AMERICAN JOURNAL OF
MATERIALS AND
NANOTECHNOLOGY

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

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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 DH 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. Resarch 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).

$$t{=}n$$

$$Q_{window} = {}^{z} \quad t{=}1 \;\; q_t dt \qquad (1)$$

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.

$$t{=}n \quad x_t$$

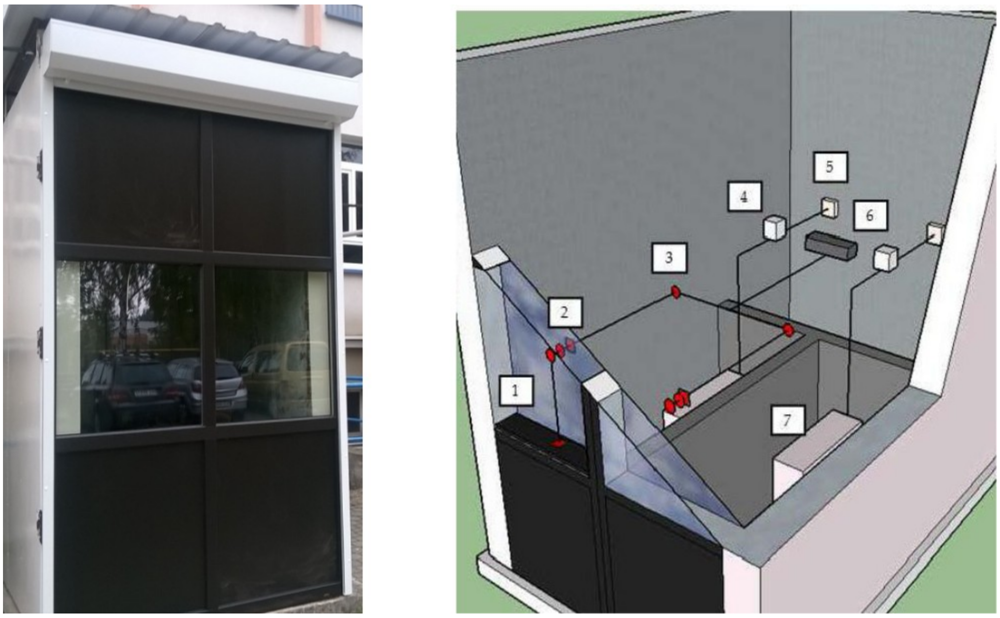
$$S_{th} = \quad (T_1 \quad T_0) \qquad (2)$$

$$=1$$

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.



(**a**) (**b**)

FigureFigure1. **1**(**a.**)(**a**Photograph)ofofthe isothermalfieldfieldtestingchamber.(**b**.)(Diagram**b**)Diagramoftheoffieldthe testingfieldtestingchamber: chamber:(1)heat (1)accumulator;heataccumulator;(2)heatmeter(2) heatwith thermocouple;meterwiththermocouple; (3)temperature(3)sensor;temperature(4)thermoregulator;sensor;(4) (5) thermoregulator;energyconsumption(5)energymeter;consumption(6)recorder;meter; (7)oil(6)heaterrecorder;. (7) oil heater.

AsAspartpartof theofthedescribedtests,esthes,thermalthermalfunctionsof 6ofcombinations6of glazingofglazingunitsunitsin ainwindowawindow withwithphasephasechangeschangesand andreferencereferencematerialsmaterialswere testedwere.testedTheparameters.Theparametersofallglazingofallunitsglazingusedunitsduringused theduringtestsarethegiventestsinareTablegiven1. TheinTabletesting1.Thofeachtestingcombinationofeachcombinationlastedbetweenlasted1andbetween1. 5months1and. 1.5 months.

TableTable1. List**1.**Listof glazingofglazingparametersusedusedduringduringteststests..

Parameter **Parameter**	**Single** **Single Glazing** **Glazing**	**DoubleGlazing** **Unit** **Unit**	**TripleGlazing** **Unit** **Unit**
Heat transfer coefficient (W/m2 K)	5	1.1	0.7
Heat transfer coefficient Transmittance (-)	0.82	0.75	0.5
Light	5	1.1	0.7
permeability2 (-)	0.89	0.78	0.6
(W/m ·K) Construction of glazing unit (mm)	/4/	/4/16 Ar/4/	/4/16Ar/4/16 Ar/4/

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

ConstructionTheconductedofglazingexperimentsunit allowed the creation of a database that was used to validate and

/4/ /4/16 Ar/4/ /4/16Ar/4/16 Ar/4/

verify the mathematical(mm) 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

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

any outdoor climate conditions.

verify the mathematical model. This will be a useful tool in determining the potential thermal gains associated2.5.Mathematicalwiththe applicationModel 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 2.5method.Mathematical.ThemodelModel 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 A model was made using equations of non-stationary heat flow and an explicit finite difference accumulator, while the other part describes two-dimensional heat flow and storage in a phase change method. 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

-

dimensional

accumulator, while the other part describes T^tT^t heatT flowTt and storage in a phase change heat

two

T^{t+1} = D B 1 2 + 3 2 C + T^t (3)

time interval lengths are presented below:

accumulator. The general heat flow formulas$_{Cw2}$and$_2$

^{0}B R_1 2 ^{R}2 3 1 C

2 B C2

1-2 Δ % 1 is the density at point

where is the Dt time interval, C_{w2} is t~~he~~ @ A 2(3)

~~spee~~

.

2, R is the heat resistance between points 1 and 2, and T^t is the temperature at point 1 during t.

where is the Δt time interval, $Cw2$ is the specific heat of the material at point 2, $\varrho 2$ is the density at point 2, $R1\text{-}2$ is the heat resistance between points 1 and 2, and $Tt1$ is the temperature at point 1 during t.

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:

$$T^{t+1}_{PCM.2,2} = \frac{\Delta t}{c_{eff}\,\rho_{PCM}}\left(\frac{T^{t}_{PCM.1,2}-T^{t}_{PCM.2,2}}{R_{1,2-2,2}} + \frac{T^{t}_{PCM.3,2}-T^{t}_{PCM.2,2}}{R_{3,2-2,2}}\right) + T^{t}_{PCM.2,2} \qquad (4)$$

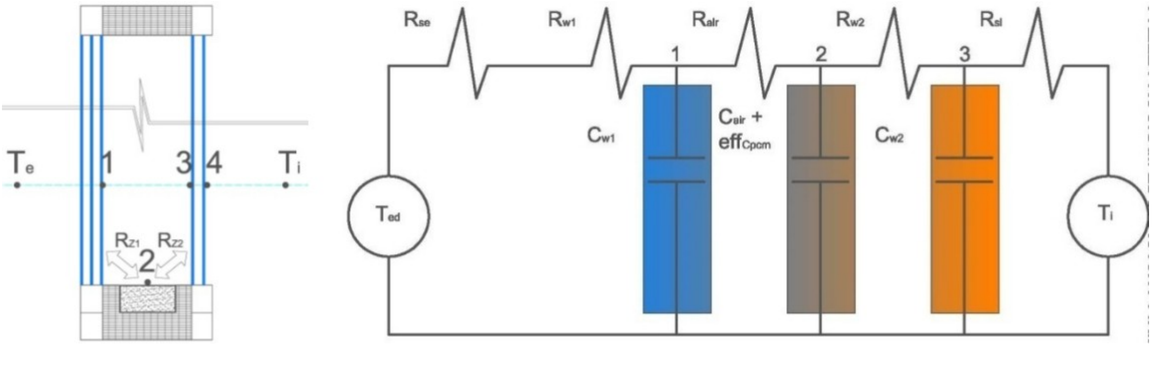
where Δt is the time interval, c_{eff} is the specific heat of the PCM, ρ_{PCM} is the density PCM, and $R_{1,2-2,2}$ are the heat-resistant PCM values between points 1,2 and 2,2.

$T^{t}_{2,2}$ temperature PCM at point 2,2 during t

$$\Delta t \le \min\left[\frac{\Delta x_i^2\, c_{w,i}\,\rho_i}{2\lambda_i}\right] \qquad (5)$$

where Δx_i^2 is the square of the element thickness i, $c_{w,i}$ is the specific heat of the material at i, ρ_i is the density at point I, and λ_i is the heat transfer coefficient i.

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



(a) (b)

Figure 2.. ((**aa**)) Graphical diagram ofof 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 ofofheatandsolarradiationthroughacompositeawindowwindowisa iscomplexacomplexissueissuethat thathas beenhas beendealt dealtwith inwithnumerousinnumerousscientificscientificpaperspapers[6–10,49[6–5110,49].When–51]. Whencreatingcreatingthispartthisof partthemodel,ofthe modecompl,excomplheat**exch**angeeatexchangebyconduction,byconduction,convection,convection,a ndradiationand betweenradiationa betweenwindow’sa individualwindow’s individualglazingwasglazingtaken wasintotakenaccountinto. accountTheessence.The essenceofthesolutionofthesolutiontothis toproblemthisproblemistodetermineistodeterminetwo twocomplexcomplexheat heattransfertransferresistancesresistancesbetweenbetweentheexttheexternalglazingglazingand theandPCMthePCMaccumulatoraccumulator(R_{Z1}),(RandZ1), andbetweenbetweenthe PCMthePCMaccum**u**mulatorandandthetheinternalglazing(R(R_{Z2}Z2).)These.complexheat resistances **are** **temp**erature functionsthattaketakeintointoaccountaccountheatheattransfertransferbyconvectionbyconvection$q_k$and qkradiationandradiationq.Theqabovr.The abovethermophysicalthermophysicalphenomenaphenomenawereconsideredwereconsideredinaccord anceinaccordancewiththewithrelationshipstherelationde**s**cribedhipsdescribedin[61]. in [61].

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

(6)

$$(t_1 \quad t_2)$$

q = (7)

k d (7)

r r 1 2 (8)

$q = h\ (t \quad t\ )$ (8)

h

where qz is the heat ^{flux}flux density transmitted by radiation and convection, qk is the heat flux^{flux} density

z k

transmitted by convection, and qr is the flux^{flux} density transmitted by radiation.

r

Performing formula substitutions and transformations for Equations (6), (7), and (8), Equation (9) was obtained in accordance with [61]:

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

Using the Jacob formula described by Pogorzelski in [61], the values of the substitute heat transfer coefficient for fluids r were determined:

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

Grashof's probability number is:

$$\frac{r}{} = 1 \text{ for } Gr < 10^3$$

$$_r = 18 \; 10^{2} (Gr)\, 4^{\frac{1}{}} \frac{1}{9}\; H \text{ for } 2 \; 10^{4} < Gr < 2 \; 10^{5} \qquad (11)$$

$$r = 65 \; 10 \; 33^{\frac{1}{}} (Gr) \frac{1}{\underline{H}^{9}} \text{ for } 2 \; 10^{5} < Gr < 11 \; 10^{6}$$

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

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

$$Gr = \frac{g \; l^3 \, DT}{v^2} \qquad (12)$$

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

where is the air thermal expansion coefficient, g is the gravitational acceleration, v is the kinetic coefficient of the air viscosity, a is the temperature equalization coefficient, and DT 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):

$$h_r = \frac{q_1 \; 2}{T_1 \; T_2} = 12\, C_0 \; \frac{1}{\;} \; 2 \; \frac{\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4}{T_1 \quad T_2} \qquad (14)$$

4 5

where C_0 is the black body radiation factor, " $_{1\text{-}2}$ is the replacement emissivity, and ' $_{1\text{-}2}$ 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 $"_{1\ 2}$ and the angular radiation factor $'_{1\text{-}2}$ were determined in accordance with Equations (15) and (16):

$$"_{1\ 2} = \frac{1}{\frac{1}{"_1} + \frac{F_1}{F_2}\left(\frac{1}{"_2}\ 1\right)} \qquad (15)$$

$$'_{1\,2} = \frac{1}{F_1} \mathbf{Z}_{F_1} \mathbf{Z}_{F_2} \frac{\cos\ N\ {}^{N}\cos\ 1}{R^2}\, 2\, dF_1 dF_2 \qquad (16)$$

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].

m_s $^{C}W.S$ $(T_L$ $T_0)$ f or T>T_L
DH
^{eff}C.PCM = D^{H}PCM = **8** $m_{L\ L}$ f or T=T_L (17)
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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*inquestion**2020**, *13*consisted,x of 200 elements (grid dimensions: 50 mm 100 mm). In addition, the extreme8of22 nodes of the discussed cross-section were modelled as the aluminium side of the accumulator, taking The functions of the change of PCM mass enthalpy during *HPCM* phase transformation over time

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 The emp rical 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 int rnal glazing, are summarized below in the form of line and bar charts into account the resistance and heat capacity of the aluminium alloy used in the field tests. (Figures 3–8). This allows observation of bo h 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

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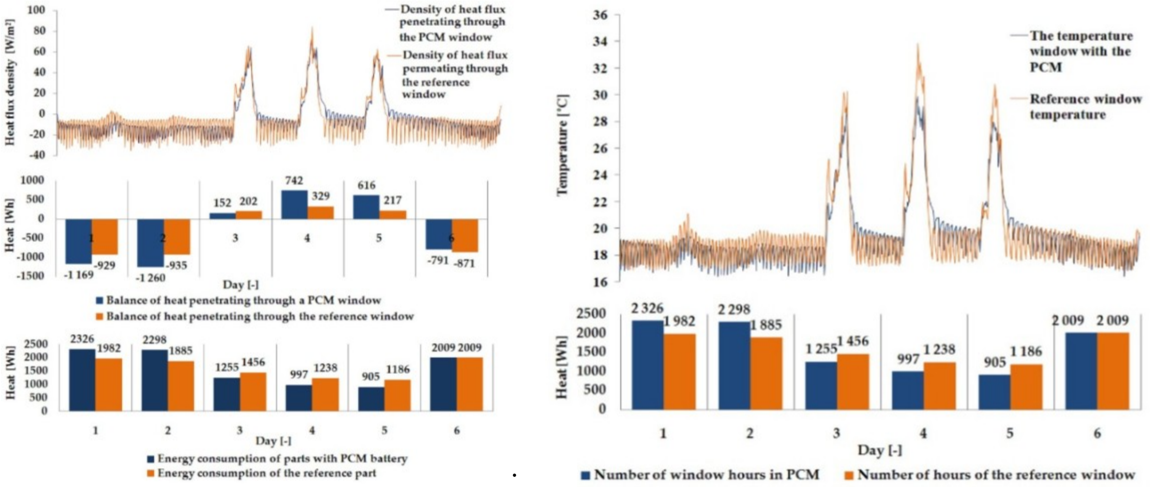
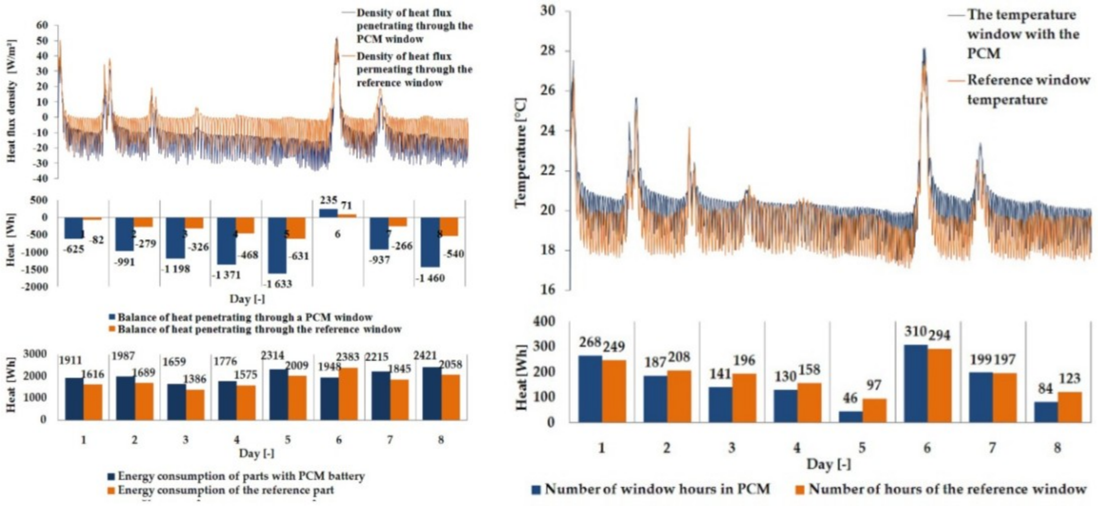
totals.



(a) (b)



(a) (b)

Figure 4.. Thermal functioning of the window with an external triple glazing unit and an internal double glazing unit. (**a**) Graph of heat **flux**flux density values recordedded on the inner surface of **the** glazingzing unit with **the PCM and the** referencece 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

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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.

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