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The Use of the Photovoltaic System in Combination With a Thermal Energy Storage for Heating and Thermoelectric Cooling

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Abstract: The article is focused on the research of the usage of modern accumulation technology. The proposed system is able to improve the thermal comfort of building interiors. That text depicts the technology, which uses a photovoltaics and other renewable energy sources for active heating and cooling. The bases of the presented technology are the phase change material and thermal energy storages. So, it passively improves the thermal capacity of the constructions of the buildings. Moreover, there is a possibility to use it for active heating and cooling. The technology contains thermoelectric assemblies, so, there is a very interesting possibility to store thermal energy with use of renewable energy sources (such as photovoltaic system) and thermoelectric coolers side by side. In the manuscript, there are shown measurements and results of the active operating modes of proposed technology. It was found the technology is able to work in active heating and cooling modes. It works quite well in active heating mode. On the other hand, thermoelectric cooling mode had a problem with overheating. In the end, the problem was solved and the cooling mode works. The measurements and results are described in the text.

Keywords: PCM; thermoelectric cooling; renewable energy sources; photovoltaic; thermal energy storage

1. Introduction

The consumption of energy by the building systems such as heating, ventilation and cooling systems (HVAC) are still rising with the ongoing increase in demand for thermal comfort [1]. Nowadays, the emissions and energy demand are being decreased by the use of the renewable energy sources. Of those sources, solar, wind, or geothermal energy and heat pumps, are suitable for buildings. These technologies, however, are not capable of dealing with an insufficient thermal storage capacity of the structures. At present, the preference is for a parameter of sufficient thermal insulation, but that does not address the accumulation of the thermal energy. The buildings, which are most problematic, are those constructed from lightweight materials, such as wood or lightweight concretes. In these, outside heat load variations during the day may cause inappropriate fluctuations of the air temperature inside the buildings. The problem with lightweight structures is that they are unable to store a sufficient amount of thermal energy that limits their ability to maintain stable conditions of the indoor environment. As a consequence, the thermal comfort is affected. Thermal energy storage addresses this problem. An optimal way for decreasing the consumption of fossil energy with increasing thermal comfort at the same time is the use of elements of thermal energy storages in combination with renewable energy sources, e.g. photovoltaic system in combination with thermoelectric coolers.

1.1. Thermal Energy Storage

Thermal energy storage (TES) is a temporary capture of thermal energy in the form of hot or cold substances for later utilisation [2]. The stored thermal energy may be used for heating or cooling applications. So, TES is useful for addressing the mismatch between the supply and demand of energy [3]. The principle of TES is based on a temperature difference (sensible TES) or change of phase (latent TES). The initial state is a solid state when the heat is added, the solid substance is heating up (sensible heat), after that, a solid-to-liquid phase change follows (latent heat). When the heat is still added, a liquid is heating up (sensible heat) and then, a liquid-to-vapour phase change occurs (latent heat) and after that, sensible heating of the vapour occurs (sensible heat) [4]. As can be seen, two forms of heat are recognized: sensible heat and latent heat. The principle of sensible heat storage is based on the material's change of heat capacity and temperature during the process of charging and discharging [5]. In case of the sensible heat, the specific heat capacity is the primary parameter. It determines the amount of energy needed to change the temperature of 1 kg of the substance by 1 K. The amount of sensible heat energy can be calculated by Equation (1).

$$Q = m \cdot \int_{T_i}^{T_f} c_p \, \mathrm{d}T, \tag{1}$$

where

m	mass	(kg),
T_i	initial temperature	(K),
T_f	final temperature	(K),
c_p	specific heat capacity	(J kg^{-1} K^{-1}).

Latent heat storage is reliant on the storage material absorbing or releasing heat as it undergoes a solid to solid, solid to liquid or liquid to gas phase change or vice versa [5]. During the phase change, the substance temperature is constant. Even so, itsability of storing and releasing a large amount of thermal energy. So, this is the reason why latent heat storage is a most efficient method of storing thermal energy [6]. The quantity of latent heat is derived from the difference in enthalpy of the two relevant states.

Thermal energy storage realised by phase change materials (PCMs) exploits especially latent heat [7]. PCM can be packaged in specialised containers (panels, tubes, and plastic bags), or it can be contained in ordinary building elements (ceiling and wallboards), or encapsulated as self-contained elements [8].

The amount of energy is given by the enthalpy difference during the phase change, according to the following Equation (2).

$$\Delta Q = m \cdot \Delta h, \tag{2}$$

where

Δh	enthalpy difference	(J·kg^{-1}).

Figure 1 shows the principle of thermal energy storage in the form of latent and sensible heat in the PCMs.

1.2. Phase Change Material

Materials to be used for phase-change TES should have phase-change temperature in the practical range of application and they must have a high latent heat of fusion and a high thermal conductivity. PCMs should also have desirable environmental properties to decrease the environmental impact of the systems during their lifecycle [9]. Different materials considered as potential PCMs include hydrated salts, paraffin waxes, fatty acids, the eutectics of organic and non-organic compounds, etc. PCMs can be divided into three main groups—based on the temperature ranges over which the TES phase-change occurs: low temperature (phase-change temperatures below 15 °C), mid temperature (the most popular—from 15 to 90 °C) and high temperature PCMs (above 90 °C) [10,11]. In our case, PCMs are classified as organic, inorganic and eutectic.

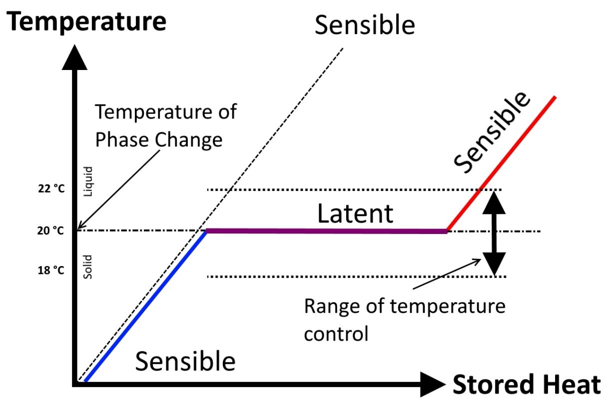

Figure 1. Latent and sensible heat, temperature range of the phase change [7].

Organic PCMs include a wide selection of organic materials such as fatty acids, esters, alcohols and glycols. The principal advantages are their chemical and thermal stability, and high latent heat of fusion. They are usually recyclable, non-corrosive, and have little or no subcooling [1,12]. Unfortunately, they have some disadvantages: flammable, non-compatible with plastic containers, relative large volume change, more expensive, low thermal conductivity, and lower phase-change enthalpy [1,13,14].

Inorganic PCMs are described as hydrates salts and metals. They cover a wide range of application. The main advantages are higher enthalpy per volume, higher thermal conductivity, non-flammable, and lower volume change. However, they have the disadvantages of phase segregation, corrosion, lack of thermal stability and subcooling [9,12].

The eutectic PCMs are a combination of chemical compounds or elements that have a single chemical composition and that solidify at a lower temperature than any other composition obtained from the same components [15]. Due to their higher density and stability in their liquid state, they have been used widely as ionic liquids in high temperature sensible thermal storage systems (thermonuclear energy, concentrated solar thermal power) [16].

Theoretically, most materials can be considered as PCMs. On the other hand, only some of them can be used for effective and predictable energy storage. Figure 2 shows some of the many materials suitable for TES. Depending on the application, the PCMs should be selected based on their phase-change temperature, should have a large latent heat, should melt congruently with minimum subcooling, and should be chemically stable, inexpensive, nontoxic, and noncorrosive [15]. The most commonly used PCMs in buildings are paraffin and salt hydrates [17,18].

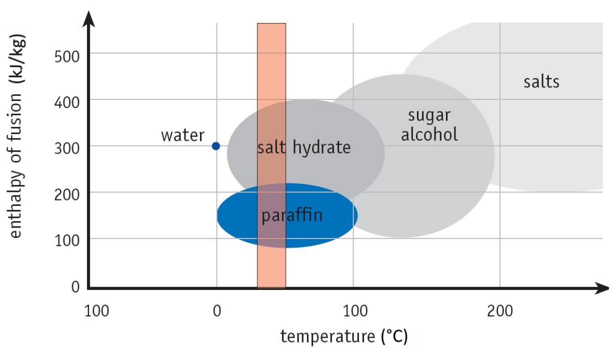

Figure 2. Classes of the phase change materials and their common parameters [19].

As previously mentioned PCMs can be incorporated into building structures. It contribute to lower energy demand by storing thermal energy in the form of heat or cold [20]. Several configurations have been proposed in the last two decades in order to incorporate PCM into construction materials. Traditionally, as one of the best option is taken application of the PCM in the envelope of the room because of its large area [21]. Some of the recent research show some improvements and specific use of the PCM in the buildings and also their advantages and disadvantages [22,23]. The efficiency is not dependent only on the location of the PCM, but also on their specific parameters, such as melting temperature range. For example, one of the research shows that the highest value of energy exiting from the indoor environment is ensured by PCM with a melting temperature equal to 20 °C [24].

Integration of the PCMs into the building's energy system can increase efficiency of the systems. These active systems use of the air flow as forced convection to increase amount of energy obtained from storage materials [25]. In common applications, PCMs serve as a reservoir of excess thermal energy for future utilisation. One of the experimental energy systems with integrated PCMs and combination with renewable energy sources is presented in this article.

1.3. Thermoelectric Cooling System

Thermoelectric coolers (TEC) are solid-state heat pumps based on the Peltier effect. It enables converting electrical energy into a temperature gradient. In commercial types, TECs are composed of many of n-type and p-type semiconductor junctions. When a direct current power source is connected, the electrical current flows from the n-type element to the p-type element, and thermoelectric cooling effect occurs. When the electrons pass from a lower energy level element (p-type) to a high energy level element (n-type) the temperature of the cold junction decreases. At the same time, the electrons carry the absorbed heat to the hot junction. This heat is transferred to the heat sink, while the electrons return to a lower energy level in the p-type semiconductor (the Peltier effect) [26].

There is also a possibility to use thermocouples reverse. That means, it possible to generate electrical energy by the temperature difference. If the thermal gradient exists between the cold and hot junction, a voltage (Seebeck voltage) directly proportional to the temperature difference is generated.

TEC systems have no mechanical moving parts and fluids, which transfer heat from the cold side to the hot side of the modules [27]. TECs have many advantages such as high reliability, low weight, and flexibility in integration. TEC systems have been applied to thermoelectric refrigerators [27,28], car seats [29,30], electronic cooling devices [31,32]. It has been also used in military, aerospace, instrument, and industrial products [33–36]. One of the areas of new research of thermoelectric technology is applying thermoelectric modules (TEM) to domestic space cooling. TEC systems can be also powered by a photovoltaic (PV) without the inverter. Some of the recent researches focused on thermoelectric coolers and generators (TEC and TEG) are defined by the combination of solar energy and PCMs. TEG is an alternative choice for converting of solar thermal energy into electricity. The technology described in this article can use energy from PV for TEC in combination with the PCM-based TES.

2. Methods

The proposed accumulation technology is based on the PCM DuPont Energain. This PCM is grouped into one active element [37]. The PCM uses molecular encapsulation that forms a highly durable PCM and it has a useable temperature range between 0 °C and 40 °C. The mass of the PCM is composed of a mixture of polyethylene and paraffin wax. When the temperature of the PCM is above 18 °C, the mass begins to melt and absorbs up to 515 $kJ \cdot m^{-2}$ of heat in the temperature range from 18 °C to 24 °C. This temperature range corresponds to common temperature conditions inside buildings.

In the paragraphs below are described the basics of the proposesd technology, its possible operation modes, used thermocouples and also photovoltaics. Other specific information about this technology is described in our previous articles [38–40].

2.1. Accumulation Device

The accumulation device (see Figure 3) was designed and made at the Faculty of Applied Informatics of TBU in Zlin (CZE—Czechia). There were also made all measurements and improvements.

The monitored room in which the technology is located has the dimensions 7 m × 5 m × 2.8 m. The room has two exterior surfaces: wall with windows and ceiling (roof). The other walls and floors are adjacent to other heated room. The total design heat loss due to transmission through walls and windows, ventilation and infiltration is about 41 WK^{-1}. In the summer it is important to know the heat gains. In our case, the maximum heat gains during the day (peak gains) from the outside are in the range of 280 to 480 W from May to September. Solar window gains are reduced by outdoor blinds.

This system is composed of two PCM-based accumulation panels with dimensions 1.25 m × 0.083 m × 2.1 m. Technology is equipped with a liquid heat exchanger and electric heating foils inside the panels. The proposed technology is design as "green technology". So, it can be supplied with power by any common energy sources, including renewable energy sources and use them for heating and cooling. Moreover, the technology is able to use photovoltaic systems in combination with thermoelectric cooling. This ability is not common in the PCM devices. So, it can be one of the biggest difference and advantage of the proposed technology against commonly available technologies.

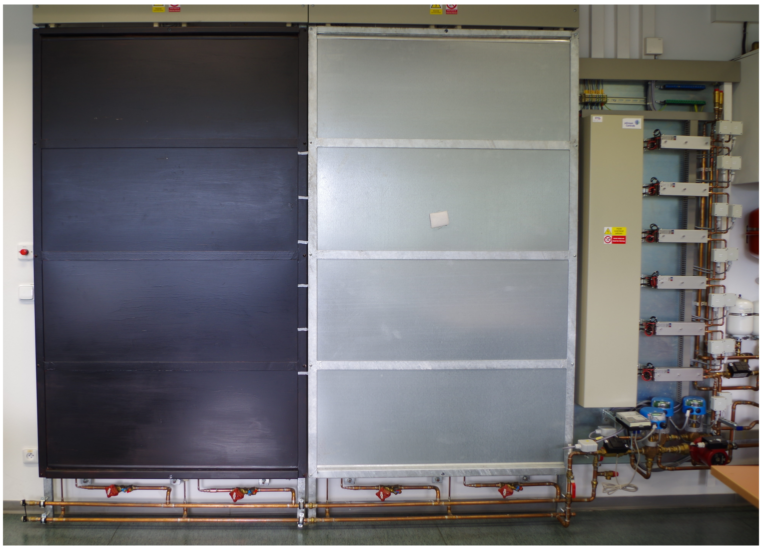

Figure 3. Accumulation device and thermoelectric assembly on the right.

The technology can be operated in many different modes. Mode choice is dependent on the requirements of particular experiments. It can work as a passive or active system. In the standard passive mode, the technology uses the common accumulation of the heat or cold by PCM. This mode can dampen peaks in indoor temperature and keep it stable during the day and night. The technology in active mode is capable of influencing the indoor temperature by releasing accumulated heat or to lower it by using external cooling. Individual active modes of operating are: disposing of the accumulated heat or heating up the cooled down panels; heating by electric heating foils or by hot water; cooling by the cold water or by thermoelectric coolers.

2.2. Thermoelectric Coolers

As previously mentioned, the technology is equipped with six thermoelectric assemblies of the type L.L.-210-24-00-00, see Figure 4. These thermoelectric coolers offer liquid-to-liquid heat transfer. TEC assemblies can be powered by the photovoltaics or from the power grid AC 230 V [41].

Figure 4. TEC assembly type L.L.-210-24-00-00.

Basic specifications of the TEC modules:

- Input power: 194 W,
- Cooling power: 208 W,
- Input voltage/current: 24 V/8.1 A DC.

For determining the number of TEC it was necessary to specify the cooling capacity of the technology. The average specific heat capacity of the thermal panel is about 11 kJ·kg^{-1} K^{-1} (16 to 27 °C) and its weight is about 129 kg.

The cooling of the accumulation panels takes est. 8 h. During this time, the accumulation device absorbed about 15.6 MJ of the cold, more precisely, this amount of heat is removed from the PCM. So, the overall performance of the thermocouples must reach about 0.55 kW. If the thermocouples have 50% efficiency the required (input) power for the thermocouples is about 1.1 kW. This means it is necessary to use six thermoelectric assemblies of type L.L.-210-24-00-00.

2.3. Photovoltaic System

The PV system is installed to supply the technology and thermocouples with electric power. The active area of the PV panels is 11.25 m^2. During the summer, solar radiation recieved by the photovoltaic panels averages at intensity of 750 W m^{-2}. Real energy efficiency of the PV was set at 10.5%. This value was result of measurement in one of our previous researches focused on verification of the photovoltaic panels effectiveness of their economic return [42,43]. The real average power output is a little bit lower than calculated and measured consumption of the whole technology. However, the photovoltaics can produce more electric power during a sunny day than the thermoelectric assemblies are capable of consuming.

3. Results and Discussion

Measurements of heating of PCMs have already come under examination many times. Our measurements and results of heating the proposed technology are shown in our previous articles [38–40]. Therefore, the crucial objective of this article was to determine the behaviour of PCM in temperature range specific for cooling. For this purpose, specific heat capacity is parameter of great importance. The value for PCM used is around 6.8 kJ·kg^{-1} K^{-1} for temperatures ranging from 10 °C to 21 °C. The cooling power is about 400 W at temperature difference 12 °C.

The risk of condensation of water vapour is the most important factor limiting the use of cooling devices. To prevent this from happening, ensuring that the temperature of their surface is at least 1 K above the dew point of the ambient air is crucial. For this purpose, the technology is able to monitor the value of the ambient temperature, humidity and dew point temperature. Technology is set to keep the temperature of the thermal panels as low as possible but still above the dew point. Simultaneously, technology is able to compared energy gained from the PV and consumed by TEC modules (or HP)—in case of low energy gains are turning off some TEC. Of course, this automatic control mode can be by-passed and the technology can be operated manually without all restriction.

The heating and cooling performance of the accumulation device is also important. For this purpose, it is important to know the specific power, which is given by the value of the heat transfer coefficient and the active area. The average heat transfer coefficient is about 6.4 $Wm^{-2}K^{-1}$ and the active area is 5.2 m^2. So, the specific heating/cooling power is around 33.2 WK^{-1}. It is, therefore, clear that the cooling power is dependent on the temperature difference between the surface of the panel and the ambient temperature. The higher temperature difference means higher the power. As previously mentioned, the used PCM has a temperature range of phase change between 18 °C and 22 °C. When active cooling is on, the sensible heat is removing as first (above 22 °C), then the phase change occurs (between 22 °C and 18 °C) and then the sensible heat is removing again (under 18 °C). The surface of the panels can be cooled to the dew point, but the most amount of energy is able to accumulate during the phase change. If the panel temperature is around 18 °C and the ambient air temperature is 25 °C, the cooling power is approximately 230 W. For example, at a temperature difference of 15 °C, the cooling power is about 500 W.

As previously mentioned, the proposed technology is designed to be able to use the power produced by the PV. Energy production covers the consumption of TEC modules with an average cooling output of about 550 W. This power is higher than the average cooling power of the accumulation panel. However, TEC modules lower the latent heat of the PCM panel, i.e., the surface temperature does not change much, but accumulation panel is able to accumulate much more energy for later utilisation. If the phase change limit value is reached, the surface temperature of the panel starts to decrease rapidly. The lower temperature increases cooling output, but when the technology is turned off, the temperature returns quite fast back to the phase change range.

During designing and initial measurements was discovered a technical problem with overheating in cooling mode. This is described in the following subsection. After this, there are presented results of measurements with solved the problem out.

3.1. Technical Problem

As we already know, heating can be provided by the electric heating foils inside the panels or by heating the panels by hot water from the hot water tank—heating by the heat pump or an electric boiler. The technology has been tested and measured in all heating modes. These measurements were successful and the technology was effective without obvious problems. After that, test measurements were performed in cooling mode. As mentioned earlier, cooling can be done by the heat pump or by thermoelectric modules. The cooling mode with the heat pump was made and measured without any problems.

There were some difficulties in measuring of the thermoelectric cooling. Above all, cooling is ineffective. Instead of decreasing the indoor temperature, it was increasing. Measurement of the original design of the technology and the thermoelectric cooling mode is shown in Figure 5 below. As can be seen, even when the room was cooling by the technology, the temperature was growing. The temperature got to start growing up very fast when the cooling by TEC was turned on. The indoor temperature was about 27.2 °C at the beginning of the measurement. After active cooling by TEC, it reached up to 30.8 °C. The result was: the technology transferred more heat to the room than it removed.

After some time, it has been found out why this problem occurs. A clear indicator was the thermographic diagnostics of the accumulation device and all parts of the thermoelectric modules with coolers. In the thermographic images below, see Figure 6, it can be seen all six thermoelectric assemblies and their temperatures. The image captures the state of the device with active thermoelectric cooling. The lowest temperature on the surface of the hot side is about 20 °C and the highest temperature is about 45 °C. This growing up the temperature is caused by connection of the liquid coolers in series. In this place, it can be said, it is also a little mistake of design. Maybe, it could be better to use the parallel connection. On the other hand, it is possible to get lower outtake temperature of chilled water.

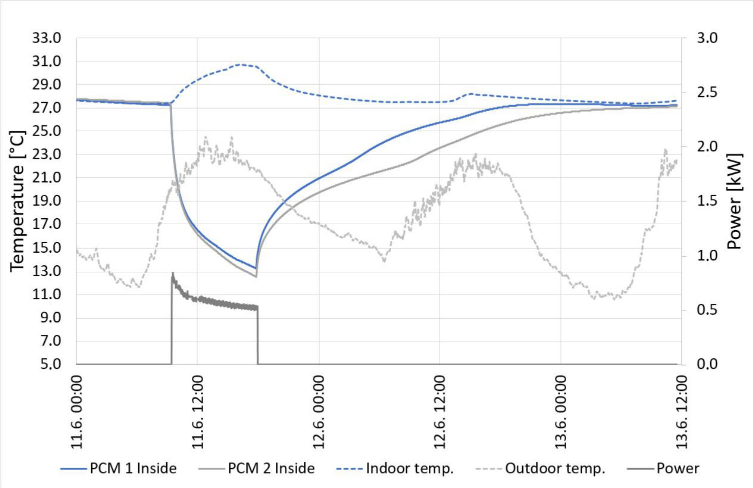

Figure 5. Technical issue with overheating.

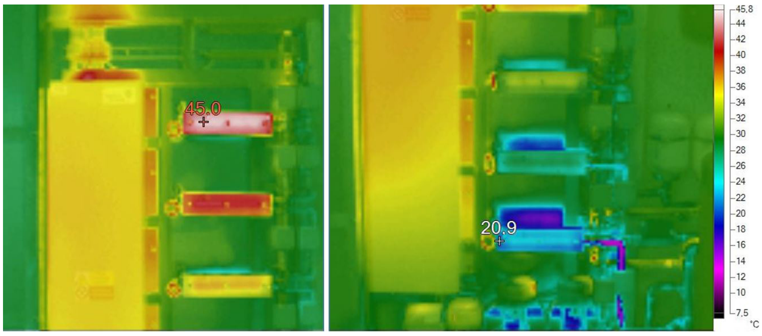

Figure 6. Technical issue—thermographic diagnostic.

In figures below, see Figure 7, it is possible to see details and temperatures of both sides of the coldest (first in the row) and hottest assembly (last in the row).

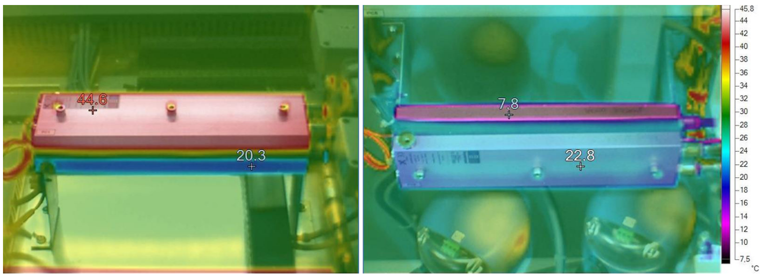

Figure 7. Technical issue—thermographic diagnostic—details.

The problem with the overheating came from the waste heat of the TEC modules. The thermoelectric modules are fitted with the liquid heat exchangers on both sides. These are for the extraction of cold and waste heat. The surface of the heat exchanger (cooler) on the warm side is very high. Therefore, the waste heat is radiated to the surroundings from the surface of the cooler. The problem can be solved by additional insulation of TEC modules and hot-water pipelines.

The problem has been solved by separating the space with thermocouples from the monitored space. Around the thermoelectric system, it was enough to build additional insulation to keep the heat in the enclosed space. However, there is still a freestanding cold water tank for absorbing the waste heat from the thermoelectric modules. On the other hand, the water tank is additionally cooled by the heat pump at a minimum temperature of 10 °C. Therefore, it was not necessary to separate the cold water tank from the monitored space. So, the final improvement was additional hot water pipes insulation. All of the following measurements in this article were performed with this adjustment.

3.2. Measurement

In the following paragraphs, there are presented measurements and results of the technology in different cooling modes.

The first measurement is focused on common passive mode—the most common use of the PCM. In this mode, the PCM-based panels reduced the temperature fluctuation and also stabilised the indoor temperature during passage of a few days of warm weather. An example of the system's behaviour can be seen in Figure 8. This passive mode managed to stabilise the indoor temperature between 23.2 °C and 24.0 °C when the outdoor temperature oscillated between 5.3 °C and 22.7 °C.

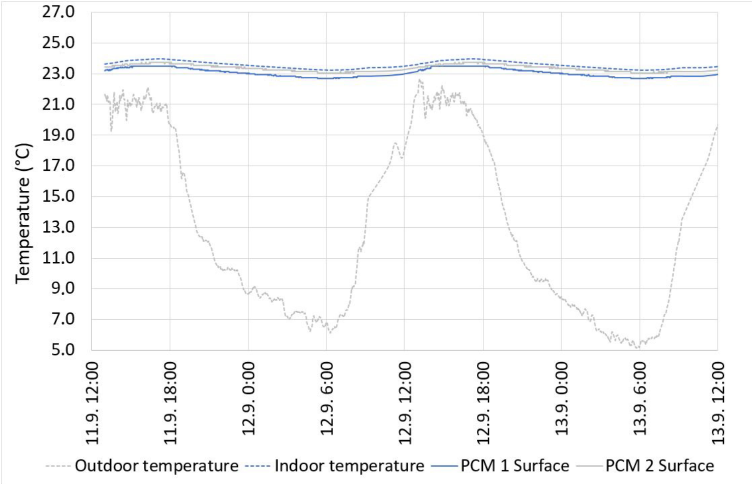

Figure 8. Passive mode.

Another experiments focus is the active cooling mode. The cooling cycle of the heat pump was used in this measurement. Results are shown in Figure 9.

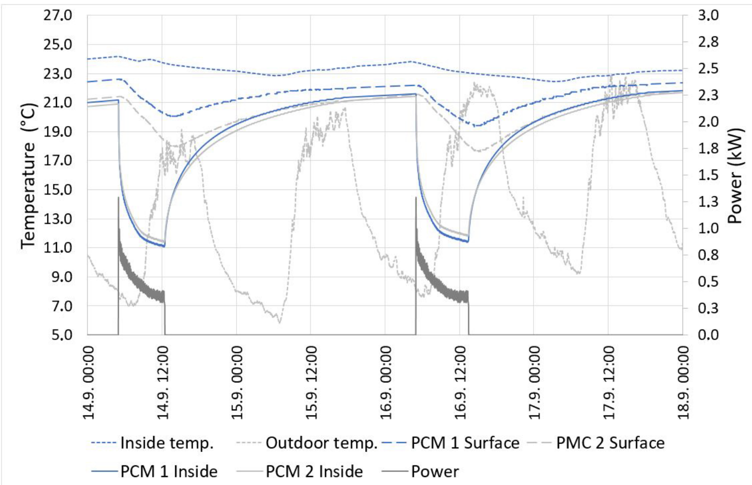

Figure 9. Active cooling—heat pump.

Every measurement is made of two cooling cycles. One cycle lasted two days. Active cooling was turned on during the first day. During the next day, the panels were left to just accumulate heat from the room. The cycle was then repeated.

During the first cooling cycle, the time it took to cool down of the surface temperatures from 21.4 °C to 17.9 °C for the unmodified surface and from 22.6 °C to 20.0 °C for the modified surface was around 7.5 h. The indoor temperature lowered from 24.3 °C to 23.1 °C during the day with the active cooling turned on. The indoor temperature continued to decrease until the next morning. The following day the technology was still left unpowered and the indoor temperature was increasing, conforming with the outdoor temperature.

In the next cycle, the measurement followed the previous one very closely. The outdoor temperature was a little bit higher in this cycle and the active cooling was in operation longer. The time it took to cool down from 21.8 °C to 17.6 °C and from 22.4 °C to 19.3 °C amounted to about 8.5 h. The indoor temperature lowered from 23.8 °C to 22.6 °C. The second half of this cycle was very similar to the second half of the first cycle. During these two cooling cycles, the sum of energy removed from thermal panels was approximately 7.9 kWh.

The following measured mode was focused on thermoelectric coolers. Thermoelectric assemblies were powered by the installed photovoltaic system. As was mentioned earlier, this measurement was also done in two cycles. Both cycles were measured during days with the outdoor temperature reaching up to 25 °C. In this cooling mode, the reduction in the indoor temperature by the thermal panels was from 24.0 °C to 22.9 °C and from 24.1 °C to 23.2 °C, respectively. Measured parameters are shown in Figure 10.

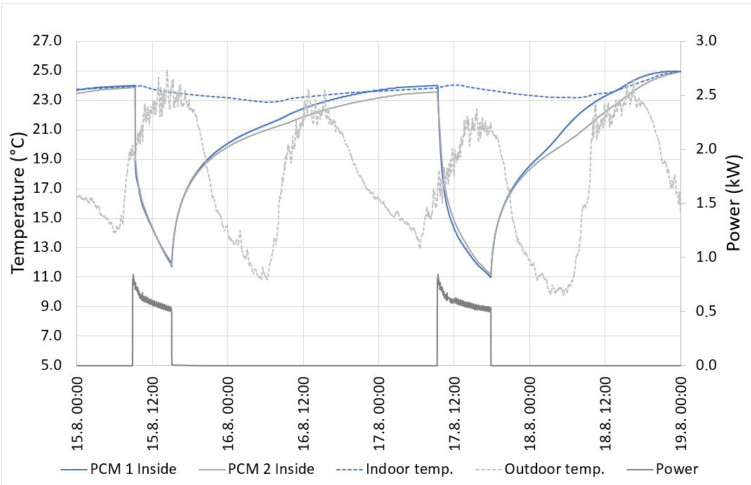

Figure 10. Active cooling—thermoelectric cooling.

In Figure 10, it is visible that the first cooling cycle was activated before 9 o'clock. Deactivation was at 15 o'clock. At first, the indoor temperature was rising in accordance with the outdoor temperature. Once the technology was activated, the indoor temperature began to fall. The temperature continued to fall all the time when the technology was turned on. After deactivation, the outdoor temperature continued to steadily fall, up to the next morning. Following that, the indoor temperature has risen again in accordance with the outdoor temperature.

The subsequent cooling cycle took the similar course and had similar results. The technology was activated after 9 o'clock. Deactivation was before 18 o'clock. The indoor temperature was falling as in the previous cycle, at first. But during the last measured day it started to rise fast. This fast increasing was caused by the higher outdoor temperature and also by the fact that the temperature of the PCM panels has gone over the range of phase change. So, the accumulation device absorbed just sensible heat, and it was not able to store latent heat.

From the obtained results, it can be determined that area of the thermal panels, compared to the total area of the measured room, is low. This can be solved by increasing heat flux. Forced convection is one option. The thermoelectric cooling (also heat pump) was powered by the photovoltaic system. This system delivered over 35.5 kWh throughot both cycles of measurement (four days, cooling by TEC). The heat which was removed from accumulation panels was totalled over 8.7 kWh. Consumed of power by the thermoelectric assemblies was over 18.5 kWh. The energy balance that is the production of energy and the consumption of it is shown in Figure 11.

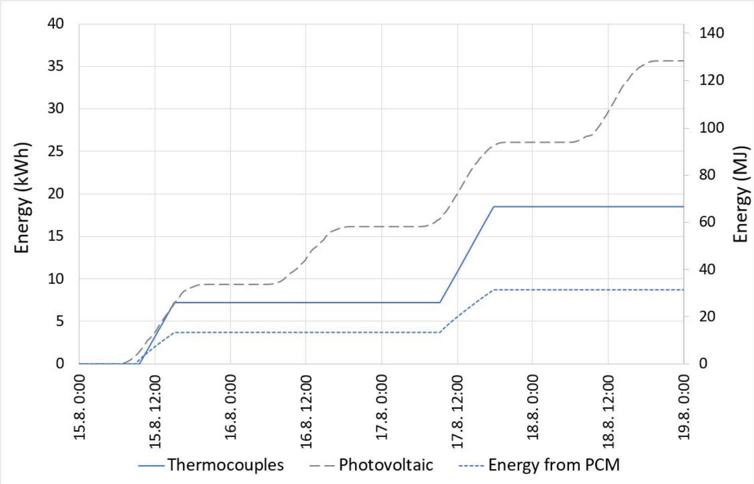

Figure 11. Balance of the energy consumption and production.

When comparing and evaluating the results, it is necessary to take into consideration that the operation and efficiency are very dependent on outdoor conditions. The comparison of both measurements is quite difficult because it is not possible to ensure the same conditions for each of them. Moreover, each mode has different conditions, for example, the speed of cooling of liquid and minimum liquid temperature. In the real conditions and operation, the temperature of the liquid from TEC could be lower than from the heat pump. In every case, it must be above the dew point temperature of course. In our both measurements was set the same temperature, about 11 °C. Measurements are shown in this article were also made when the outdoor conditions were similar, i.e., sunny days and outdoor temperatures between 7 °C and 25 °C.

Table 1 shows the balance of energy produced by the photovoltaic system, energy consumed by the heat pump or by the thermocouples and energy removed from the thermal panels. The table shows values measured during one cooling cycle in the previous year (2016) and values measured during two cycles in this year (2017). In both cases, the one cooling cycle was about two days long. During the first day, the technology was turned on, and the rest of time was turned off.

The installed heat pump has average Coefficient of Performance (COP) over 3.5 and Energy Efficiency Rating (EER) over 2.7. The table shows energies removed from the thermal panels (PCM), the energy produced by the photovoltaic system (PV), energy consumed by the heat pump (HP) or by the thermoelectric coolers (TEC), and the last one is the balance of these energies (SUM).

Table 1. Energy balance of the modes used in 2016 and 2017.

Year	Mode	PCM (kWh)	PV (kWh)	HP (kWh)	TEC (kWh)	SUM (kWh)
2016	Cooling	1.94	1.86	1.14	-	0.72
2016	TEC	5.02	14.24	2.37	11.27	0.60
2017	Cooling	7.84	20.03	4.51	-	15.52
2017	TEC	8.74	35.65	3.91	18.51	13.23

Energy balance remains possitive in all of these examples. Performance and efficiency of the system are, however, dependent on both weather condition and more importantly on the energy source being applied in proper range of temperature. The biggest disadvantage of the thermoelectric cooling is production of large quantities of waste heat on the thermocouples opposite side. This waste heat caused also our technical issue mentioned earlier in the manuscript. The hot side of TEC is cooled by a liquid cooler connected to the cold water tank. This waste heat can be used to save energy of another system. For example, using the waste heat to pre-heating water for another utilisation.

The waste heat from the TEC was up to 35 MJ (9.76 kWh) during both cooling cycles (four days). This energy could be used for preheating domestic hot water (DHW). The amount of heat needed for preparing DHW (Q_{DHW}) can be calculated by the equation below.

$$Q_{\mathrm{DHW}} = (1+z)\frac{\rho c_p \dot{V}_{\mathrm{DHW}}(\theta_{hot} - \theta_{cold})}{3600}, \tag{3}$$

where

z	system heat loss coefficient	(-),
θ_{cold}	intake water temperature	(°C),
θ_{hot}	hot water temperature	(°C),
ρ	density	($\mathrm{kg{\cdot}m^{-3}}$),
c_p	specific heat capacity	($\mathrm{J\ kg^{-1}\ K^{-1}}$).

The following example is very simplified. However, it can show some of the possibilities of using the waste heat. We want to know the average volume flow during four days of these conditions: intake water temperature is about 15 °C, outtake temperature is about 40 °C and the heat loss coefficient of the ideal system is 0.

$$\dot{V}_{\mathrm{DHW}} = \frac{Q_{\mathrm{DHW}} \cdot 3600}{(1+z)\rho c_p(\theta_{hot} - \theta_{cold})} = 0.084\ \mathrm{m^3\ d^{-1}}. \tag{4}$$

The results show that the waste heat could be used for preheating DHW from 15 °C up to 40 °C with volume flow about 84 L per day. The value corresponds to the amount of DHW consumed by two persons in the ordinary household per day.

Another possibility is using the waste heat for heating of a swimming pool. In case of the standard swimming pool with volume of about 10 $\mathrm{m^3}$, the theoretical maximum temperature difference is about 0.7 °C. This value is quite small, but it is better from the point of view of the almost constant temperature and flow.

4. Conclusions

The article presents interesting PCM-based accumulation technology. We have shown the possibilities of using the PCM in the non-standard active system. The main benefit of the technology is the combination of PCM and the available sources for the active heating and cooling mode. The primary aim of PCM is passive increasing of the storage capacity of an object, especially in light constructions. An additional feature is the application of the PCM in the active system. One of the advantages is that it is possible to use standard energy sources and renewable energy sources. Moreover, the biggest advantage and non-standard solution is thermoelectric cooling of the PCM-based panels in combination with the photovoltaics. So, the technology demonstrates that it is possible to use solar radiation to cool buildings during hot months. This solution is not commonly used and it can be placed for new knowledge and improvements of the HVAC systems. The article shows the results of the measurement technology in active cooling modes. The active cooling mode using with the heat pump worked quite well without any problems. The thermoelectric cooling had the problem with overheating of the thermoelectric assemblies. The problem was solved and the technology is able to work in this mode, too. On the other hand, the measurements show that the efficiency of the cooling is not so high and there is place for improvements, for example, by forced convection. These measurements indicate the possible further application of the proposed combination of the photovoltaics (or other renewable energy sources), thermoelectric cooling and PCM. We have shown the energy balance of the energy gains from the photovoltaics and consumption of the technology was positive. In the future, system efficiency could be improved by utilisation of the waste heat from the thermoelectric assembly.

For example, it can by used to preheat domestic hot water, swimming pool water or stored to thermal energy storage, etc.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
COP	Coefficient of performance
DC	Direct current
DHW	Domestic hot water
EER	Energy efficiency rating
HP	Heat pump
HVAC	Heating, ventilation and air conditioning
LON	Local operating network
PCM	Phase change material
PV	Photovoltaic
TEC	Thermoelectric cooler
TEG	Thermoelectric generator
TES	Thermal energy storage

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