

Experimental Analysis of the Function of a Window with a Phase Change Heat Accumulator

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Abstract: The article presents the results of long-term field tests and their mathematical analysis regarding the impacts of innovative phase change materials on the energy efficiency of composite windows with various glazing parameters. Research was conducted on six glazing combinations throughout the heating season in a temperate climate in Rzeszów (Poland). The empirical results obtained during the spring months showed an improvement in the monthly heat balance for windows with phase change materials compared to the reference window by as much as 34.09%. In addition, the empirical results allowed the development and verification of a mathematical model describing the transport and distribution of heat within a window with a phase change heat accumulator. The model was made using equations of non-stationary heat flow and an explicit finite difference method using calorimetric thermograms describing the phase change eutectic mixture used in the research. Carrying out the Snedecor–Fischer test proved the statistical adequacy of the developed model in 4 out of 6 tested combinations of glazing units. Good matching of the empirical and theoretical quantities was also confirmed using the quasi-Newton method. The article is a solution to the problem of the effective use of solar energy within transparent building partitions, while presenting a useful mathematical tool that determines potential thermal gains in various climatic conditions.

Keywords: innovative phase change material; passive solar system; mathematical model of blurred phase change; heat-storing windows

1. Introduction

From the beginning of the creation of buildings, people have sought to illuminate their interiors with sunlight while protecting themselves against changing climatic conditions. This has resulted in the development of the solar architecture trend cited in [1,2], as well as the creation of constantly improving transparent building partitions [2]. Along with the next stages of scientific, technological, and economic development, more attention is being paid to aspects of energy-saving construction, renewable energy sources, and innovative building materials. In modern times, there has been an acyclical increase of ecological awareness in the world, which according to [2] is a consequence of sudden increases in the functioning costs or construction of buildings. In addition, the sudden increase in the human population in the 20th century and the limited materials and energy resources in the world have led to a change in the perception of the relationship between human activity and the natural environment, which allowed the formulation of the Brundtland report (UN 1987), which stated that “meeting the needs of the present cannot compromise the ability of future generations to meet their own needs” [3]. The change in the current attitude to the above-mentioned issues was justified by the fact that, as shown in [3,4], all of the processes for the production of building materials, construction of buildings, and their operation and demolition consumes 40% of the electricity produced, 50% of the total processed mass, and generates 35% of greenhouse gases. This resulted in the life cycle costing

(LCC) of buildings being considered during the design process and the issue of building permits for the building or extension of buildings with a correspondingly low value for the building's primary energy demand [5]. Considering the above economic aspects, the location and availability of renewable energy sources, as well as the nature of the external climate and the dissemination of technology, solar energy is one of the most commonly used renewable energy sources in construction.

According to [6–9], the use of passive solutions and direct gain systems, such as the innovative modification of transparent building partitions, is one of the possibilities to increase the share of heat gains from solar energy conversion.

Due to their structure and function, transparent building partitions are characterized by high instantaneous efficiency, while being susceptible to changes in atmospheric conditions. This is due to their low heat capacity. On the other hand, by using glazing of various values, depending on the orientation towards the world and the nature of the climate, transmittance, absorption, reflectivity, thermal resistance, and light transmittance, it is possible to partly influence the heat gains and losses generated by a building window [7,10]. Considering the above advantages and disadvantages of transparent construction partitions, one of the solutions affecting the increase of their energy efficiency and improvement, according to [8,9], is the increase of their heat capacity, for example through the use of phase change materials.

The thermal capacity of transparent partitions is increased by isothermal storage of heat absorbed by a phase change material (PCM) at the temperature at which its phase transformation occurs [7,10]. The two basic quantities characterizing the justification for using a given phase change material in a selected place are its phase transition enthalpy ΔH and the temperature range in which it occurs. In the next step, other physical and chemical properties are considered, such as the thermal conductivity, thermal expansion, toxicity, chemical affinity, chemical aggressiveness, polymorphism ability, combustion temperature, and aging ability after many cycles of phase transformations [11]. Phase change materials according to [12–18] are divided into organic, inorganic, and eutectic mixtures according to their physical and chemical properties.

Organic compounds are saturated hydrocarbons, carboxylic acids, esters, alcohols, and some polymers, which are characterized by phase transition enthalpy in the range of 100–200 J/g and which are partly resistant to overheating or sub-cooling [19]. In addition, they are characterized by low fire resistance, low solid thermal conductivity, and relatively high prices. In turn, organic compounds are most often hydrated salts of the main groups of the periodic table, as well as some carbides, sulfides, and silicas. They are characterized by enthalpy of the phase transformation in the range of 150–350 J/g and are not resistant to overheating or sub-cooling. In addition, they are characterized by high fire resistance, good solid thermal conductivity, and relatively low prices. An undoubted disadvantage of this PCM group is the frequent phenomenon of irreversible separation of hydrate crystallization water from the solid part of the salt, which according to [20–22] is due to the sedimentation of the heavier particles to the bottom of the containers in which they are located. The last of the groups of phase change materials cited in the scientific literature are eutectic mixtures [17,18,23–26]. These are materials that under conditions of constant pressure, concentration of components, and temperature may occur in two or more physical states. They are usually mixtures of the above two PCM groups that are created to obtain materials possessing the advantages of organic and inorganic PCMs, while eliminating their disadvantages.

Considering the advantages and disadvantages of phase change materials, their applications in construction, and their planned application in research, the phase change material independently developed and produced by the authors described in [27] was used, which is the subject of a patent application [28]. This PCM, which is a eutectic mixture of two carboxylic acid esters, was chosen due to its melting and solidification enthalpy values and the invariability of its thermophysical properties, even after 2000 phase transformation cycles [19].

The use of phase change materials in construction has been the subject of numerous scientific studies since the 1970s [29–33], but many technical and scientific problems related to their

economically justified use in construction and modeling of their thermal functions have not been resolved. These include:

- Incorrect selection of PCMs used in the application location in question;
- Unsealing forms moulds with PCMs applied;
- Change of physicochemical properties of PCMs after many phase transformation cycles;
- Insufficient ability of solid-state PCMs to conduct heat.

In the scientific literature [34,35], phase change materials are used directly in transparent building partitions to improve their energy function; as fillings for the inter-pane space [35–38]; as light permeable coatings [39]; as fillings for window shading systems, such as shutters or blinds [40–44]; or in heat accumulators installed within the double façade [45]. In addition, these types of materials have been tested by applying them inside glass blocks [46]. Phase change materials in the above places are used in the form of microcapsules and microgranules [47–50], in the form of composites with a stable shape SSPCM [51–54], in the form of capsules or packages coated with a PCM retaining the coating in the assumed place [19,51,55], or in direct form [40,41,56].

When conducting a search of the scientific literature on the modeling of the thermal function and heat storage using phase change materials, it can be seen that most studies refer to Stefan's solution for the problem described in [6]. By knowing the PCM temperature field we can calculate the amount of heat stored in it, neglecting changes in the internal energy of the system caused by changes in the temperatures of the liquid and solid PCM. The above approach has become the starting point for numerous scientific papers in this field [6,7,57,58], but nevertheless it is dedicated to substances characterized by phase changes at the "point". Unfortunately, according to [11], only some of the non-coherent hydrates of inorganic salts with a very ordered crystal structure are characterized by the above properties. Therefore, modeling of heat storage in phase change materials is done by determining the temperature field using glued functions, in which the changing heat capacity values when the material is in a solid state, liquid, or during phase transformation are written separately. The weakest point of this approach is the appropriate mapping of the temperature field in the phase transition. As in the previous case, the limit is the temperature range at which the PCM phase transformation takes place. The above approach according to [59,60] is used for organic and inorganic PCMs, which are characterized by their high purity, resulting in a narrow temperature range for their phase transitions. The problem is the modeling of heat storage and distribution in PCMs that are characterized by a wide range of phase transition temperatures (e.g., 10–15 °C). At the same time, they are the cheapest and easily available compounds and mixtures enabling the expected thermal benefits under selected conditions.

The references cited in the literature present the results of research and analysis of selected application cases and specific phase change materials, showing their potential advantages and disadvantages. However, no general rules and relationships have been presented that would allow simulation of the thermal behaviour of a greater number of PCMs in a single solution, or a specific solution containing a specific PCM that would function in different climatic conditions around the world. For this reason, the authors' method of conducting investigative experiments together with the development of a mathematical model with wide application possibilities is a complete solution to the studied problem, while allowing simulation of the thermal effects of the tested solution in other climatic conditions.

2. Materials and Methods

2.1. Materials

Phase change material (self-produced eutectic mixture of two esters: propyl palmitate and butyl stearate). The method of production as well as physical and chemical properties are presented in [27,28];

2 mm thick aluminum sheet, covered with matt black paint.

2.2. Apparatus

Almemo 2890-9 recorder, company Ahlborn, Ilmenau, Germany;

Pt1000 temperature sensor, company Salus, Kobielice, Poland;

Heat flux density sensor: FQA020C, company Ahlborn, Ilmenau, Germany;

LT 019008 thermocouple, company Ahlborn, Ilmenau, Germany;

Almemo FLA 613 GS pyranometer, company Ahlborn, Ilmenau, Germany.

2.3. Research Method

In the discussed problem, energy efficiency is understood as the ratio of the heat balance of the transparent partition with PCM to the heat balance of the reference transparent partition. In both cases, the heat balance was determined as the least-squares integral recorded on the internal glazing of the examined windows for heat flux density values as a function of time, according to Equation (1).

$$Q_{\text{window}} = \int_{t=1}^{t=n} q_t dt \quad (1)$$

where t is time.

Another physical quantity used in the work to demonstrate a change in the energy efficiency of the tested windows was the number of degree-hours. The number of degree-hours is understood to be the sum of the differences in the glazing temperature and the planned air temperature inside the chamber that is maintained for a given time. As such, the smaller the number of degree-hours, the better the adjustment of the heat gains generated by the window to the heat demand profile of the adjacent room.

$$S_{\text{th}} = \sum_{t=1}^{t=n} (T_1 - T_0) \quad (2)$$

Assessments of the obtained results for heat balance and the number of degree-hours were carried out in terms of short and long periods of time.

2.4. Experimental Tests

The experimental tests were conducted in an isothermal field testing chamber, functioning in real conditions of the external climate. The research was carried out during the heating season (from October to April) in Rzeszów in Poland. The field testing chamber had a steel skeleton structure thermally insulated with a 20 cm layer of mineral wool. The chambers external dimensions were 280 cm long, 190 cm wide, and 270 cm high. From the south side of the chamber, two identical windows with dimensions of 90 cm 60 cm were installed (Figure 1). The interior of the chamber was divided into two identical volumes, in which identical windows, oil heaters, thermoregulators, and electronic meters of electricity consumption were installed. The windows in both parts of the chamber consisted of two glazing units, creating a 15 cm space between them. Within the space between the panes of one of the windows, a heat accumulator was placed in the form of an aluminium box measuring 650 mm 100 mm

50 mm, inside which phase change material was applied. The material used is a eutectic mixture of propyl palmitate and butyl stearate, developed and produced by the author of [27]. During the tests, the intensity of solar radiation was recorded along with the temperatures of internal and external air and the internal panes in both windows. In addition, the density of the heat flux penetrating the glazing and the amount of electricity needed to supply oil heaters were recorded. Data were recorded simultaneously in both parts of the chamber at 10 min time intervals. This research is a continuation and extension of the research carried out by the authors and described in [19,27,28,40,41] on the

possibilities of the effective use of thermal gains from solar radiation to reduce the cost of heating buildings.

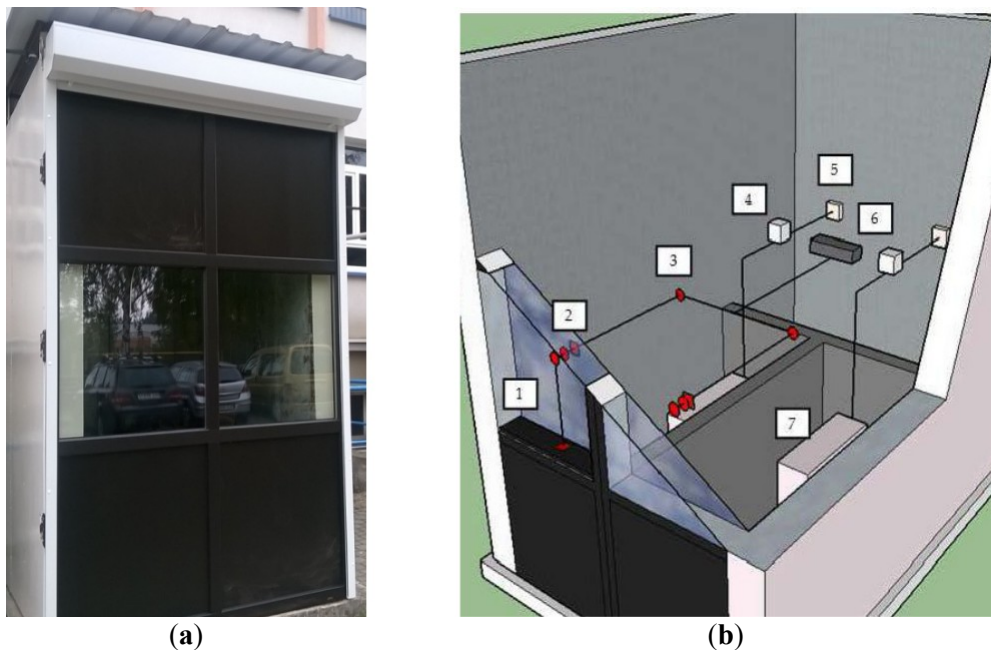


Figure 1. (a.) (a Photograph) of the isothermal field testing chamber. (b.) (Diagram) of the testing chamber:

chamber: (1) heat accumulator; (2) heatmeter; (3) temperature sensor; (4) thermoregulator; (5) energy consumption meter; (6) recorder; (7) oil heater.

As a part of the described tests, the thermal functions of 6 combinations of glazing units in a window with phase changes and reference materials were

tested. The parameters of all glazing units used during the tests are given in Table 1.

The testing of each combination lasted between 1 and 1.5 months.

Table 1. List of glazing parameters used during tests.

Parameter	Single Glazing	Double Glazing	Triple Glazing
Parameter	Unit	Unit	Unit
Heat transfer coefficient (W/m ² ·K)	1.1	0.7	
Heat transfer coefficient (-)	0.82	0.75	0.5
Light transmittance (-)	0.89	0.78	0.6
Construction of glazing unit (mm)	/4/	/4/16 Ar/4/	/4/16 Ar/4/16 Ar/4/

Transmittance (-)	0.82	0.75	0.5
Light permeability (-)	0.89	0.78	0.6

The conducted of glazing experiments unit allowed the creation of a database that was used to validate and

verify the mathematical model. This will be a useful tool in determining the potential thermal gains associated with the application of a discussed solution with an innovative phase change material in

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verify the mathematical model. This will be a useful tool in determining the potential thermal gains associated with the application of a discussed solution with an innovative phase change material in any outdoor climate conditions.

A model was made using equations of non-stationary heat flow and an explicit finite difference method. The model consisted of two connected parts with an identical time interval length of 10 min. One part of the model describes one-dimensional heat flow within a window combined with a heat accumulator, while the other part describes two-dimensional heat flow and storage in a phase change material. The model consisted of two connected parts with an identical time interval length of 10 min. One heat accumulator. The general heat flow formulas and time interval lengths are presented below: part of the model describes one-dimensional heat flow within a window combined with a heat

accumulator, while the other part describes one-dimensional heat flow and storage in a phase change heat accumulator. The general heat flow formulas and time interval lengths are presented below:

where Δt is the time interval, C_{w2} is the specific heat of the material at point 2, ρ_2 is the density at point 2, R_{1-2} is the heat resistance between points 1 and 2, and T_{1t} is the temperature at point 1 during t.

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In turn, the determination of the two-dimensional map of the temperature fields inside the accumulator with the PCM in the time step $t + 1$ was determined by the formula:

$$T_{PCM,2,2}^{t+1} = \frac{\rho_{PCM} C_{PCM} \Delta x_i \Delta y_i \Delta z_i}{\Delta t} \left(T_{PCM,1,2}^t + T_{PCM,3,2}^t + T_{PCM,2,1}^t + T_{PCM,2,3}^t + T_{PCM,2,2}^t \right) + T_{PCM,2,2}^t \quad (4)$$

where Δt is the time interval, ρ_{PCM} is the density of the PCM, C_{PCM} is the specific heat of the PCM, and Δx_i is the square of the element thickness i .

$R_{1,2-2,2}$ are the heat-resistant PCM values between points 1,2 and 2,2. ρ_{PCM} is the density PCM, and C_{PCM} is the specific heat of the PCM.

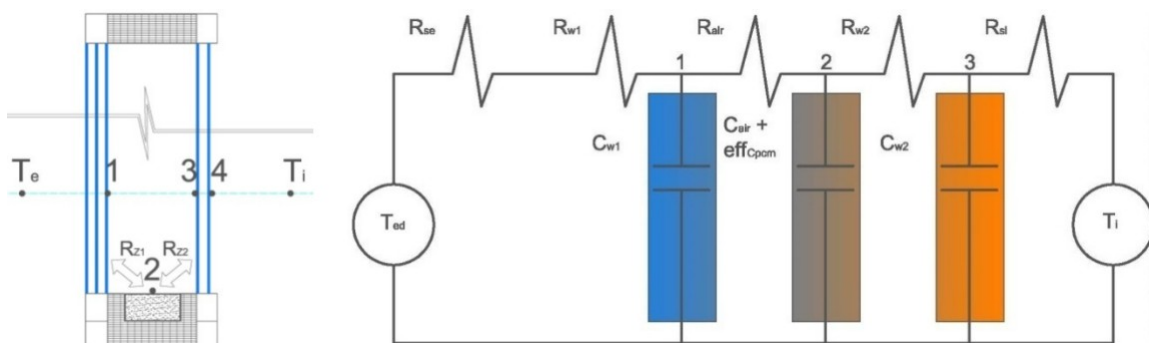
where Δt is the time interval, eff is the efficiency of the PCM, Δx_i is the square of the element thickness i , and Δy_i is the square of the element thickness i .

$$T_{2,2}^{t+1} = \frac{\rho_{PCM} C_{PCM} \Delta x_i \Delta y_i \Delta z_i}{\Delta t} \left(T_{PCM,1,2}^t + T_{PCM,3,2}^t + T_{PCM,2,1}^t + T_{PCM,2,3}^t + T_{PCM,2,2}^t \right) + T_{PCM,2,2}^t \quad (5)$$

where Δx_i is the square of the element thickness i , C_{PCM} is the specific heat of the PCM, ρ_{PCM} is the density PCM, and Δy_i is the square of the element thickness i .

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The graphical and analogous electric diagram of the mathematical model is presented below in Figure 2.



(a)

(b)

Figure 2.. ((aa)) Graphical diagram of the mathematical model of a composite window with a phase change heat accumulator. **(b)** Analogous electric diagram of the mathematical model of a composite window with a phase change heat accumulator..

The transmittance of heat and solar radiation through a composite window is a complex issue that has been dealt with in numerous scientific papers [6–10, 49–51].

When creating this part of the model, the modes of heat exchange by conduction, convection, and radiation between window's individual glazing was taken into account. The essence of the solution to this problem is to determine two

complex heat

transfer resistances between the external glazing and

the PCM accumulator (R_{z1}), and between the

PCM accumulator and the internal glazing (R_{z2}). These heat resistances

are temperature

functions that take into account heat transfer by convection q_k and

radiation q_r . The

above thermophysical phenomena were reconsidered in accordance

with the relationships described in [61].

$$q_z = q_k + q_r \quad (6)$$

$$q = \frac{k}{d} (t_1 - t_2) \quad (7)$$

$$q_r = \frac{h}{2} (t_1 - t_2) \quad (8)$$

$$q = h (t_1 - t_2) \quad (8)$$

where q_z is the heat flux density transmitted by radiation and convection, q_k is the heat flux density transmitted by convection, and q_r is the flux density transmitted by radiation.

was obtained in accordance with [61]:

$$R_z = \frac{t_1 \ t_2}{q_z} = \frac{1}{h_r} \frac{1}{d + h_r} \quad (9)$$

transfer coefficient for fluids r were determined:

$$\frac{r}{r_0} = F(Gr, Pr) \quad (10)$$

Grashof's probability number is:

$$\frac{I}{r} = 1 \text{ f or } Gr < 10^3$$
$$r = 18 \cdot 10^{-2} (Gr)^{\frac{1}{9}} \text{ f or } 4 \leq Gr < 2 \cdot 10^6$$
$$(Gr)^{\frac{1}{9}} \text{ H}^{\frac{1}{2}} \text{ f or } 2 \cdot 10^5 < Gr < 11 \cdot 10^6$$
$$r = 65 \cdot 10^{-3} (Gr)^{\frac{1}{9}} \text{ H}^{\frac{1}{2}} \text{ f or } 2 \cdot 10^5 < Gr < 11 \cdot 10^6 \quad (11)$$

where b, H are the width and height of the air gap.

Grashof and Prandtl probability numbers, according to [61], are expressed by the formulas presented below:

$$\text{Gr} = \frac{g l^3 \text{DT}}{v^2} \quad (12)$$

$$\text{Pr} = \frac{v}{a} \quad (13)$$

where β is the air thermal expansion coefficient, g is the gravitational acceleration, ν is the kinetic coefficient of the air viscosity, a is the temperature equalization coefficient, and ΔT is the temperature and air difference at a distance.

Radiation heat exchange in the unventilated space between the panes was taken into account according to Equation (14):

$$h_f = \frac{1}{q_1} \frac{2}{2} = \frac{1}{2} \frac{2}{2} = \frac{1}{2} \quad (14)$$

where C_0 is the black body radiation factor, ϵ_{1-2}^4 is the replacement emissivity, and γ_{1-2}^5 is the angle radiation factor (so-called configuration factor).

Due to the fact that heat exchange by radiation occurs at a right angle between the surface of the heat accumulator absorber F_1 and glazing surface F_2 , the equivalent emissivity ϵ_{1-2} and the angular radiation factor γ_{1-2} were determined in accordance with Equations (15) and (16):

$$\epsilon_{1-2} = \frac{1}{\frac{1}{\epsilon_1} + \frac{F_1}{F_2} \frac{1}{\epsilon_2}} \quad (15)$$

$$\gamma_{1-2} = \frac{1}{F_1} \int_{F_1} \int_{F_2} \frac{\cos \theta_1 \cos \theta_2}{R^2} dF_1 dF_2 \quad (16)$$

On the other hand, the heat flow and distribution within the phase change heat accumulator was determined based on Equation (3) in two-dimensional terms and the glued function of enthalpy increase inside the PCM as a function of temperature, in accordance with Equation (17). The above approach was used in numerous scientific works [6,56,57].

$$\begin{aligned}
\text{eff C.PCM} = D^H_{\text{PCM}} = & \begin{cases} m_s c_{w,s} (T_L - T_0) & \text{for } T > T_L \\ m_L L & \text{for } T = T_L \\ 0 & \text{for } T < T_L \end{cases} \quad (17)
\end{aligned}$$

The functions of the change of PCM mass enthalpy during H_{PCM} phase transformation over time were developed using the calorimetric thermogram obtained and described by the author [27]. The above approach is analogous to solving Stefan's problem [6,59], except that it concerns compounds with blurred melting and solidification. For the needs of this model, a discrete accumulator grid from PCM was selected with a width of $dx = dy = 5$ mm. Therefore, the cross-section of the accumulator

Materials in question 2020, 13 consisted of 200 elements (grid dimensions: 50 mm × 100 mm). In addition, the extreme 8 of 22 nodes of the discussed cross-section were modelled as the aluminium side of the accumulator, taking into account the resistance and heat capacity of the aluminium alloy used in the field tests.

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question consisted of 200 elements (grid dimensions: 50 mm × 100 mm). In addition, the extreme 8 of 22 nodes of the discussed cross-section were modelled as the aluminium side of the accumulator, taking into account the resistance and heat capacity of the aluminium alloy used in the field tests. The empirical results of heat flux density and temperature obtained during the tests, recorded nodes of the discussed cross-section were modelled as the aluminium side of the accumulator, taking on the inner surface of the internal glazing, are summarized below in the form of line and bar charts (Figures 3–8). This allows observation of both the momentary waveforms of the PCM and the reference values recorded in the modified windows, as well as their daily totals.

3. Results
In Figures 3–5, one can observe a diminishing influence of PCM on the instantaneous temperature and flux density distributions of heat passing through the window when comparing the modified

3.1. Experimental Results

window to the reference window. With an increase in heat resistance and a decrease in the transmissivity of

the internal glazing, results the phase of heat shift flux of density the curve and describing temperature the

PCM obtained window during become the tests, less recorded visible in

on relation the inner to the surface curve of describe the internal being the glazing, reference are windows summarized.

There below is also in the visible form trend of line of and reductions bar chart of (Figure 3–8). This allows during observation of the sunny and both cloudy the

days momentary of temperature waveform values of and the heat PCM flux and density the

referenceforthewindowvalues

withrecordedPCMintocomparedthetmodifiedtothewindows,referenceaswindowwellas valuetheir.daily totals.

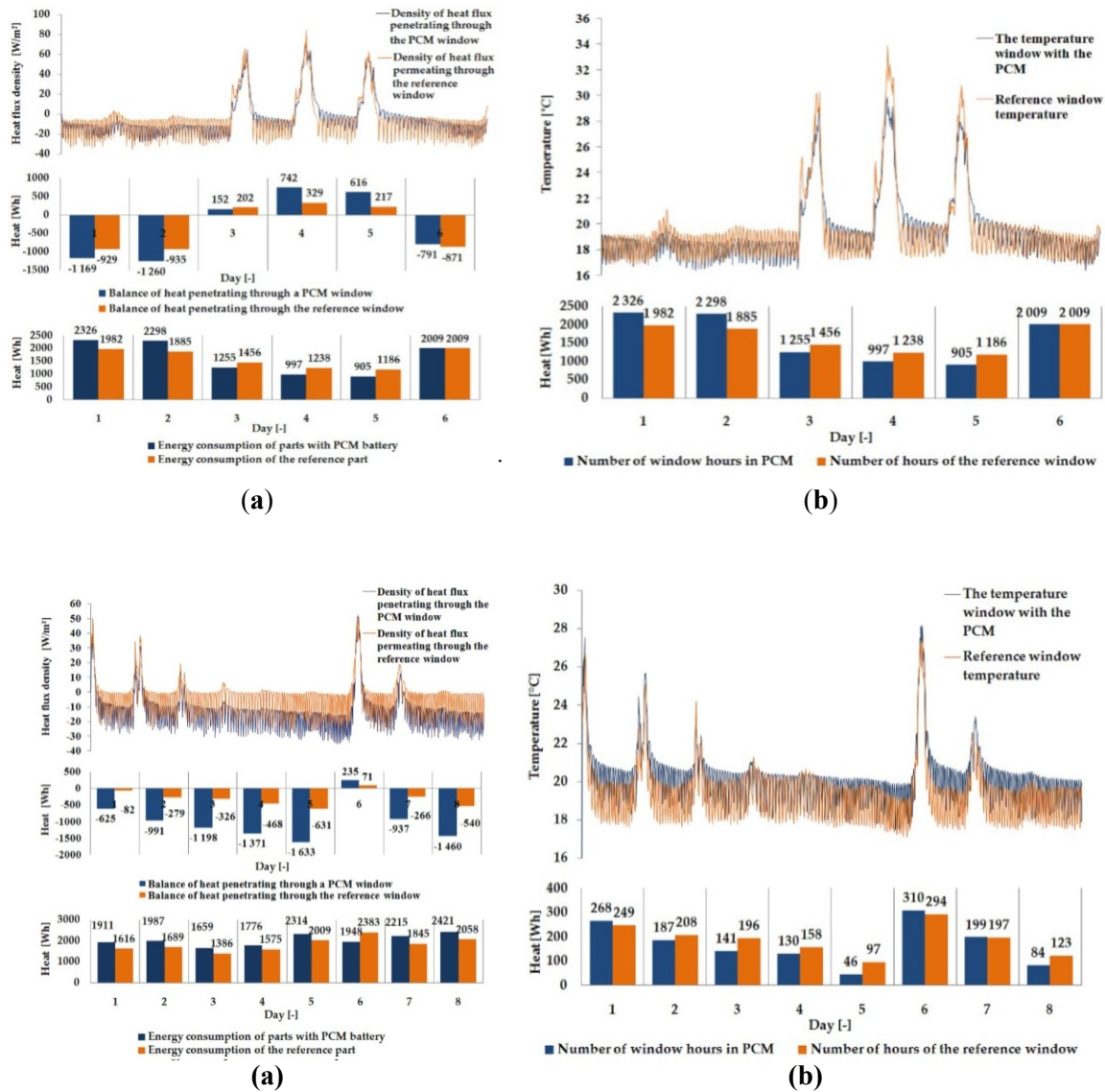


Figure 4.. Thermal functioning of the window with an external triple glazing unit and an internal double glazing unit. **(a)** Graph of heat flux density values recorded on the inner surface of the glazing unit with the PCM and the reference window.. **(b)** Graph of temperature values recorded on the inner surface of the PCM glazing unit part and the reference window.

The simulation results prove that except for one case (window with a triple external glazing unit and single internal glazing unit in October) each month, each combination of glazing with a variable phase heat accumulator generated greater heat loss than their reference windows. However, in most cases the values of losses generated exceeded the values of profits generated. This adversely affected the values of the average monthly heat balances of PCM-modified windows relative to reference ones. Analyzing the data contained in Figure 22, we can see the more favourable monthly values for heat balance with PCM-modified windows compared to reference windows in spring and autumn, for example in October, March, and April. This clearly proves the thermal benefits resulting

from the application of the considered solution on a monthly basis, and also when considering locations with a warmer climate on a seasonal basis.

4. Discussion

Comprehensive, extensive all-season field tests in a large-scale isothermal chamber with 6 different combinations of building window glazing units allowed clear evidence to be obtained of the improved thermal performance of composite windows with a phase change heat accumulator. The presented results of the experimental studies have proven the impacts of using a phase change heat accumulator on the thermal efficiency of a composite window. The above function was proved via both the temperature and density of the heat flux recorded on the inner surface of the glazing, as well as the recorded energy consumption for heating both parts of the field testing chamber.

There was a decrease in PCM glazing peak temperatures and a time shift in the charts for the recorded temperature and heat flux density during sunny days for each of the combinations tested. Nevertheless, the PCM heat accumulator was not subject to the thermal functioning of the composite window during cloudy days and contributed to the increase of the window heat loss. This allowed exclusion of some climate zones as being economically unjustified in terms of applying the tested solution.

The presented mathematical model, implemented on the basis of non-stationary heat flow equations of the finite difference method and taking into account complex heat exchange, underwent verification of its statistical adequacy through the F (Snedecor) test, using experimental data for 4 out of 6 tested glazing combinations. The two cases that did not meet the conditions of the null hypothesis and the alternative test were the combinations of single and double glazing units with high thermal diffusivity. For these and similar cases, better-matched models should be developed using non-simplified thermodynamics and fluid mechanics equations.

The positively verified combinations of glazing units can be successfully used to conduct analyses of the impacts of the tested solutions on a window's thermal balance in various climatic conditions due to the very good matching of empirical and theoretical results, as evidenced by the close unity of the values obtained for direction and determination coefficients and the quasi-Newton analysis of fit. The results of the analysis conducted on the basis of data from a typical meteorological year for the climate of Rzeszów (Poland) prove that in the considered location the tested solution causes a decrease in the heat balance of the entire heating season.

An improvement in the adjustment of heat gains from solar radiation to the heat demand profile of the internal glazing of the PCM window was recorded in comparison with the reference window for the combination of an external triple glazing unit and internal single glazing unit.

In terms of the entire heating season, the smallest reduction in the heat balance of the PCM window relative to the reference window was noted for the combination of an external triple glazing unit and internal double glazing unit. In turn, the largest decrease was noted with the combination of an external double glazing unit and internal triple glazing unit.

The above facts are a result of the nature of the climate in question, where there are approximately 100 sunny days a year on average. Therefore, in order to improve the heat balance of the window, this solution with the proposed phase change material should be used in a slightly warmer climate, e.g., moderate warm or Mediterranean. The above empirical and theoretical results, as well as the analyses carried out and the cognitive values, have enabled the creation of a tool that can be used in the design of new buildings and in thermomodernization of existing ones.

5. Conclusions

The implementation and dissemination of the tested solution has a chance of success due to rising energy prices and the increase in ecological awareness of societies. While the prices of organic phase change materials have dropped significantly compared to recent years, technological problems related to the effective application of PCM in the accumulator need to be solved. Another aspect that requires additional research is the increase in the intensity of charging and heat reception from the accumulator over time. An advantage of the proposed solution is the easy and relatively inexpensive modernization of the windows of existing buildings by installing additional glazing on the inside of the window and an accumulator with a PCM in the space created between the panes. The next steps in the implementation of this solution should be the development of an inexpensive modular system for installing a heat accumulator, with the lower part being thermally insulated. In addition, software should be made available to companies producing windows so that at the design stage this solution, along with information about the thermal and financial benefits associated with its application, can be offered to potential buyers.

6. Patents

1. Lichołai L., Musiał M., Szyszka J. Mobile window insulation nr: EP.15461528.0 from 04.05.2015.
2. Musiał M. Phase-change material and method of producing phase-change material nr: P.425190 from 12.04.2018.

Author Contributions: Conceptualization, M.M. and L.L.; methodology, M.M. and L.L.; validation, M.M.; formal analysis, M.M.; investigation, M.M. and L.L.; resources, M.M.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, M.M.; visualization, M.M.; supervision, L.L.; project administration, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We are grateful to the General Building Department, Rzeszow University of Technology for providing research equipment.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jachimowicz, L. Xenophon Socratic Letters. Memories of Socrates; Translation from the Greek original; Polish scientific publisher: Warsaw, Poland, 1967; pp. 22–78. (In Polish)
2. Wehle-Strzelecka, S. Development of solar energy gaining concept in architectural and urban solutions: First generation of solar architecture. *Tech. Transac. Arch.* **2008**, *7*, 149–185. (In Polish)
3. Czarnecki, L.; Kapron, M.; Piasecki, M.; Wall, S. Sustainable construction means construction of future. *Eng. Const.* **2012**, *68*, 18–21. (In Polish)
4. Pawłowski, A.; Pawłowski, L. Sustainable Development in Contemporary Civilisation. Part 1: The Environment and Sustainable Development. *Prob. Sustainab. Develop.* **2008**, *3*, 53–65. (In Polish)
5. Pos. 926 Amending the Regulation on the Technical Conditions to be Met by Buildings and Their Location; Regulation of the Minister of Transport, Construction and Maritime Economy: Warsaw, Poland, 2013. (In Polish)

6. Smolec, W. Photothermal Solar Energy Conversion; Polish Scientific Publisher: Warsaw, Poland, 2000. (In Polish)
7. Chwieduk, D. Solar Energy Building; Arkady: Warsaw, Poland, 2011. (In Polish)
8. Klemm, P. General Construction 2. Building Physics; Arkady: Warsaw, Poland, 2005. (In Polish)
9. Dylla, A. Buildings' Thermal Physics in Practice; Polish scientific publisher: Warsaw, Poland, 2015. (In Polish)
10. Chwieduk, D.; Jaworski, M. Renewable Energy in Construction. Heat Storage; Polish scientific publisher: Warsaw, Poland, 2018. (In Polish)
11. Vogel, A.I. Organic Preparation; Polish scientific publisher: Warsaw, Poland, 2006. (In Polish)
12. Busico, V.; Cafagna, C.; Salerno, V.; Vacatello, M.; Fittipaldi, F. The layer perovskites as thermal energy storage systems. *Sol. Energy* **1980**, 24, 575. [[CrossRef](#)]
13. Benson, D.K.; Burrows, R.W.; Webb, J.B. Solid state phase transitions in pentaerythriol and related polyhydric alcohols. *Sol. Energy Mater.* **1986**, 13, 133–152. [[CrossRef](#)]
14. Memon, S.A. Phase change materials integrated in building walls: A state of the art review. *Renew. Sustain. Energy Rev.* **2014**, 31, 870–906. [[CrossRef](#)]
15. Zalba, B.; Marin, J.M.; Cabeza, L.F.; Mehling, H. Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications. *Appl. Therm. Eng.* **2003**, 23, 251–283. [[CrossRef](#)]
16. Farid, M.; Khudhair, A.M.; Razack, S.A.K.; Al-Hallaj, S. A review on phase change energy storage: Materials and applications. *Energy Convers. Manag.* **2004**, 45, 1597–1615. [[CrossRef](#)]
17. Zhou, D.; Zhao, C.; Tian, Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. *Appl. Energy* **2012**, 92, 593–605. [[CrossRef](#)]
18. Rodriguez-Ubinas, E.; Valero, L.R.; Vega, S.; Neila, J. Applications of Phase Change Material in highly energy-efficient houses. *Energy Build.* **2012**, 50, 49–62. [[CrossRef](#)]
19. Licholai, L.; Musiał, M. Use of copolymers of vinyl acetate and alkyl acrylates for coating organic phase change materials. *Przem. Chem.* **2018**, 97, 1852. [[CrossRef](#)]
20. Pigoń, K.; Ruzewicz, Z. Physical Chemistry Part 1; Polish scientific publisher: Warsaw, Poland, 1993. (In Polish)
21. Lane, G.A. Solar Heat Storage; Latent Heat Materials; CRC Press: Boca Raton, FL, USA, 1983. [[CrossRef](#)]
22. Schröder, J.; Gawron, K. Latent Heat Storage. *Int. J. Energy Res.* **1981**, 5, 103. [[CrossRef](#)]
23. Tyagi, V.; Buddhi, D. PCM thermal storage in buildings: A state of art. *Renew. Sustain. Energy Rev.* **2007**, 11, 1146–1166. [[CrossRef](#)]
24. Kenisarin, M.; Mahkamov, K. Solar energy storage using phase change materials. *Renew. Sustain. Energy Rev.* **2007**, 11, 1913–1965. [[CrossRef](#)]
25. Zhang, Y.; Zhou, G.; Lin, K.; Zhang, Q.; Di, H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Build. Environ.* **2007**, 42, 2197–2209. [[CrossRef](#)]
26. Sharma, A.; Tyagi, V.; Chen, C.; Buddhi, D. Review on thermal energy storage with phase change materials and applications. *Renew. Sustain. Energy Rev.* **2009**, 13, 318–345. [[CrossRef](#)]
27. Musiał, M. Use of organic aliphatic esters to obtain an energy-efficient eutectic mixture. *Przem. Chem.* **2018**, 97, 1855. [[CrossRef](#)]
28. Musiał, M. Phase-Change Material and Method of Producing Phase-Change Material. PL Patent Application No. P.425,190, 12 April 2018.

29. Dalenbäck, J.O.; Tech, L. The Sáro Projekt: A solar heating plant with seasonal storage. In *Energy Conservation in Buildings*; University of Reading: Reading, UK, 1990; pp. 254–259. [[CrossRef](#)]
30. Bankston, C.A. *The Status and Potential of Central Solar Heating Plants with Seasonal Storage*; American Solar Energy Society: Boulder, CO, USA, 1986.
31. Lin, W.; Huang, R.; Fang, X.; Zhang, Z. Improvement of thermal performance of novel heat exchanger with latent heat storage. *Int. J. Heat Mass Transf.* **2019**, *140*, 877–885. [[CrossRef](#)]
32. Ardahaie, S.S.; Hosseini, M.; Ranjbar, A.; Rahimi, M. Energy storage in latent heat storage of a solar thermal system using a novel flat spiral tube heat exchanger. *Appl. Therm. Eng.* **2019**, *159*, 113900. [[CrossRef](#)]
33. Taler, D.; Dzierwa, P.; Trojan, M.; Sacharczuk, J.; Kaczmarek, K.; Taler, J. Numerical modeling of transient heat transfer in heat storage unit with channel structure. *Appl. Therm. Eng.* **2019**, *149*, 841–853. [[CrossRef](#)]
34. Soares, N.; Costa, J.J.; Gaspar, A.R.; Santos, P. Review of passive PCM latent heat thermal energy storage systems towards building's energy efficiency. *Energy Build.* **2013**, *59*, 82–103. [[CrossRef](#)]
35. Vigna, I.; Bianco, L.; Goia, F.; Serra, V. Phase Change Materials in Transparent Building Envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) Analysis. *Energies* **2018**, *11*, 111. [[CrossRef](#)]
36. Hu, Y.; Heiselberg, P.K. A new ventilated window with PCM heat exchanger—Performance analysis and design optimization. *Energy Build.* **2018**, *169*, 185–194. [[CrossRef](#)]
37. Weinläder, H.; Beck, A.; Fricke, J. PCM-facade-panel for daylighting and room heating. *Sol. Energy* **2005**, *78*, 177–186. [[CrossRef](#)]
38. Li, S.; Zou, K.; Sun, G.; Zhang, X. Simulation research on the dynamic thermal performance of a novel triple-glazed window filled with PCM. *Sustain. Cities Soc.* **2018**, *40*, 266–273. [[CrossRef](#)]
39. Li, D.; Wu, Y.; Liu, C.; Zhang, G.; Arıcı, M. Numerical investigation of thermal and optical performance of window units filled with nanoparticle enhanced PCM. *Int. J. Heat Mass Transf.* **2018**, *125*, 1321–1332. [[CrossRef](#)]
40. Musiał, M. Analysis of the impact of selected factors on the effectiveness of using PCM in mobile window insulation. *E3S Web Conf.* **2018**, *49*, 00073. [[CrossRef](#)]
41. Musiał, M. Evaluation of the energy efficiency of an internal blind containing PCM. *E3S Web Conf.* **2018**, *49*, 00074. [[CrossRef](#)]
42. Lichołaj, L.; Musiał, M.; Szyszka, J. International Patent Application. PL Patent Application No. P.15461528.0, 4 May 2015.
43. Mehling, H. Strategic project 'Innovative PCM-Technology'—Results and future perspectives. In *Proceedings of the 8th Expert Meeting and Workshop*, Kizkalesi, Turkey, 18–25 April 2005; pp. 18–20.
44. Weinlaeder, H.; Koerner, W.; Heidenfelder, M. Monitoring results of an interior sun protection system with integrated latent heat storage. *Energy Build.* **2011**, *43*, 2468–2475. [[CrossRef](#)]
45. Li, Y.; Darkwa, J.; Kokogiannakis, G.; Su, W. Phase change material blind system for double skin façade integration: System development and thermal performance evaluation. *Appl. Energy* **2019**, *252*, 113376. [[CrossRef](#)]
46. Bontemps, A.; Ahmad, M.; Johannes, K.; Sallee, H. Experimental and modelling study of twin cells with latent heat storage walls. *Energy Build.* **2011**, *43*, 2456–2461. [[CrossRef](#)]

47. Jaworski, M.; Abeid, S. Thermal conductivity of gypsum with incorporated phase change material (PCM) for building applications. *J. Power Technol.* **2011**, *91*, 49–53.
48. Wnuk, R.; Jaworski, M. Investigation of thermal characteristics of heat accumulating building elements containing PCM (phase change materials). *Polish Solar Energy* **2010**, *2*, 5–11. (In Polish)
49. Cabeza, L.F.; Castellón, C.; Nogués, M.; Medrano, M.; Leppers, R.; Zubillaga, O. Use of microencapsulated PCM in concrete walls for energy savings. *Energy Build.* **2007**, *39*, 113–119. [[CrossRef](#)]
50. Cabeza, L.F.; Medrano, M.; Castellón, C.; Castell, A.; Solé, C.; Roca, J.; Nogués, M. Thermal energy storage with phase change materials in building envelopes. *Contrib. Sci.* **2007**, *3*, 501–510. [[CrossRef](#)]
51. Zhu, N.; Wang, S.; Xu, X.; Ma, Z. A simplified dynamic model of building structures integrated with shaped-stabilized phase change materials. *Int. J. Therm. Sci.* **2010**, *49*, 1722–1731. [[CrossRef](#)]
52. Xiao, M.; Feng, B.; Gong, K. Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity. *Energy Convers. Manag.* **2002**, *43*, 103–108. [[CrossRef](#)]
53. Sarı, A. Form-stable paraffin/high density polyethylene composites as solid–liquid phase change material for thermal energy storage: Preparation and thermal properties. *Energy Convers. Manag.* **2004**, *45*, 2033–2042. [[CrossRef](#)]
54. Xiao, M.; Feng, B.; Gong, K. Thermal performance of a high conductive shape-stabilized thermal storage material. *Sol. Energy Mater. Sol. Cells* **2001**, *69*, 293–296. [[CrossRef](#)]
55. Zhou, G.; Yang, Y.; Xu, H. Energy performance of a hybrid space-cooling system in an office building using SSPCM thermal storage and night ventilation. *Sol. Energy* **2011**, *85*, 477–485. [[CrossRef](#)]
56. Musiał, M. Analysis of the impact of PCM elements' geometry on their heat storage efficiency. *Bauphysik* **2019**, *6*, 324–330. [[CrossRef](#)]
57. Charach, C.; Zarmi, Y.; Zemel, A. Simple Method for Assessing the Thermal Performance of PCM Panels; Biennial Congress of the International Solar Energy Society: Hamburg, Germany, 1987. [[CrossRef](#)]
58. Taler, J.; Duda, P. Solving Simple and Inverse Heat Conduction Problems; Scientific and Technical Publishing House: Warsaw, Poland, 2006. (In Polish)
59. Zastawna-Rumin, A.; Kisilewicz, T.; Berardi, U. Novel Simulation Algorithm for Modeling the Hysteresis of Phase Change Materials. *Energies* **2020**, *13*, 1200. [[CrossRef](#)]
60. Heim, D.; Mrowiec, A.; Prałat, K. Determination of heat conductivity of liquid organic acids by the hot wire method. *Chem. Eng. Equipm.* **2010**, *49*, 51–52. (In Polish)
61. Pogorzelski, J.A. Building Thermal Physics; Polish scientific publisher: Warsaw, Poland, 1976. (In Polish)