Engineering Project

Application of Phase Change Material in Building Component (Ceiling)

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Chapter 1 Introduction

The high energy consumption in buildings is often attributed to the low thermal capacity (ability to accumulate/release heat) of lightweight construction materials, which leads to the energy demand of the air-conditioning system for heating/cooling to achieve the thermal comfort of the building. Using heavy construction to increase thermal inertia is a common approach to raise the heat capacity of the building. Still, it results in higher embodied energy, energy for production, construction, and demolition, and environmental impact over the life-cycle of the building [1]. Therefore, materials undergoing melting and solidification, called phase change materials (PCMs), are introduced.

Phase Change Materials (PCMs) are being extensively researched for their potential to increase the thermal capacity of building envelopes. They can enhance adequate thermal ability when integrated into building materials like concrete and gypsum. The successful application of this technology requires consideration of various factors, such as the chemical type of the material, the method of encapsulation and integration, and the geometry of the storage unit. Introducing PCMs into building materials can revolutionize the energy efficiency of buildings by providing superior thermal management.

It was proposed to integrate PCMs directly into building materials and combine them into ventilation ducts with the building's elements, usually the ceiling structure. The active cooling of Phase Change Material (PCM) can be achieved using a heat exchanger. This heat exchanger is based on internal capillary tubes and is embedded within a building structure. This method accelerates the solidification of the PCM, enhancing its effectiveness in thermal regulation. This project studies the structure of ceiling panels made of PCM-based composite with the feature of PCM-based heat exchangers located in air channels.

There are many proposals for integrating PCM into building structures: facade, floor, and ceiling. However, many factors, such as PCM distribution, shape, and method of capsulation, must be considered to optimize PCM usage. Therefore, incorporating PCM within ventilation ducts, often in the ceiling structure, is purposed to maximize heat transfer between air and PCM. This solution enhances thermal capacity and provides sustainable solutions for reducing energy consumption in buildings. During the day, when temperatures are high, the PCM can absorb and store excess heat, preventing it from entering the indoor space. When temperatures drop, the stored heat can be released at night, helping to keep the indoor space warm. This cycle can repeat daily, providing continuous thermal normalization. Therefore, the area with high-temperature oscillation can benefit from thermal fluctuation, which increases energy efficiency by reducing the necessity of heating and cooling systems and improving the thermal comfort of occupants.

Chapter 2 Theory and Principle

1. Phase Change Material

Phase Change Materials (PCMs) are substances that transition between solid and liquid phases, commonly known as the melting-solidification cycle. This transformation occurs at a temperature within the operational range of a specific thermal application. When a material shifts from a solid to a liquid state, it absorbs energy from its surroundings. This energy elevates the vibrational state of the constituent atom. As the material reaches its melting temperature, atomic bonds loosen, transitioning from solid to liquid. Solidification, the reverse process, involves the material releasing energy to its surroundings, causing molecules to lose energy and arrange themselves into a solid phase. The energy exchange, whether absorbed or released, during the melting-solidification cycle is termed the latent heat of fusion. Latent heat is distinctive in that it represents energy absorbed by the material without a corresponding increase in its temperature.

1.1 Type of PCMs and properties

Different types of PCMs contain different properties. Ideal PCMs should have a high transformation enthalpy per unit mass, complete transition reversal ability at an adequate transition temperature domain, chemical stability, non-toxicity, limited volume change during phase transformations, and low operational costs. Therefore, selecting the proper specific type of PCMs for each different application is mandatory. PCMs can be broadly categorized into organic PCMs, inorganic PCMs, and eutectics. Each category has its advantages and disadvantages. Figure 1 introduces the general classification of PCMs and their properties.

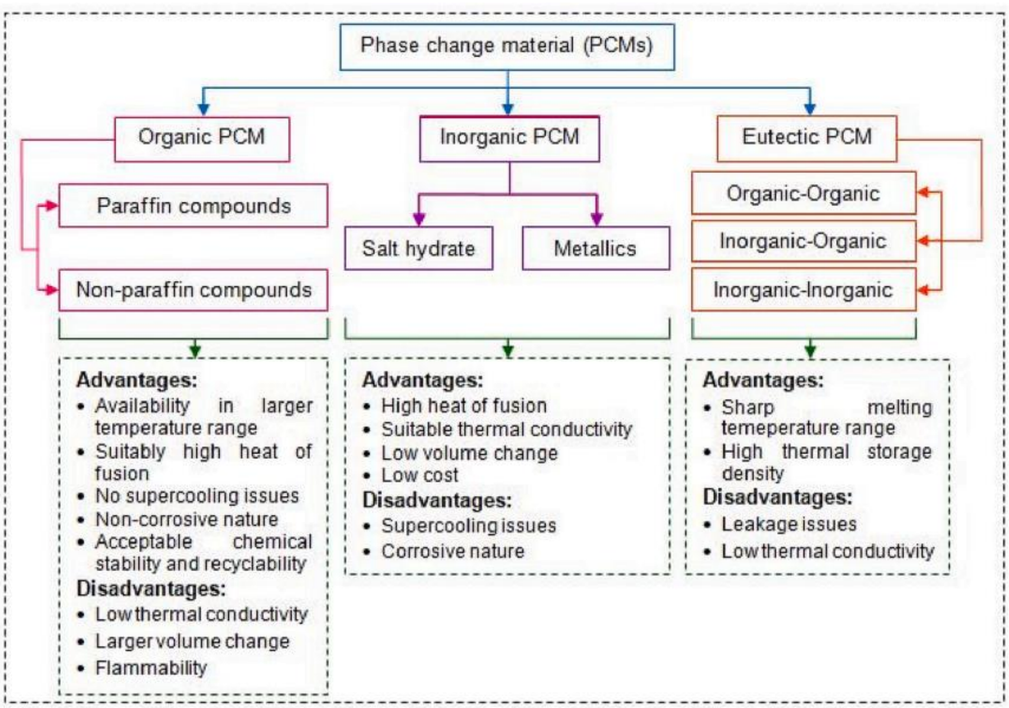


Figure 1 General classification of PCMs [2]

1.2 PCMs selection criteria

As stated, various types of PCMs contain different properties, so selecting PCMs according to their main application is vital. The main selection criteria are as follows:

- Melting point: The PCM should have a melting point that matches the application's temperature range. This allows the PCM to absorb or release heat effectively during the cycles.
- Latent heat: The PCM should have a high latent heat of fusion, which means it can store or release heat during phase change. This increases the thermal capacity of the element usage and reduces the temperature fluctuations.
- Thermal conductivity: The PCM should have a high thermal conductivity, which means the heat transfer rate within the material. This enhances the heat exchange between the PCM and the environment or other elements.
- Stability and compatibility: The PCM should be stable and compatible with the integrated material, such as gypsum or concrete. This means the PCM should not degrade, leak, or react with the material over time and under different conditions.

Table 1

Example of thermo-physical properties of different types of PCM [3]

Heat Storage Material	Melting Point (°C)	Heat of fusion (kJ/kg)	Heat Conductivity (W/mK)
Organic PCM			
Capric Acid	30.1	150-158	1.95
Hexadecane	18.1	236	N/A
Erythritol	120	339.8	N/A
Paraffin 56	56	72-86	0.75
Inorganic PCM			
$NaCH_3COO \cdot 3H_2O$	58	267	0.63
$Na_2S_2O_3 \cdot 5H_2O$	48	201-206	N/A
$Mg(NO_3)_2 \cdot 6H_2O$	89.3-89.9	167-175	0.57
Eutectic			
Octadecasane + heneicosane	25.8-26	173.93	
Carpic acid + lauric acid	18-19.5	140.8	0.143/0.139
$Mg(NO_3)_2 \cdot 6H_2O + NH_4NO_3$	48.7-51	118-126	0.34

2. Ventilation system

Designing a ventilation system for a building involves consideration of various factors such as building size, occupancy, purpose, local climate, and energy efficiency goals. One approach is Natural Ventilation, which leverages natural forces such as wind to facilitate airflow through the building. This approach relies on strategic building orientation, window placement, and design features to maximize the inflow of fresh air. It requires low operating costs and the provision of fresh air, but it has limitations regarding control over airflows, as it depends on external conditions.

Another common approach is Mechanical Ventilation, employing mechanical systems, for example, fans, to force air movement. Key design considerations include system capacity, air distribution, filtration, and control systems. Mechanical ventilation provides greater control over indoor air quality and is effective in various climates, making it suitable for tightly sealed buildings. However, it comes with higher energy consumption and operational costs. Mixed-Mode Ventilation combines natural and mechanical systems, offering an energy-efficient and responsive solution. Its design involves integrating different ventilation systems and implementing effective control strategies. While it provides flexibility, it also introduces complexity in design and control, potentially leading to higher initial costs. In building design, the selection of a ventilation approach depends on the specific requirements of the building, local climate, and energy efficiency goals. A combination of these approaches is often employed to achieve optimal ventilation results.

Night ventilation, also known as night flushing, is a passive cooling technique that leverages the outdoor daily temperature swing and the building's thermal mass. During the day, windows and other passive ventilation openings are kept closed to prevent the entry of warm air. At night, these openings are left open and allow the warm air inside the building to be flushed out and replaced with cooler outdoor air. The cooler air helps reduce the building's thermal mass temperature. When the building is occupied the following day, this pre-cooled thermal mass can absorb heat, resulting in radiant cooling. This technique is particularly efficient in arid regions with insufficient daytime ventilation to ensure thermal comfort. It can also improve thermal comfort and indoor air quality. The effectiveness of night ventilation techniques is determined by the climatic conditions, building characteristics, and location. Integration of this technique to PCMs in the building envelope can sustain the amplitude of temperature oscillation, which relies on the thermal capacity of the building.

3. Integrated PCM into the ventilation system of the building component

In sustainable building practices, the implantation of PCMs into the building is one of the subjects that can be applied. This approach involves incorporating PCMs into different building elements, such as walls or roofs, to improve energy efficiency. The goal is to utilize these materials' unique heat absorption and release properties. To reach it, many approaches were used: hanging boards with PCMs under the ceiling, using slabs made of composite PCMs, and integrating PCMs into the ventilation system by locating PCM units directly.

PCM storage units are integrated into the ventilation ducts to regulate the airflow temperature. They can reduce the energy consumption of the HVAC system by utilizing the free cooling potential of the night air and improving the building's thermal comfort and indoor air quality by dampening the daily temperature fluctuations. However, selecting PCM types with different properties, i.e., melting temperature, thermal capacity, and heat transfer rate, and some risks, i.e., leakage, corrosion, and degradation, require careful consideration.

A possible way to extend PCM storage units in ventilation ducts is a PCM-air heat exchanger configuration by Arkar et al. [4]. A numerical model (LHTES model) that simulates the transient thermal response of a latent heat thermal energy storage (LHTES) integrated into the ventilation system. The model accounts for the non-uniform radial distribution of the air velocity, the conduction in the spheres containing PCM, and the temperature-dependent PCM properties. It reduces the size and cost of the mechanical ventilation system, improves thermal comfort and indoor air quality, and saves energy and emissions.

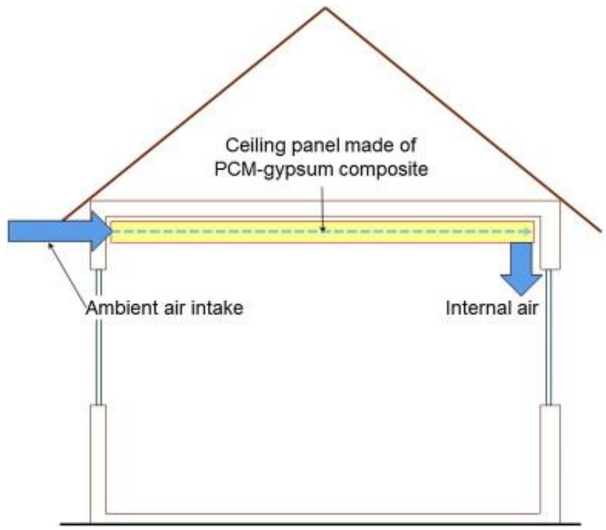


Figure 2 Scheme of operation of ceiling panel with ventilation channels [5]

PCMs can also typically be enclosed in various containers due to a phase change during exploitation, packed in containers, and integrated into the building component. Investigations into the chemical compatibility of low-temperature PCMs and the materials used in the design structure have revealed that stainless steel, polypropylene, and polyolefin are suitable container materials in most cases. For example, polyolefin and polypropylene encapsulate their PCM products, packed in spherical balls or rectangular or cylindrical bars and then hermetically sealed. Each polyolefin capsule can hold approximately 180 ml of PCM, with a plastic ball thickness of 1.2 mm. Utilizing stainless-steel balls with a 100 mm diameter and a 3 mm thickness and storing them in a tank can also be effectively used as thermal storage.

Chapter 3 Aim and scope of the study

A new ceiling panel design that can improve the thermal performance of building materials with phase change materials (PCMs) will be introduced. For conventional façade layers with low thermal conductivity and limited heat transfer rates, encapsulated PCM in a container is presented in the ventilation channel above the ceiling. The container acts as a heat exchanger in the building's ventilation system. It can adjust the temperature of the air coming from the outside to a comfortable level by absorbing or releasing heat to the PCM. The melting point of the PCM is chosen according to the daily temperature variations in the climatic zone. Therefore, this study will be conducted based on Warsaw's temperature data (In the year 2022) to investigate the performance of PCMs to reach the thermal comfort condition of the building and reduce the cost of heating to maintain the typical temperature value of the room. This study will use MATLAB to analyze the PCM's performance after implementing it in the system.

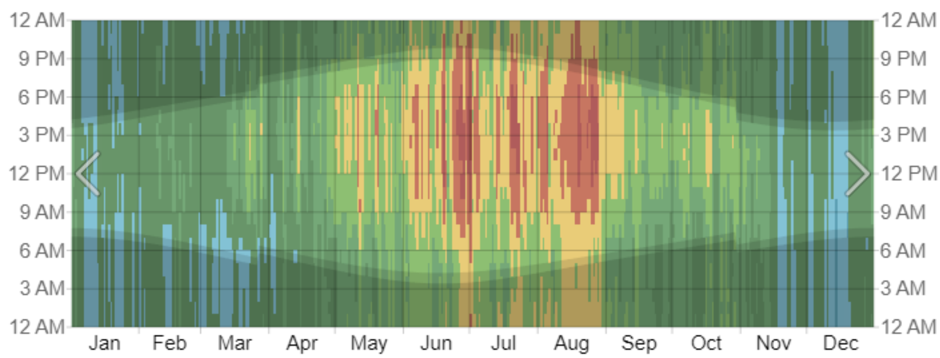


Figure 3 The hourly reported temperature (The year 2022 data)

Sources: https://weatherspark.com/h/y/87583/2022/Historical-Weather-during-2022-in-Warsaw-Poland#Figures-ColorTemperature

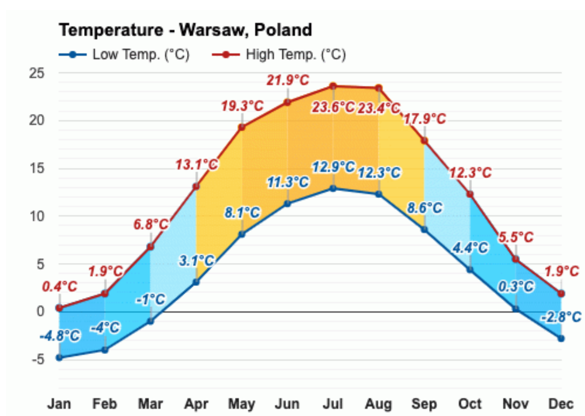


Figure 4 Historical data of temperature of Warsaw, Poland

Sources: https://www.weather-atlas.com/es/polonia/varsovia-el-tiempo-en-septiembreChapter 4 System Analysis

Chapter 4 System Analysis

1. Experiment condition assumption set up

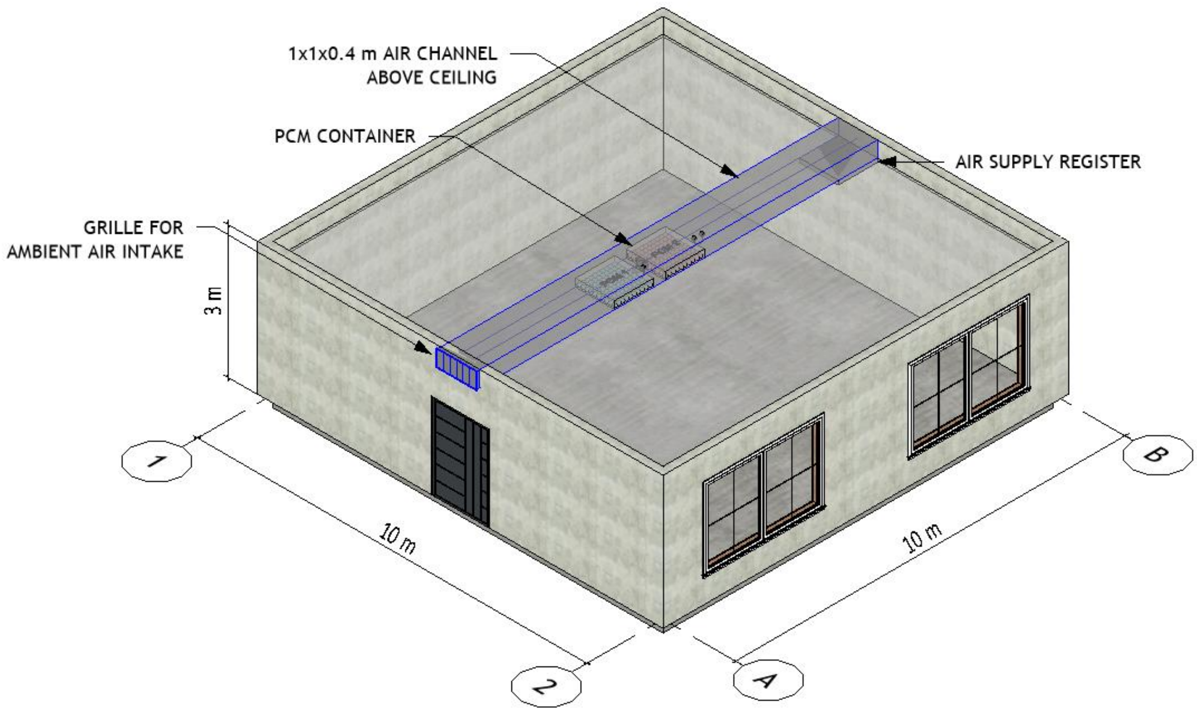


Figure 5 Visualization model of experiment condition set up

- For simplification in investigating the performance of PCMs embedded in buildings, It is assumed that a 1x1 m^2 channel for airflow is above the ceiling for ventilation purposes of a 10x10 m^2 room with 3 m height. In the channel, sphere-encapsulated PCMs in a square cross-section 1x1 m^2 container are worked as heat storage. The basis of the moderate air speed inside channels for required airflow is applied to analyze the system using the natural heat convection method. So, the room has to be in a negative pressure condition to ensure air transfer. The room temperature is expected to be 22℃, considered a thermal comfort condition. The room's design and material must also be considered for heat transfer.
- The area of the window to the wall (WWR) is 20%, considering that Poland is in the north hemisphere and there is a daylight utilization to apply the heat radiation for the Sun. Madeehe Altaf [6] states that WWR should be around 10-30% in such conditions. Single-pane clear glass 6 mm glazing window is used to achieve the highest solar heat gain coefficient (SHGC) [7]

Type of window glazing	Shading coefficient	Solar heat gain coefficient	Visible light transmittance
Single-pane 6 mm glazing			
- Clear glass (base case)	1.00	0.86	90%
- Clear with tinted film	0.50	0.43	48%
- Clear with reflective film	0.29	0.25	15%
- Clear with spectrally selective film	0.51	0.44	69%

Figure 6 Properties of clear glass with different types of the film [7]

SHGC of single-pane clear glass 6 mm glazing is 0.86, and the approximation area is 0.2*(4*10*3), equal to 24 m^2 from 20% of the total area of the exterior of the room.

- The area of the wall is 80% of the total area after deducting the window area, which is equal to 96 m^2. The assumption is that every side of the walls is exposed to ambient air, and the material is Structural lightweight aggregate concrete (SLWAC) with Argex as aggregate, with thermal conductivity equal to 0.94 W/mK [8].

Type of concrete	Type of aggregate	f_{cm} (MPa)	ρ (kg/m^3)	λ (W/m K)	c_ρ ($\times10^3$ J/m^3 K)	$c_p = c_\rho/\rho$ (J/kg K)	α ($\times10^{-6}$ m^2/s)
NWC	Gravel	57.7	2248	1.98	1666	741	1.17
SLWAC	Stalite	49.9	1811	1.21	1688	932	0.73
	Lytag	41.2	1739	1.14	1654	951	0.70
	Leca	37.6	1659	1.06	1568	945	0.69
	Argex	26.1	1541	0.94	1545	1002	0.62

Figure 7 Properties of concrete with different types of aggregate [8]

- The ambient temperature might be higher than the certain melting point of PCMs, which can lead PCMs to evaporate after receiving an amount of energy that exceeds some typical level. To prevent the evaporation of PCMs, the container has to stop the heat transfer from the ambient environment, and the following approach is introduced. Temperature sensors will be installed inside the container, and a vacuum pump will transfer air in and out. If the temperature reaches the evaporation point, the sensor will send a signal to operate the pump to transfer air out of the container and make it in a vacuum to stop heat transfer to PCMs. In contrast, if the temperature drops to a certain level below the melting point, the pump will transfer air in and allow PCMs to release heat into the room. Furthermore, after considering the temperature in Warsaw for the whole year, it can be noted that there is a large gap of fluctuation during the day. However, PCMs can only operate at specific temperatures, which might lead to ineffective operation; e.g., PCMs with high melting points stay solid for the whole winter. Therefore, the following model is implemented.

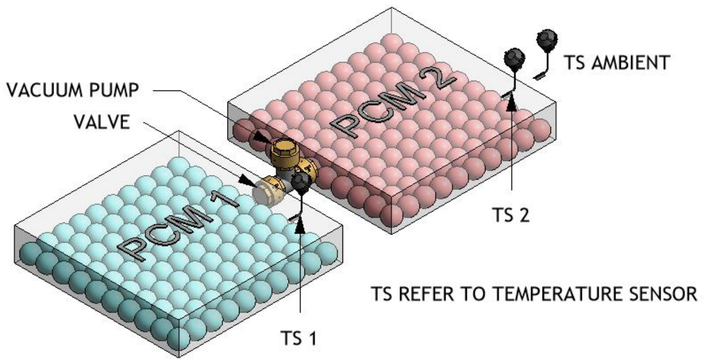


Figure 8 Visualization model of PCM assembly with other equipment

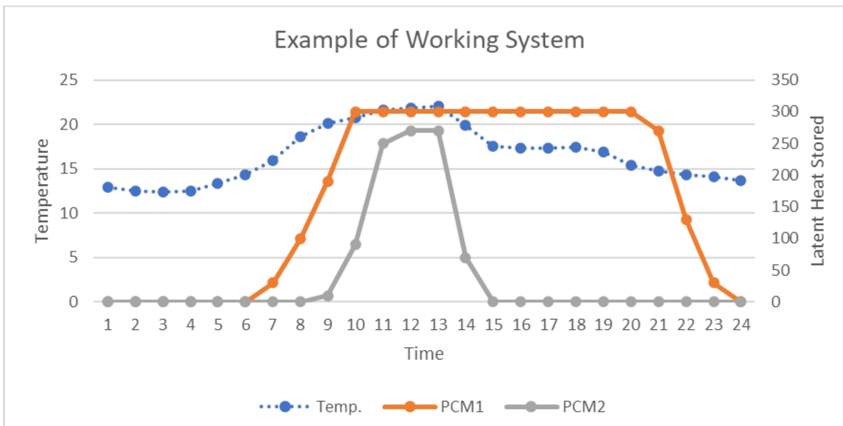


Figure 9 Chart demonstrates PCM operation with daily fluctuating temperatures.

The system consists of two different melting points, PCM, low and high melting temperatures. For example, in the system with PCMs with 15°C and 20°C, PCMs with low melting points start collecting energy earlier, storing energy at some level, and releasing heat after ambient temperature drops below 15°C. On the other hand, PCMs with 20°C melting points undergo the same process but within different periods. Overall, the system can provide heat to varying periods in different ambient temperatures, resulting in more effective heat release.

- To analyze the heat supply and estimate the electricity demand, the assumption of equipment that provides heat must be made. The actual value of COP from technical data can be used in the system. Therefore, the following specific heat pump is used, and the Vitocal 350-G BW 351.B33 with COP equal to 5.0 is chosen.

VITOCAL 350-G (BRINE/WATER)

Vitocal 350-G (single stage, master)	Type	BW 351.B20	BW 351.B27	BW 351.B33	BW 351.B42
Vitocal 350-G (2-stage, slave without own control unit)	Type	BWS 351.B20	BWS 351.B27	BWS 351.B33	BWS 351.B42
Performance data					
(to EN 14511, B0/W35°C, 5 K spread)					
Rated heating output	kW	20.5	28.7	32.7	42.3
COP ε in heating mode		4.8	4.9	5.0	4.8
Maximum flow temperature (5 K/12 K spread)	°C	65/70	65/70	65/70	65/70
Refrigerant circuit					
Refrigerant		R410A	R410A	R410A	R410A
– Refrigerant charge	kg	5.5	7.3	9.0	9.25
– Global warming potential (GWP)		2088	2088	2088	2088
– CO_2 equivalent	t	11.5	15.2	18.8	19.3
Dimensions					
Length (depth)	mm	1085	1085	1085	1085
Width	mm	780	780	780	780
Height (control unit open)	mm	1267	1267	1267	1267
Weight					
Type BW	kg	270	285	310	315
Type BWS	kg	265	280	305	310
Energy efficiency class*		A++ / A++	A++ / A++	A++ / A++	A++ / A++

Figure 10 Specification of selected heat pump

2. Heat demand of the room without PCM integration

2.1 Heat demand assumption

After determining the condition of the room and the ambient condition, heat demand can be calculated from such conditions by the following equation:

$$\dot{Q}_{demand} = \dot{Q}_{gain} + \dot{Q}_{loss}$$

- Heat rate gain ($\dot{Q}_{gain}$)

It can be calculated from solar heat gain through the window, which combines direct radiation, diffusion radiation from the sky, and reflected radiation from the ground. [9] However, for simplification, only direct radiation will be taken into consideration by the following equation:

$$q_s = SHGC_{dir} G(i)$$

Where q_s is solar heat gain from direct radiation $SHGC_{dir}$ is solar heat gain coefficient, and G(i) is Global irradiance on the inclined plane (plane of the array).

- Heat rate loss ($\dot{Q}_{loss}$)

It can be calculated by heat loss through building components, ventilation, and infiltration. Heat loss from ventilation and infiltration is neglected due to the heat recovery systems from PCMs and the positive pressure conditions of room assumption. Therefore, only heat loss through building components, e.g., walls, windows, and roofs, is considered and will be focused on heat conduction through the wall.

$$q_{cond} = -kA\,dT/dx$$

Where k is heat conductivity coefficient, A is area, and dx is thickness.

2.2 Heat demand analysis

```
HouseArea = 100;
WindowsSArea = 24;
WallArea = 96;
WallThickness = 0.1;

k = 0.94; %Select SLWAC Argex concrete
T_internal = 22; %Thermal Comfort Temperature
SHGC = 0.86; %Ingle-pane clear glass

Heat = readtable("ML_Heat_y.csv");
HeatTransfer = Heat(:,["m", "d", "h"]);
HeatTransfer.T = Temp.T_amb;

Q_cond = k*WallArea*(metoData.T_amb - T_internal)/WallThickness; %[W]
Q_solar = WindowsSArea*SHGC*metoData.G_i__W_m2_; %[W]
HeatTransfer.Q_net = Q_solar + Q_cond;

Q_demand_before = min(Q_solar + Q_cond, 0);
HeatTransfer.Q_Demand = Q_demand_before; %[W]
```

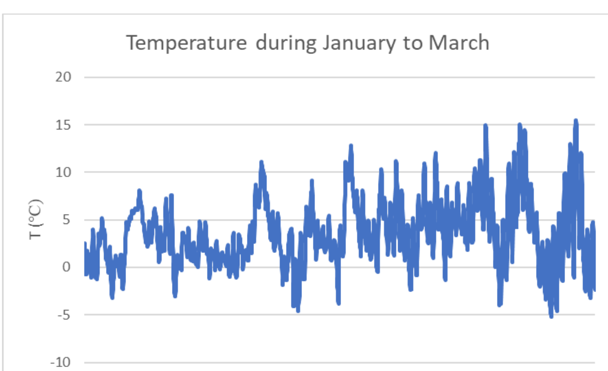
Figure 11 Analysis of Heat Demand of the room without PCMs integration using MATLAB

After complying with the system's assumption value, the room conditions and heat demand before PCM implementation can be estimated as 79.99 MW in total.

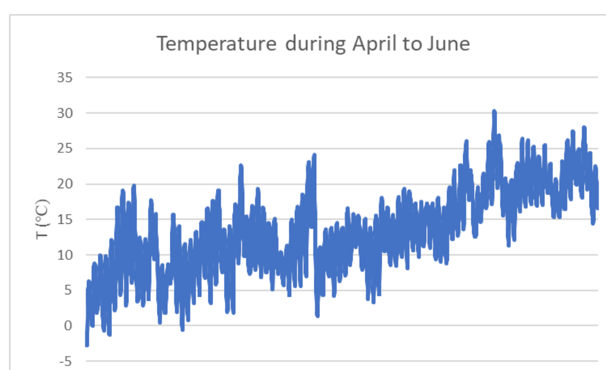
3. Heat demand of the room with PCM integration

3.1 PCMs selection

PCMs are elected based on the variations in ambient temperature each day. To store energy, the temperature during the day has to be more than the melting point so that PCMs can pass through the phase change process. According to historical data of Warsaw, two PCMs in a system with melting points around 4-6°C (for operating at the lower range temperature) and 17-19°C (for performing at the higher range temperature) are selected to ensure the phase change transition.



(a)



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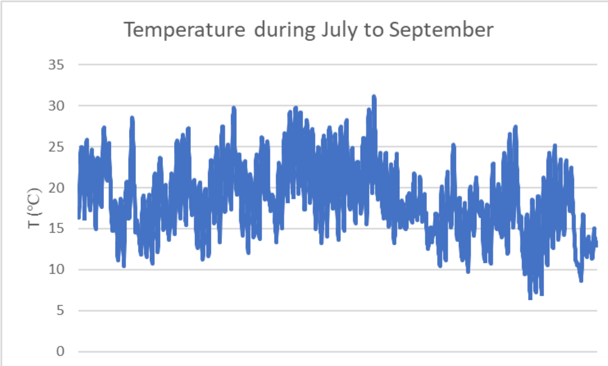

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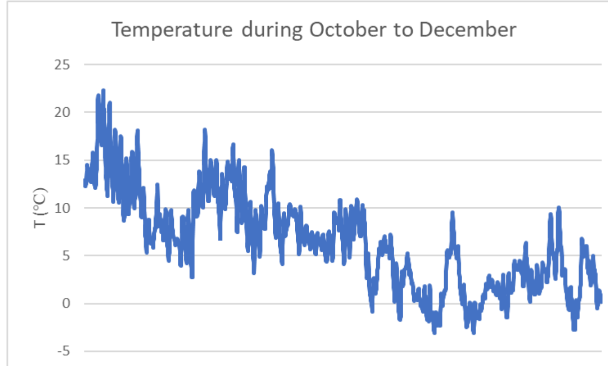

(d)

Figure 12 Annually historical data of Warsaw temperature, (a) January to March, (b) April to June, (c) July to September, (d) October to December

Moreover, to meet the environmental aspect of this project, organic PCMs are mainly considered to avoid corrosive and leakage problems. Therefore, the following PCMs are selected with the following properties:

- Hexadecane
    - PCM type: Organic pure n-alkanes
    - Chemical formula: $C_{16}H_{34}$
    - Melting point: 18.1°C
    - Heat of fusion: 236 kJ/kg
    - Sensible heat: 2.22 kJ/kg °C
    - Density: 0.77 kg/l
- Tetradecane
    - PCM type: Organic pure n-alkanes
    - Chemical formula: $C_{14}H_{30}$
    - Melting point: 5.9°C
    - Heat of fusion: 258 kJ/kg
    - Sensible heat: 2.22 kJ/kg °C
    - Density: 0.77 kg/l

3.2 Heat demand analysis

Heat demand after integrated PCMs in the system can be defined by heat demand before the integration subtracted by heat release from PCMs in each hour after accumulating heat in some range of time.

```
for hour = 2:height(Temp)

    Q_conv(hour) = ConvCoeff*PlateArea*(Temp.T_amb(hour)-PCM1.MeltingTemp)*3600; %[J/h]
    Q_PCM_store_S(hour) = Q_PCM_store_S(hour-1) + Q_conv(hour);
    if Q_PCM_store_S(hour) < 0
        Q_PCM_store_S(hour) = 0;
    elseif Q_PCM_store_S(hour) >= PCM1.Q_Latent
        Q_PCM_store_S(hour) = PCM1.Q_Latent;
    end

    for hour = 2:height(Temp)
        if Q_PCM_store_S(hour) < Q_PCM_store_S(hour-1)
            Q_PCM_release_S(hour) = Q_PCM_release_S(hour)+Q_conv(hour);
            if abs(Q_PCM_release_S(hour)) >= Q_PCM_store_S(hour-1)
                Q_PCM_release_S(hour) = -(Q_PCM_store_S(hour-1));
            end
        else
            Q_PCM_release_S(hour) = 0;
        end
    end
end

HeatTransfer.Q_PCM_store_S = Q_PCM_store_S;
HeatTransfer.Q_PCM_release_S = Q_PCM_release_S;
```

Figure 13 Analysis of Heat Demand of the room with PCMs integration using MATLAB

After complying with PCM properties to the system, heat release from PCM is 3.74 MW, and heat demand from the room after the integration equals 76.25 MW.

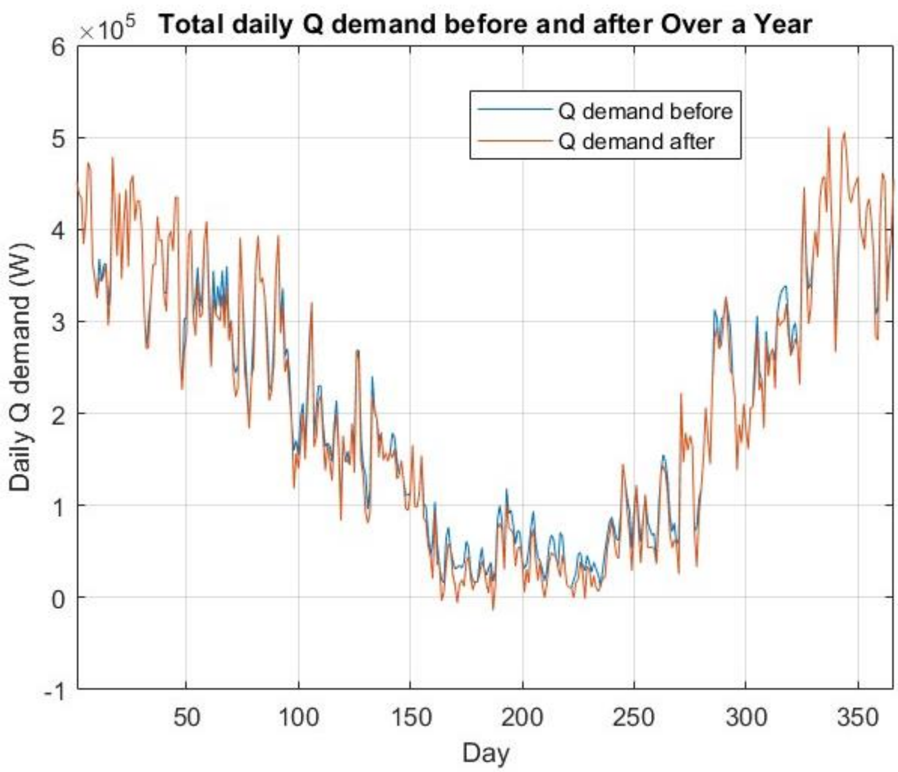

Figure 14 Comparison graph of the daily heat demand of the system

4. Economical aspect

4.1 Investment Cost

The estimated price list of the equipment is presented to calculate the investment cost.

Table 2

Estimate price list of the equipment of the system

Item	Price per unit	Amount	Total Price (PLN)
PCM [1]			
Hexadecane	28.13 PLN/kg	40.3 kg	1133.64
Tetradecane	28.13 PLN/kg	40.3 kg	1133.64
Mini vacuum pump	101.06 PLN/unit	1 unit	101.06
Temperature sensor	35.85 PLN/unit	3 units	107.55
Automatic solenoid valve	80.81 PLN/unit	2 units	161.62
		Total	**2637.51**

[1] Use pure-grade icosane as a reference price

- PCM

Material	Type of PCM	Cost (US $/kg)
Paraffin Wax	Organic	1.88–2.00
Technical Grade Icosane	Organic	7.04
Pure Grade Icosane	Organic	53.9
Stearic Acid	Fatty Acid	1.43–1.56
Palmitic Acid	Fatty Acid	1.61–1.72
Oleic Acid	Fatty Acid	1.67–1.76
Crude Glycerine	Fatty Acid	0.22–0.29
M-27	Commercially Available Fatty Acid	14.26
M-51	Commercially Available Fatty Acid	11.13
M-91	Commercially Available Fatty Acid	10.12
Calcium Chloride	Inorganic-Salt Hydrate	0.20
Latest™29T	Commercially Available Salt Hydrate	4.95

Figure 15 Cost reference of typical types of PCMs [10]

This project uses the price of technical grade icosane PCM (C20H42), as the system doesn't require a high level of purity, which refers to the cost per unit of hexadecane (C16H34) and tetradecane (C14H30) PCM because of the lack of actual information on the price. In general, PCMs with complex structures cost more than simpler ones because of the manufacturing process. Therefore, the expected overall price will be less than the presented project.

- Mini vacuum pump

Use a 12V DC Chemical Sampling Mini Vacuum Pump that can provide up to -55 kPa condition of the container, considered as high vacuum pressure, and efficiently minimize heat transfer.

Figure 16 Selected mini vacuum pump with specification

Source: China Manufacturers Custom High Quality Micro Diaphragm Air Pump 12v Dc Chemical Sampling Mini Vacuum Pump - Buy Medical Mini Vacuum Pump,Micro Diaphragm Air Pump,Dc Vacuum Pump Product on Alibaba.com

- Temperature sensor

The system requires three temperatures to indicate the temperature of both boxes and surroundings, then sends a signal to operate the vacuum pump.

Figure 17 Selected temperature sensor
Source: Temperature sensor - Harvst

- Automatic solenoid valve

Use a 12V Automatic, normally closed brass gas Waterproof Coil solenoid valve to control airflow in and out of the container.

Figure 18 Selected automatic solenoid valve
Source: Factory Price 12v Two Position Way Solar Power Automatic Normally Closed Brass Gas Waterproof Coil Solenoid Valve - Buy Electric Water Valves,Electric Solenoid Water Valve,Irrigation Solenoid Valve Product on Alibaba.com

4.2 Electrical price

After the electrical demand of the air heat pump is determined by heat supply and the typical value of COP, the annual electrical expense can be calculated by the product of electrical demand times the wholesale price of electricity. The number fluctuates each month, and the data for Poland in 2022 is shown in the following figure.

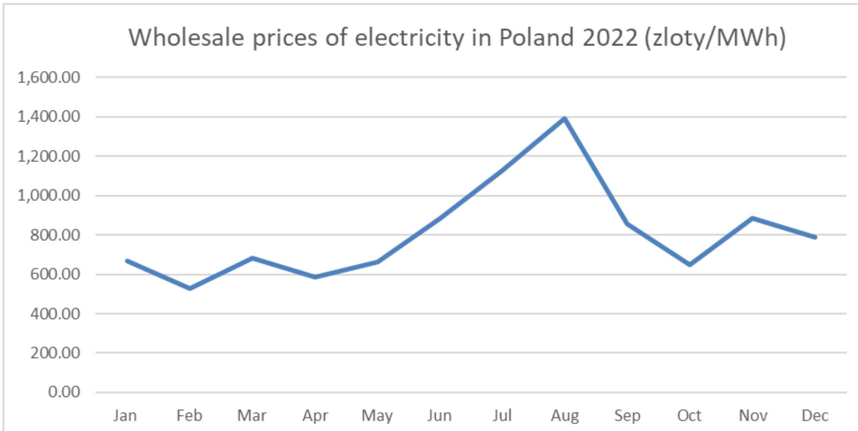

Figure 19 Monthly wholesale prices of electricity in Poland 2022

Source: https://www.statista.com/statistics/1066654/poland-wholesale-electricity-prices/

```
Q_demand_before_m = splitapply(@sum, HeatTransfer.Q_Demand, HeatTransfer.m); %[W]
Q_demand_after_m = splitapply(@sum, HeatTransfer.Q_demand_after, HeatTransfer.m);
P_after_m = abs(Q_demand_after_m)/COP/10^6; %[MWh]
P_before_m = abs(Q_demand_before_m)/COP/10^6;

ElecPaid_before_m = E_price.P.*P_before_m;
ElecPaid_after_m = E_price.P.*P_after_m;
ElecPaid_Reduction_m = abs(ElecPaid_after_m - ElecPaid_before_m);
ElecPaid_Reduction_y = sum(ElecPaid_Reduction_m);

plot(ElecPaid_before_m, 'DisplayName', 'E paid before');
hold on
plot(ElecPaid_after_m, 'DisplayName', 'E paid after');
extended_xlimE = [1, 12];
xlim(extended_xlimE);
extended_ylimE = [0, 2200];
ylim(extended_ylimE);
legend('show');
title('Monthly electrical paid (PLN)');

Total_Investment = 2637.51;
PayBackPeriod = ceil(Total_Investment/ElecPaid_Reduction_y);
```

Figure 20 Economical aspect calculation using MATLAB

Chapter 5 Result

1. Heat demand

According to the system, after analyzing heat demand before and after PCM integration, their value is 79.99 and 76.25 MW, respectively. The heat demand decreases by 4.68% after adding PCM.

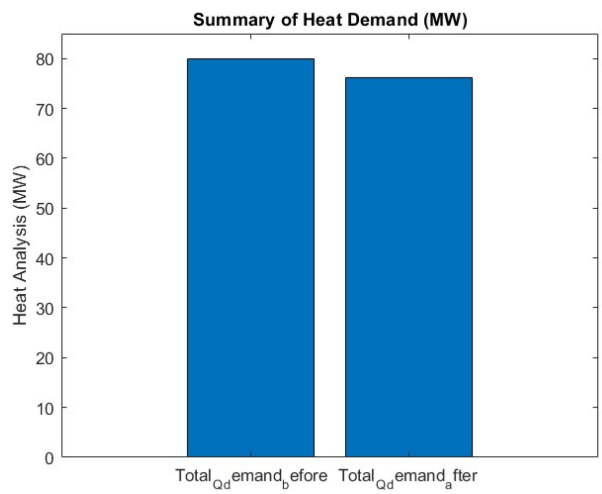

Figure 21 Comparison graph of the total heat demand of the system

2. Electrical usage and saving

The value of electrical usage for heat supply is in the same direction as heat demand because the value of COP of a heat pump is identical for before and after conditions (COP = 5), and they are about 16 and 15.25 MWh, respectively. Therefore, the system can save approximately 0.75 MWh per year.

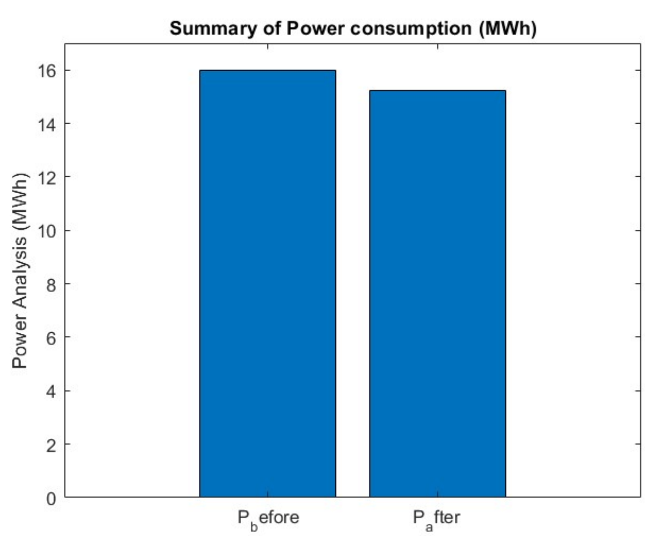

Figure 22 Comparison graph of power consumption of heat pump reduction

3. Economical aspects

The results from the economic point of view are carried out after considering both investment costs and potential savings. The estimated cost is approximately 2640 PLN, and annual electrical expense savings are 638 PLN, as demonstrated in the figure (from the assumption that the monthly price in each year will not have a big difference).

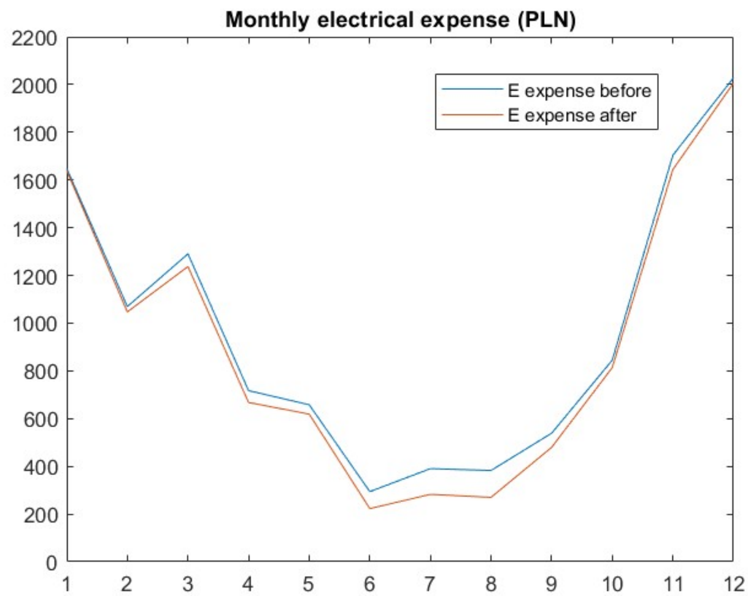

Figure 23 Comparison graph of monthly electrical expense

The payback period, total investment over average annual net gain, is five years, which means the potential of electrical savings will start to be considered as profit in year six.

Chapter 6 Conclusion

In conclusion, integrating Phase Change Materials (PCM) into the system has shown a notable reduction in heat demand, decreasing from 79.99 MW to 76.25 MW, reflecting a 4.68% improvement. This decrease in heat demand is directly reflected in the electrical usage for heat supply, resulting in annual savings of approximately 0.75 MWh, considering COP is 5.

From an economic standpoint, the assessment of both investment costs and potential savings reveals an overall estimated cost of 2640 PLN, with annual electrical savings amounting to 638 PLN. The calculated payback period, which considers the total investment over the average yearly net gain, is projected to be five years. This indicates that the potential electrical savings will transition into a profit starting from year six.

These findings affirm the feasibility and economic viability of implementing PCM in the system, providing a promising avenue for energy efficiency and cost-effectiveness. The demonstrated reduction in heat demand and corresponding electrical savings substantiate the long-term benefits, making this integrated system a viable and environmentally sustainable solution.

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