight percentage ratios with respect to temperature. Curves are valid for melting process and PCM with melting point at 23 [$^{\circ}\text{C}$].

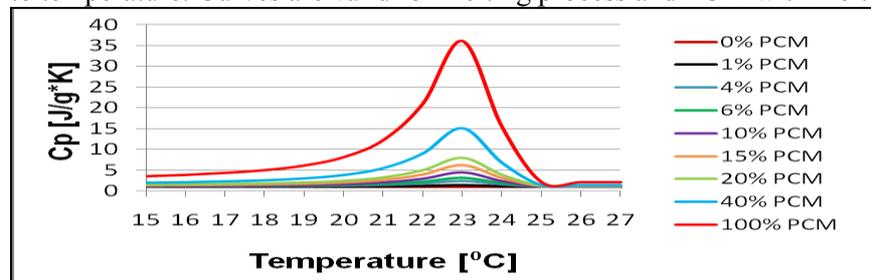


Fig. 4. Calculated specific heat capacities for different ratios of PCM and concrete as a function of temperature

2.3 Sensitivity analysis of location and percentage of integrated PCM

The sensitivity analysis of location and amount of integrated PCM was performed based on simulation done in the COMSOL Multiphysics program.



Fig. 5. COMSOL models: Model without PCM and with highlighted various location and thickness of layer with combined concrete and PCM.

Several models with different percentage of the incorporated PCM and different location of combined PCM and concrete material were simulated in order to find which model has ability to store highest amount of heat. Improvement of ability to store heat was measured in comparative manner with respect to performance of the original deck made without PCM. Due to the symmetry and geometric repeatability of the deck construction COMSOL models could have been simplified to the sections presented in Fig.5.

2.4 Boundary condition

For the purposes of this study, the hollow core deck that is simulated in the COMSOL Multiphysics is simplified to 2D model and one section with pipe and air hollow core, see Fig. 5. Due to the fact that in the real model, vertical boundaries are facing almost the same sections, these boundaries are defined as symmetric. Secondly, it is assumed that temperature on the upper and lower surface is fluctuating with diurnal sinusoidal pattern between 20 and 26 degrees in order to imitate indoor temperature condition in the building. Moreover, on the upper and lower surface is applied combined heat transfer coefficient for convection and radiation, which in this study is varying between 2 and 30 [$\text{W}/\text{m}^2\text{K}$]. Thirdly, when diurnal dynamic heat storage capacity is calculated, which means that deck is passive, water in the pipe is only defined as material and none boundary is applied. However, when deck is simulated as thermally activated, pipe perimeter is defined as boundary condition and heat transfer coefficient on the internal surface of the pipe is defined at 15000 [$\text{W}/\text{m}^2\text{K}$]. In this study temperature of the water is defined for three scenarios: 16, 18 and 20 °C. Finally, the air void is simplified to air chamber with standing still air and without radiation. Boundary conditions are conserved for all simulated models. This allows comparison of results between models.

2.4 Thermal activation of hollow core deck element

Although TABS concept can be used for both heating and cooling, in this study focus is put only on its cooling performance. Respectively, investigation was carried out for carrier temperature of 16, 18 and 20 °C which is in all cases either below or equal to lowest assumed indoor temperature. Research on TABS, which were presented in (Babiak 2007), indicated that low cooled ceiling temperatures are not an issue with respect to normative requirements for temperature asymmetry of construction elements. However, in number of publication limit for cooled ceiling temperature is connected with risk of condensation on the construction elements.

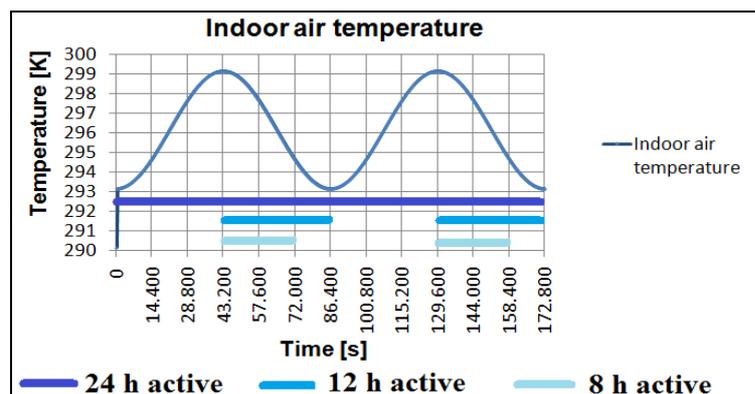


Fig. 7. Thermal activation periods with respect to indoor temperature fluctuation.

Moreover, in this study, are considered two different water pipe locations. First, where centre of the pipe is 50 mm and second, where centre of the pipe is 20 mm from the bottom surface of the hollow core slab. In both cases the diameter of water pipe is set to be 20 mm and spacing between pipes is 150 mm.

Investigation is carried out for different control mode. Full time mode considers that TABS is in operation 24 hours a day, which means always. Secondly, investigation with shorter time mode is carried out, and respectively 12 and 8 hour mode is considered. For sake of cost efficiency of operated system and with efficient utilization of high heat storage capacity of the PCM, it would be recommended to operate activated system as presented in the Fig. 7.

3. Results

Due to the fact that investigation presented in this paper is focused on two possible implementation of the hollow core deck element with PCM and thermally activated system, these results are split into two parts. First one will present results for passive implementation of hollow core deck element with PCM; water flow is deactivated. Respectively, second part will illustrate results for thermally activated hollow core deck element; water flow is activated. Finally, results for validation of BSim calculation with regards to heat storage calculation and PCM implementation are presented.

3.1 Results from passive implementation

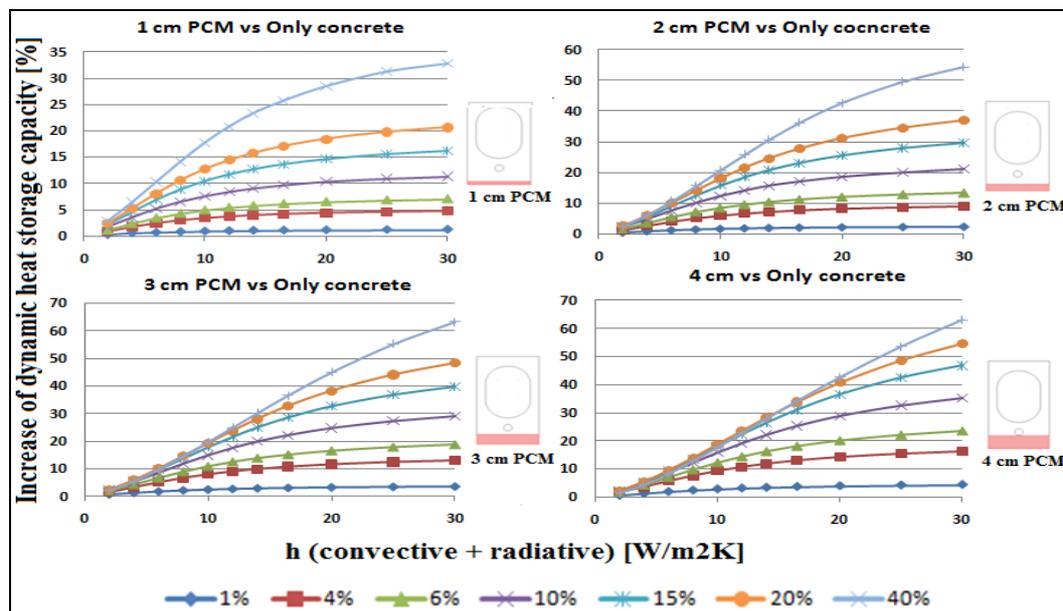


Fig. 8. Increase of dynamic heat storage capacity for slab with PCM layer attached to the bottom of the deck.

In the Fig. 9, are presented results for case where PCM layer of constant thickness is moved towards the centre of the hollow core deck element.

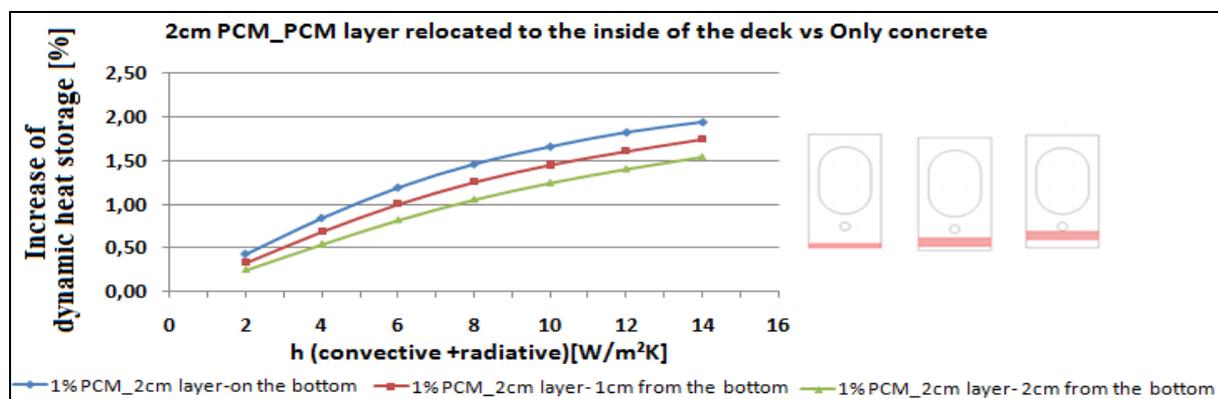


Fig. 9. Increase of dynamic heat storage capacity for slab with PCM layer gradually relocated to the inside of the deck.

3.2 Results from active implementation

Results presented in the Fig. 10, for activated deck, are valid for the deck with 1 cm thick layer with PCM that is attached to the bottom of the deck.

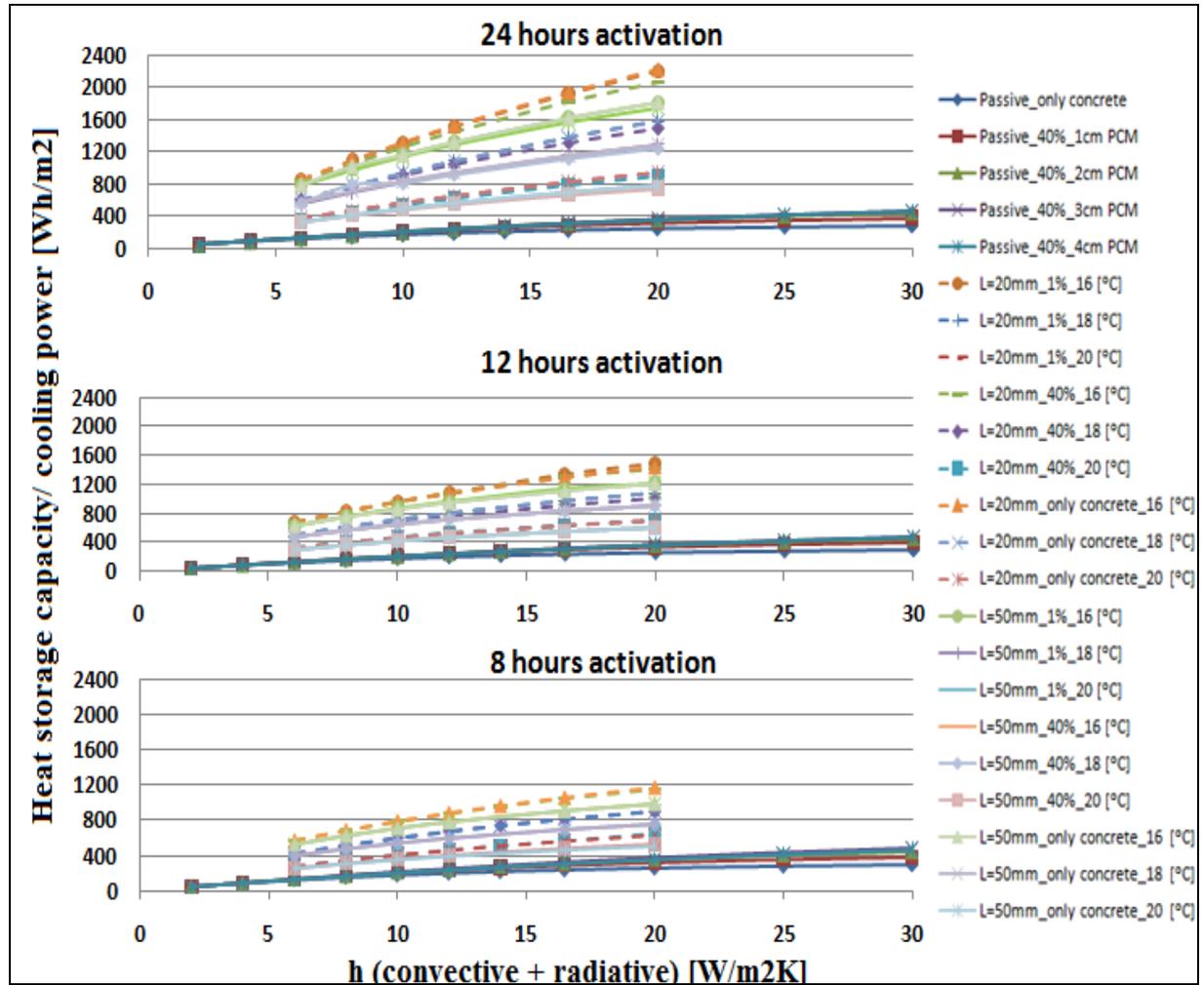


Fig. 10. Calculated daily cooling power of thermally activated deck and heat storage capacity of passive deck for chosen deck configurations.

3.3 Validation of heat storage calculation in BSim

BSim is whole building simulation program for calculating and analyzing indoor climate condition, power demand and energy consumption in the building. Calculations are performed based on hourly values of attached weather data. Heat transfer within construction elements is simplified to 1D problem and calculation engine is based on control volume method. Each construction element consists of one or more homogeneous layer. Each zone in BSim is presented as only one nodal point. It is assumed that the air in the zone is fully mixed. Whereas BSim is dedicated for simplified but time efficient whole building energy simulations, COMSOL Multiphysics program is more suitable for solving dynamic problems in smaller domains but with much higher accuracy. In COMSOL it is possible to solve dynamic problems within 1D, 2D or 3D geometry. This geometry can then be

divided into very small domains by defining mesh type, accuracy and distribution. For a chosen domain, can be defined boundary conditions that represent miscellaneous physics. For transient simulations, time step for solving the model can be defined individually depending on required accuracy. In this investigation, in BSim was created a simple model that was made of two rooms. Between these two rooms is located internal floor which has the same geometrical and thermal properties as the model created in COMSOL and that is representing homogeneous concrete deck element. Boundary properties on the upper and lower surface of the deck are varied but are always the same as in the COMSOL program. Therefore, comparison of results from both programs is possible and is presented in Fig. 11.

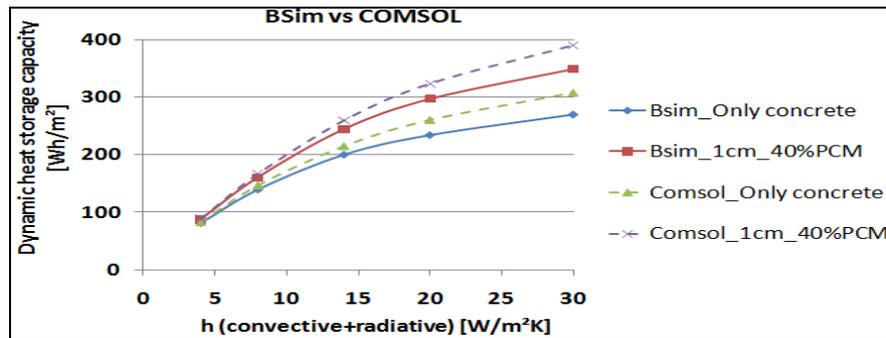


Fig. 11. Calculated in BSim and in COMSOL diurnal dynamic heat storage capacity for both, homogeneous construction deck made of only concrete and for deck with 1cm layer with PCM that is located on the bottom of the deck.

4. Discussion

In the Fig. 8 is presented calculated improvement of diurnal dynamic heat storage capacity for the hollow core deck element with different thickness of layer with PCM with respect to deck made of only concrete. Results for different ratio of implemented PCM are presented as a function of combined heat transfer coefficient for radiation and convection. Results are valid for the decks with a layer of PCM attached to the bottom of the deck. At some point, it can be observed, that for low percentage of PCM and high heat transfer coefficient there is no improvement. This means, that all thermal mass is utilized. On the other hand, for very high percentage of PCM it can be observed that not all thermal mass is utilized even for very high heat transfer coefficient. Moreover in the Fig. 8, it can be noticed that improvement of the dynamic heat storage capacity between the deck with 1 and 2 cm is more significant than between the deck with 2 and 3 cm thick layer of PCM. Finally, improvement between deck with 3 and 4 cm thick layer of PCM is almost none for full range of PCM ratios. The reason for that kind of results is due to the fact that with increased amount of implemented PCM, decreases heat conductivity of the combined material. Low heat conductivity number decreases heat penetration into the deck, which cause that bigger part of the deck is not activated.

In the Fig. 9, is used the same approach for presenting the results as in Fig. 8. In Fig. 9, results are valid for the deck with layer with PCM of constant thickness of 2 cm. In this investigation layer is relocated with step of 1cm to the inside of the deck element. Although results presented in the Fig. 9, indicate that there is improvement in dynamic heat storage with respect to the deck made of only concrete, it can also be observed that the further layer is located from the bottom surface of the deck the lower becomes improvement. Based on results presented in Fig. 8 and Fig. 9, it can be concluded that layer with PCM should be always attached to the bottom surface of the hollow core deck element. Moreover, it is not recommended that layer with PCM is thicker than 3cm. Finally, it can be noticed that heat transfer coefficient on the surface has a dominant role in activating the thermal mass of the construction element.

In the Fig. 10, are depicted results of daily cooling power of the thermally activated deck element. In the same figure are depicted results of calculated heat storage capacity for chosen simulations with passive deck implementation. With regards to activated system, results are presented for three activation modes: 24 (correspond to 100% cooling capacity), 12 (50% cooling capacity), and 8 hour (33% cooling capacity). Firstly, it can be noticed, that the longer the water flow is activated and the lower is the water temperature, the higher is the cooling performance. Secondly, for the deck with pipes located 20 mm from the bottom of the deck cooling effect is higher than for the deck with pipes located 50 mm from the surface. Moreover, it can be observed that layer of PCM can have damping effect on cooling performance of the thermally activated deck. Finally, in all three charts presented in the Fig. 10, it can be noticed, that cooling effect regardless of activation mode, water temperature and pipe location is much higher than the heat capacity that can be stored in the deck. This means that TABS system should be able to discharge even high heat loads from the building of approximately up to 55 [W/m²] within realistic heat transfer coefficient range of up to 10 [W/m²K].

Fig. 11 shows calculated in BSim and COMSOL results of the heat storage capacity in function of heat transfer coefficient. One comparison is made for the deck element, which is made of only concrete and another is for the same element but with 1cm layer of 40% PCM in the bottom of the deck. The discrepancy in results from these two programs is increasing with rising heat transfer coefficient. Moreover, discrepancies for both types of slabs are almost the same which indicate that error appear not due to calculation module for PCM implemented in BSim program. Results calculated by BSim are underestimated with regards to the one obtained from precise calculation in COMSOL.

5. Conclusion

The presented results of simulation study on combined PCM and TABS concept indicate possibly best configuration with regards to heat storage capacity. The results also indicate feasible performance range within investigated factors variation.

It has to be kept in mind that the obtained results are valid for theoretically calculated thermal properties of combined PCM and concrete. In the future scheduled activities, it is foreseen to update existing simulation models with experimentally determined thermal properties for various PCM and concrete ratios.

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