"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.259
DOI: https://doi.org/10.3846/enviro.2017.259

Experimental Study of Heat Storage Unit Made of PCM-gypsum Composite Integrated with the Ventilation System of the Building

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Abstract. In the paper a special heat storage unit for building applications is presented. It has a form of a ceiling panel that is made of PCM-gypsum mortar composite and it contains internal channels for air flow, since it is designed as a part of ventilation system of the building. The panel works as a regenerative heat exchanger with phase change material (PCM) as a prevailing heat storage medium. When a melting point of PCM is properly chosen it is possible that air temperature flowing into the building reach a level corresponding to thermal comfort conditions, regardless the temperature at the intake. Warm air (during a day) releases heat basically to PCM causing its melting. During night time cool ambient air is heated up while it takes back heat accumulated in PCM. An experimental set-up based on the above concept was developed. A series of tests in different conditions (for variable inlet air temperatures, air flow rates) were performed. Information on thermal performance of the ceiling panel as well as detailed data on heat transfer process were obtained and discussed in the paper.

Keywords: Phase change materials, thermal energy storage, night ventilation, building materials.

Conference topic: Energy for Buildings.

Introduction

Thermal inertia of the building is an important factor influencing the energy demand for heating and air conditioning. High thermal capacity of the building's envelope stabilizes internal temperature. Modern building technologies are based on light, but with a high strength construction materials. Insulation materials which are designed to provide the required thermal properties of building walls, have a virtually negligible thermal capacity (e.g. fibrous or foam insulations). The thermal inertia of such buildings is so low, that the thermal conditions in the interior are very susceptible to changes in environmental conditions (temperature, wind speed, insolation), as well as to the change of internal heat sources. Maintaining the inner temperature at an appropriate level requires a relatively high energy consumption, despite the good insulation of external walls. In recent years, there has been increased interest in the development of technologies allowing the formation of such building structures that are lightweight, having good thermal insulation and, simultaneously, with high potential for accumulation of heat (cold), i.e. a large heat capacity. This goal can be achieved by the use of phase change materials (PCMs), that have very high thermal capacity, since they undergo phase transition of high latent heat. These materials can be directly introduced into building materials or used as a medium in heat/cold storage units incorporated in different parts of the buildings. Basic characteristics of this type of materials in the context of their applications in the buildings, as well as the methods of manufacturing building elements impregnated with PCMs may be found in many review papers (Kuznik *et al.* 2011; Ling, Poon 2013; Soares *et al.* 2013; Tatsidjodoung *et al.* 2013; Waqas, Din Zia 2013).

The use of PCMs in construction is particularly effective as a supplement to free cooling technique. This technique allows to achieve the required thermal comfort conditions in the rooms through the use of cold air from the environment (during the night) as a source of cold (Grzebielec *et al.* 2014, 2015; Rusowicz *et al.* 2014; Waqas, Din Zia 2013). For example, an office building heats up during the day as a result of external influences (high temperature, sunshine), but mainly because of the large internal heat gains, such as electrical equipment, employees, etc. At night the building is cooled by its intensive ventilation. Range of temperature oscillations in the daily cycle depends on the size of the heat source during the day, nocturnal air temperature and the ventilation rate, as well as and the thermal inertia of the building's structure. If the heat capacity (ability to accumulate heat) is large, the temperature oscillations are smaller, which manifests itself primarily to lower the maximum temperature in the room during the day. A large heat capacity of the building can be achieved without significantly increasing of its weight, using PCM material.

The effectiveness of the free cooling techniques supplemented by PCM depends not only on the amount of PCM incorporated in the buildings envelope, but also on the intensity of nocturnal ventilation as well as heat transfer surface between the cool air and the building elements containing PCM. The simplest and most common method of PCM incorporation into building structure consists of adding it to the internal facades, e.g. into gypsum plasterboards. The disadvantage of this approach is relatively small heat transfer surface area and intensity of heat transfer, which is due to natural convection. This results in a small degree of PCM's thermal capacity utilization, i.e. for thick gypsum mortar layers not the whole PCM undergoes a phase change at daily cycle. Therefore researchers are constantly looking for new ways of incorporating PCMs into building elements, including elements of the ventilation systems (de Gracia *et al.* 2016; Marin *et al.* 2016; Osterman *et al.* 2015).

The use of PCM in construction is of considerable interest for many research centers, as evidenced by the number of publications on these issues. The problem that draws especially a lot of attention is the choice of the structure of the heat storage unit and its location in the ventilation system (or generally within the air flow) to provide high intensity of heat transfer. Most of the proposals are addressed to office and public buildings, due to the large variety of possible designs of heat accumulators that can be adopted. In such buildings it is a common practice to perform suspended ceilings, thus creating a relatively large space, in which heat storage units can be located. They are made of composite materials containing PCM or flat metal plates filled with PCM, such units are placed above the ceiling panels (Yanbing *et al*. 2003). A similar concept is described by (Susman *et al.* 2011). They studied thermal characteristics of thin discs containing PCM suspended below the ceiling. High efficiency of this solution results from the large heat transfer surface area. The aforementioned plasterboards, due to the deterioration of mechanical properties, contain a small amount of material PCM, approximately 25%. In addition, they have a low effective thermal conductivity, making it difficult for both heat accumulation and heat release. It is proposed to perform the internal facades of the rooms using special PCM composite (co called shape stabilized PCM), that is made of a fibrous matrix of high porosity, which may contain up to 80% of PCM, while maintaining the shape after it is melted (Zhou 2011). Fraisse *et al.* (2010) investigated a double wall comprising a PCM, wherein the inner slot has a ventilation duct. The research described in (Pomianowski *et al.* 2012) was on a complex thermally activated building system. Heat storage units in this system were in the form of slabs, which were filled with PCM material, and aslo contain inside special heat exchangers to ensure control of the process of charging and discharging. Thermal efficiency of the building elements that are designed as heat storage units depend on several factors, including PCM material distribution in the element, the thermo-physical properties (such as the phase transition temperature), as well as the spatial orientation of the building element. Detailed studies on the above issues can be found e.g. in (Evola *et al.* 2013; Izquierdo *et al.* 2012; Marin *et al.* 2016; Osterman *et al.* 2015).

The above described exemplary techniques use structural elements of the building (walls, ceilings, floors) as heat storage units. Another approach is to design special heat accumulators, which are placed in the ventilation ducts. The units of this type may not be as high as building elements, however, the amount of PCM incorporated may be substantially higher, as well as their shapes may be optimized from the point of view of heat transfer intensity. In literature many proposals of this type of storage units with different geometrical configurations can be found. Dolado *et al.* (2011) conducted experimental studies and computer simulations of processes of melting and solidification of PCM in thin aluminum panels, that formed heat storage unit. Plate heat storage units were also analyzed by Mosaffa (2013) and Tyagi *et al*. (2012), among others investigating the use of PCMs of different melting points in order to increase exergy efficiency of the process of heat accumulation and release. Unusual heat accumulator was proposed by Raj and Velraj (2011), PCM is contained in disks with a plurality of holes. After setting up these discs in stacks the holes form channels for the flow of the air. A ventilated external facade of the building containing PCM, was an object of extensive studies performed by de Gracia (2013, 2016). A comprehensive review of the various configurations of the heat accumulators with PCMs for the use in buildings can be found in the paper (Rodriguez *et al.* 2012).

The aim of the study

The paper presents a new concept of heat storage unit with PCM as a storage medium. The unit is integrated with the building structure, namely it is a ceiling panel (board) with internal channels for the air flow. The panel is a part of the ventilation system. It is made of the composite consisting of gypsum mortar and PCM. The concept involves the use of this system mainly during the summer for pre-cooling / pre-heating the air taken from the environment for ventilation purposes. In moderate climate zones, in the summer the air temperature during the day often exceeds 30 °C, while at night falls below 15 °C. Using regenerative heat exchanger in the ventilation system it is possible to flatten the daily variations of air temperature to the level corresponding to the conditions of thermal comfort. In the proposed solution the ceiling panel is such a regenerative heat exchanger. The warm air taken from the environment flows through the channels of the ceiling panel releasing heat primarily to the PCM. Fusion temperature of PCM is selected according to the requirements of thermal comfort, as well as to the range of temperature variations in the environment. In the case discussed in this paper this temperature is about 23 °C and is approximately in the middle of the range of daily ambient temperature oscillations. PCM accumulates heat in the phase change (melting), and thus cools the air to a temperature slightly above the melting point. At night, cool air flows through the same channels in a previously heated ceiling panel (with molten PCM). In this phase of the cycle the air is heated to temperature just below the melting point of the PCM, and the material is solidified and therefore is ready to absorb heat in the next cycle. Schematically, the principle of a ceiling panel as a heat storage unit is shown in Figure 1. As compared to conventional solutions of building elements that operates as heat accumulators (such as wall, floors, suspended ceiling elements), the proposed solution has important advantages, namely, much larger heat transfer surface area and a greater heat transfer intensity due to force convection conditions. Its thermal characteristics, namely the intensity of heat transfer during charging and discharging should be significantly improved.

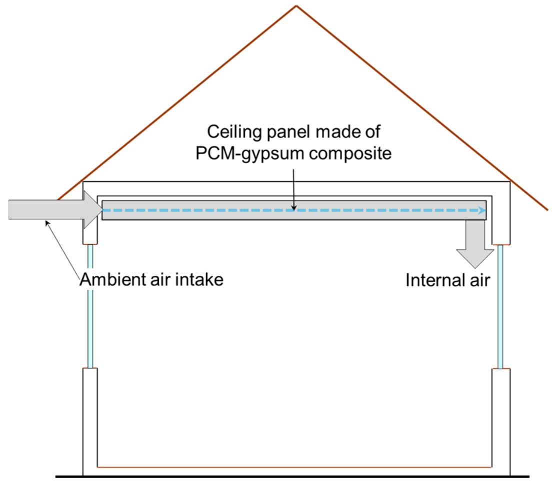

Fig. 1. The principle of operation of the ceiling panel as heat storage unit integrated with a ventilation system of the building

The aim of the study was to determine experimentally the thermal characteristics of the ceiling panel as a heat storage unit. For this purpose, the model of the repetitive part of the panel, covering one entire ventilation duct of a real length, was done. Tests were performed for both simplified boundary conditions (in terms of temperature oscillations at daily cycle), as well as in conditions close to actual, when the air was taken from the surroundings of the laboratory building.

Experimental set-up

It was assumed that the ventilation channels are evenly distributed in the ceiling panel, and that each of parallel paths consist of two channels, i.e. that the inlet and outlet are located on the same side of the board. This solution provides higher heat transfer surface area on the air stream side. Two neighboring channels form a repetitive part of the ceiling which was included in an experimental set-up, scheme of which is shown in Figure 2. The dimensions of the set-up shown in this figure were determined on the basis of the assumptions regarding the rate of air flow in the duct (which is associated with air change rate) and taking into account the possibility of manufacturing the panel using standard plasteboards containing PCM, that are usually 15 mm thick. The board, which is a fundamental part of the model, is 6 cm thick, 12 cm wide and 3 m in length. It was placed on a polystyrene, insulating layer having a thickness of 5 cm, as well its side surfaces were also insulated with the same polystyrene plate. Only the upper surface of the board was exposed to the environment, with the ability to exchange heat – this surface corresponded to the lower surface of the ceiling which is exposed to the interior of the room. The reversal of the system was dictated by practical considerations and had no significant effect on the outcome of the research, because the dominant heat exchange between the plate and the air stream takes place on the inner surfaces of the channel.

The plate is made of a composite which is a mixture of gypsum mortar (Knauf Bauprodukte) and microencapsulated PCM (Micronal DS-5008X, BASF). PCM content is about 27.6% (30% of dry ingredients). With such a relatively low share of the PCM mechanical properties of the composite are not degraded, fire safety requirements are aslo met (Micronal conatins basically hydrocarbons). Thermophysical properties of the composite were determined using a differential scanning calorimeter DSC (Jaworski *et al.* 2014). PCM phase change temperature is about 22.8 °C, heat of fusion 103 kJ/kg, the specific heat of solid and liquid phases 2.42 kJ/(kg·K) and 2.30 kJ/(kg·K) respectivelly. The thermal conductivity of the composite was measured using a miniaturized plate apparatus (Poensgen type) – the average value in a temperature range 15–30 °C is 0.17 W/(m·K) (Jaworski, Abeid 2011).

Inside the channel several temperature sensors were located (thermocouples of type K, diameter 0.5 mm, Omega, USA). These sensors allowed the measurement of the air temperature along the channel as well as the temperature of the internal surface of the duct. Several sensors were also attached to the external surface of the board. Temperatures were recorded using an ADDA converetor (National Instrument, PCI-6281 with module SCB-68). In order to controll the air temperature at the inlet to the channel a heat exchanger was installed – it was supplied with heat transfer fluid from a thermostat, both heating and cooling of the air was possible. The air flow rate was controlled using two fans powered with DC power supply with adjustable voltage. Using an anemometer (HHF141A, Omega, USA) a relation between air flow rate and the supply voltage was determined. This control system allowed for adjusting the speed of the air flow (in the channel) in the range from 0.5 to 3 m/s. The scheme of the control and measurement system is shown in Figure 3.

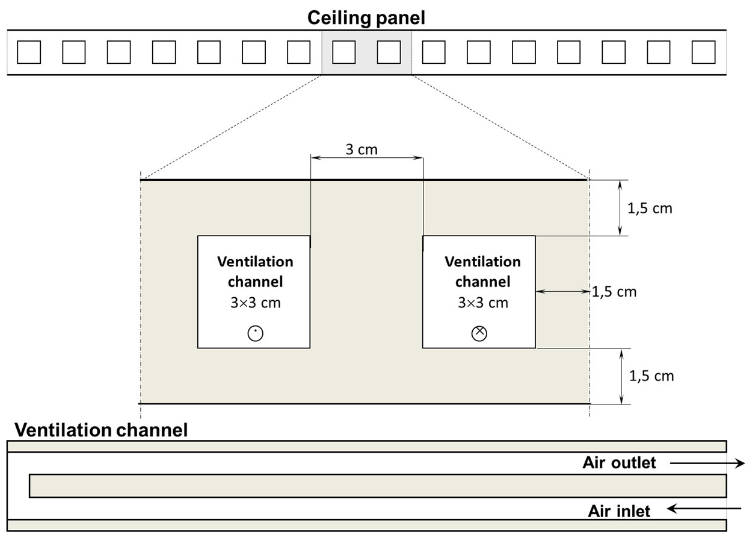

Fig. 2. The scheme of an experimental set-up – a repetitive element of the ceiling panel with ventilation channels

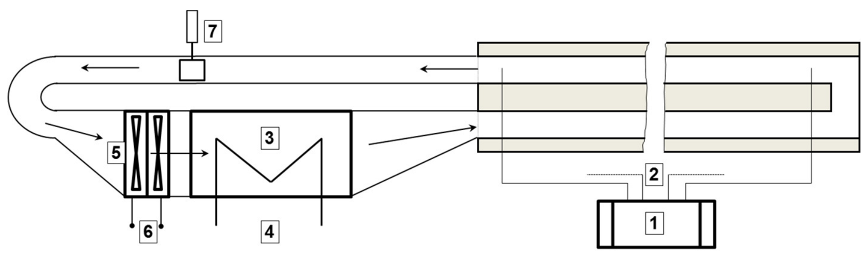

Fig. 3. The scheme of the control and measurement modules in an experimental set-up; 1 – data acquisition station, 2 – extension cables of TCs, 3 – water-air heat exchanger, 4 – supplier of heat exchanger (thermal bath), 5 – set of fans, 6 – supplier of fans (DC supplier), 7 – rotating vane anemometer

To determine the thermal characteristics of the model storage unit several tests have been performed in different conditions. Part of the tests were carried out under lab conditions, with full control of the air temperature at the inlet to the channel using heat exchanger (3) (Fig. 3). These studies were primarily designed to assess the intensity of the processes of heat transfer during charging and discharging of the unit, in particular a rate of phase change of PCM. Several tests under more realistic conditions were also performed – in these cases the air was taken from outside the laboratory building. In this phase of the research the overall thermal characteristics of the unit were determined, that is, its ability to suppress the daily oscillations of the air temperature for ventilation of the building.

The results of the tests

In the first part of the research the damping of the temperature oscillations of the air flowing through the channel was investigated. It was assumed that air temperature profile at the inlet was rectangular, i.e. for several hours temperature was constant at high level (about 30 °C) and for the rest time of the day it was also constant but at low level (about 15 °C) – solid lines in Figure 4.

Figure 4 shows the air temperature variations at the inlet and outlet of the channel during the test lasting 4 days. Air flow rate was equal to 2 m/s. Significant suppression of the air temperature oscillations is visible. Temperature of the air entering the room (at the outlet of the channel) in the daily cycle oscillates in the range approximately 3.2 °C, while in the environment (at the inlet to the channel) the range of oscillations is approx. 13.6 °C (such a range of daily temperature variations is typical for the summertime in Central Poland (Climate Data 2017)). The study was carried out also for other air flow rates, e.g. for velocity equal to 3 m/s the air temperature range at the outlet was measured to be 4.4 °C, a little higher due to larger thermal capacity of the air stream (Jaworski 2014).

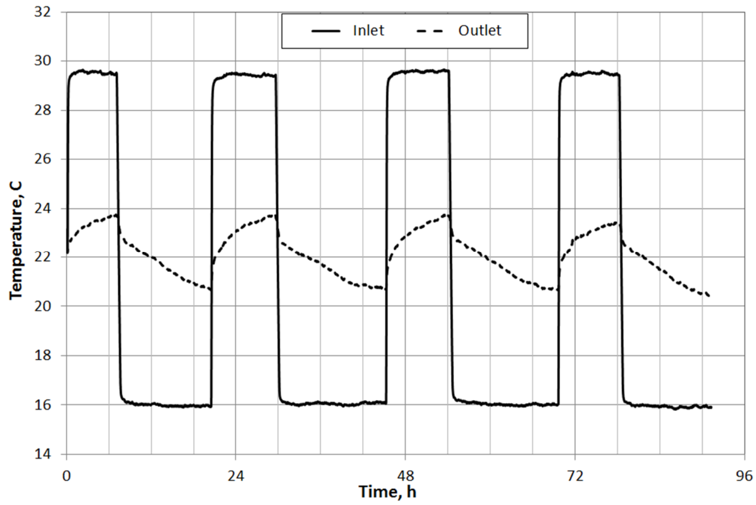

Fig. 4. Air temperature variations at the inlet and outlet to the channel for air flow rate 2 m/s

Figure 5 shows the air temperature variations along the channel during heating at air flow rate of 2 m/s. The air temperature at the inlet to the channel is approx. 29,5 °C. During this phase of the process heat storage unit is charged – PCM absorbs heat from the air stream and melts. A clear drop of the air temperature while it flows through the bend of the channel shows significant increas of the intensity of the heat transfer in this area, which is associated with a strong turbulence of the flow. Quantitative analysis of changes in air temperature allows to evaluate the intensity of the charging and discharging of the unit, and the amount of heat accumulated during one cycle. The intensity of the heat transfer rate for air flow equal to 2 m/s was estimated to vary from about 44 to about 35 W/m^2 (during 8 hours lasting charging phase), and the total amount of stored heat was approximately 1.2 MJ/m^2 (Jaworski 2014) (all these values were related to the size of the unit area of the ceiling panel).

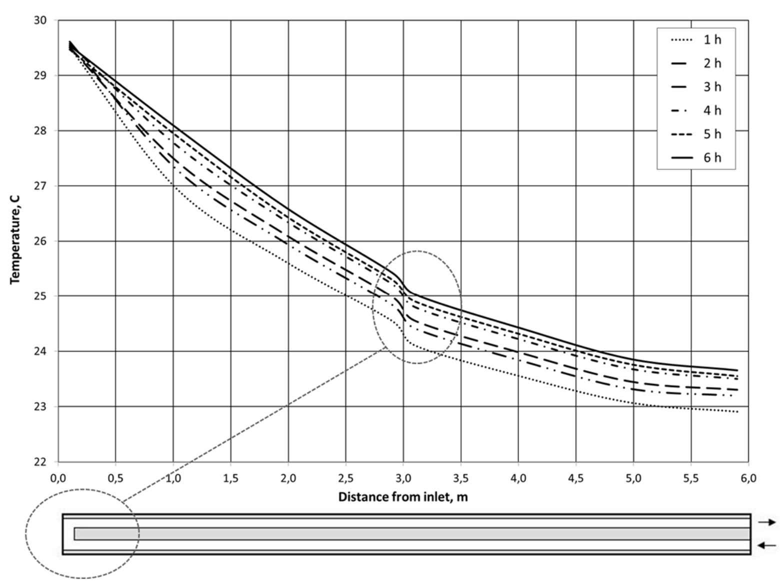

Fig. 5. Air temperature varaitions along the channel for diferent times from the beginning of the charging phase (heating)

Figure 6 shows the temperature variations on the inner surface of the channel at different distances from the inlet during heating for the third cycle of heating/cooling. Also is shown the temperature on the outer surface at the inlet to the channel. Analysing the shape of the temperature curves it is possible to assess to which extent the potential of PCM to accumulate heat is utilized, i.e. what part of PCM, contained in the composite, undergoes a phase change during the whole cycle. The measurements show that only close to the inlet of the channel (storage unit) phase change material completely melts during heating period. In the remaining part of the unit PCM "works" only partially, only part of it, in the vicinity of the surface, melts and solidifies. An important conclusion from these tests is that the channel walls are too thick, or that the distribution of PCM in the composite should be rearranged.

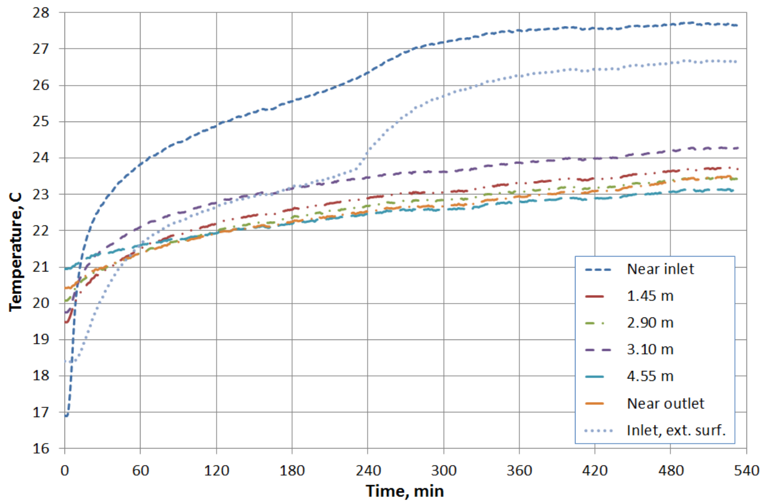

Fig. 6. Temporal variations of temperatures at the internal surface of the channel along air path during heating; thick dashed line indicates the temperature at the external surface near air inlet

In the following two Figures, 7 and 8, there are shown the results of measurements that were made in conditions similar to the real ones. The tests were performed during the summer (July-August) also in cycles of several days (5 to 8). Due to some unforeseen disturbances in the vicinity of the intake manifold it has not managed to fully reproduce the actual characteristics of the ambient temperature, i.e. fluctuations in the temperature at the inlet to the channel were much smaller than the actual ones. However, since in the long term (few days), the average temperature of the environment has changed significantly, it was possible to observe the influence of the phase change material on the thermal characteristics of storage unit.

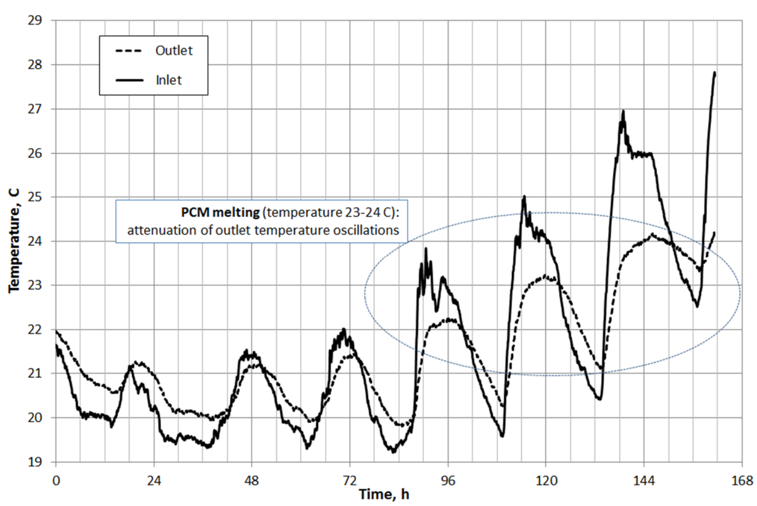

Fig. 7. Temperature fluctuations at the inlet and at the outlet of the panel, results of the test performed during the rise of ambient air temperature

Figure 7 shows changes in the air temperature at the inlet an at the outlet of the channel during the test lasting a whole week. During the first three days the ambient temperature was relatively stable and its average daily temperature kept below phase change temperature of the PCM. Because of these conditions, PCM was not able to undergo phase transition (melting and solidification), its impact on the damping of oscillations of the air temperature was negligible. The change took place in the following days, when the average air temperature began to rise and reached a level higher than the melting point of PCM (which equals to approx. 23 °C). In three days, the air temperature during the day varied in a relatively wide range around the melting temperature of the PCM. PCM underwent (at least partially) melting and solidification during the daily cycle, which is visible in Figure 7 as clear suppression of outlet temperature oscillations. Similar behavior of the storage unit is shown in Figure 8, which shows the results of temperature recording during the test, during which the average temperature gradually decreased from a level above the melting point of the PCM to the level below this temperature.

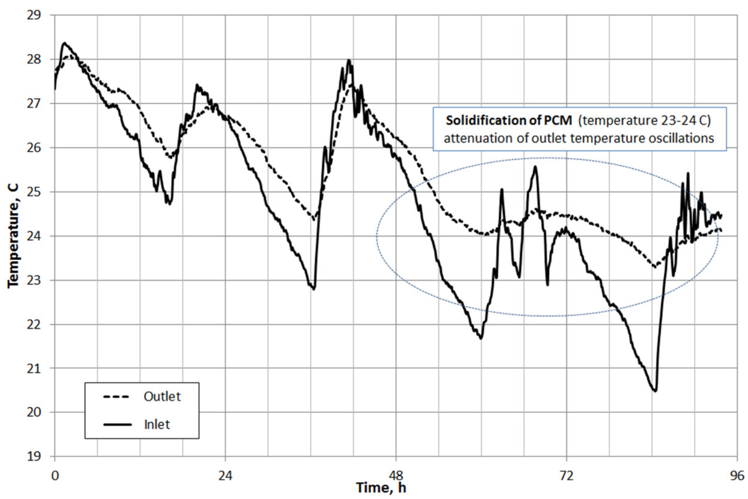

Fig. 8. Temperature fluctuations at the inlet and at the outlet of the panel, results of the test performed in natural conditions

Conclusions

The paper presents the results of experimental studies, which aim was to determine the thermal characteristics of special heat accumulator which is part of the ventilation system of the building. Heat accumulating material is formed from a composite made of gypsum mortar with an addition of PCM of a high thermal capacity. The concept presented in the work assumes that a ceiling panel with ventilation ducts is made using this composite.

The experimental tests have confirmed the effectiveness of the proposed solution as a regenerative heat exchanger. Also detailed information on the intensity of the processes of heat transfer in the phase of charging and discharging of the tray were obtained. The knowledge on the process allow to optimize the heat storage units integrated with the building structure such as that described in the work, but also to design PCM based heat storage units of other structures for integration with buildings envelopes. The factors, that should be especially taken into account when heat storage units of this type are designed, are their dimensions (in this case, the wall thickness of the channel), but also the manner of distribution of PCM in the composite.

Funding

This project has received funding from the Warsaw University of Technology in the framework of statutory activity as well as from the European Union's Horizon 2020 research and innovation programme under grant agreement No 657466 (INPATH-TES).

Disclosure statement

Authors hereby declare that they do not have any competing financial, professional, or personal interests from other parties.

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