Analysis of the impact of selected factors on the effectiveness of using PCM in mobile window insulation

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Abstract. This article presents the results of experimental research, carried out on the elements of vertical and internal blinds, containing phase-change material in its. The research was aimed at determining the significance of such factors as: ambient temperature, shape of profiles containing PCM and the intensity of their heating to the actual amount of energy required for complete melting of PCM Samples of aluminum profiles of various cross-sectional shapes containing commercial RT 28 phase-changing material. The author carried out the research presented below on the basis of a poly-selective orthogonal plan. The analysis was performed using the finite element method, in the Statistica 12 program. The obtained effects of the performed tests and the conducted analysis enabled an independent statistical evaluation of the factors of the approximate polynomial.

1 Introduction

In recent years, a noticeable trend in construction has been the desire to reduce the cost of thermal functioning of buildings. The elements of the thermal housing of the building, which may cause an increase in the above costs, are transparent partitions. These partitions, due to their nature, may cause overheating adjoining rooms in the summer and their overcooling in the winter. One of the possibilities to improve the energy efficiency of transparent partitions may be installing blinds or roller shutters containing phase change material.

The effectiveness of this solution will depend on the properties of the contained PCM, the thermal conditions prevailing in the surroundings of PCM, and the material parameters of the blinds and their shape.

The following is a paper in which the authors used phase change materials to improve the energy efficiency of transparent partitions.

In [1] Safari et al., The results of the simulation of the phase change temperatures depending on the climate in which PCM is to operate are presented. The above simulation refers to the range of thermal comfort 19–26°C, described in more detail in [2–3]. The presented results indicate that in the case of the desire not to overheat the rooms, the

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most effective are PCMs with melting points of 24–28°C. In turn, to counteract overcooling of rooms, PCMs should be used, which solidify at temperatures of 18–22°C.

Liu et al. [4] conducted research on a roof window with one-chamber glazing in which phase-change material was applied between the panes. Modification of the window, provided its translucency and changed the physical and thermal properties. Researchers observed a phase shift in diurnal temperature changes compared to the reference window. In turn, no significant changes were observed in the values of the internal air temperature, through the use of PCM in the window construction.

In [5] Bianco, Vigna and Serra presented the results of experimental research conducted at the field tests stand in Turin. They tested polycarbonate panels, chamber, filled with polycarbonate bubbles, each polycarbonate bubble was filled with phase-changing materials (salt hydrates and mixtures of paraffins). After the tests, the authors indicated a reduction in the amount of solar radiation passing through the chambers by 40% in relation to the reference stands, a reduction in the peak temperature by 4–5°C and a 3 hour delay in the direction of the heat flux through the transparent partition after sunset.

Liu, Wu, Li, Zhou, Wang and Liu, in paper [6] presented the results of numerical and field tests needed to validate the above model. The study was subjected to a chamber window, double-glazed. The window was modified by selected phase-change materials with melting ranges of 14–16°C, 16–18°C, 18–20°C, used different thicknesses of PCM (4–50 mm). The research was carried out during the heating season in north-eastern China. The obtained results allowed the selection of the most favorable combinations of PCM layer thickness (12–30 mm) and melting temperature 14–16°C for the considered location. The authors also indicate the scope of applicability of the obtained model, related to limiting the transmissiveness of transparent partitions with larger PCM thicknesses. This is also related to the poorer use of the PCM applied, due to the fact that fewer of it undergo a phase transformation.

The results presented by Li, Sun, Zou and Zhang in [7] present experimental research on a three-layer, two-chamber window, containing phase-changing material in the inner, and in the outer space between the panes. In addition, parallel testing of reference windows was carried out. The presented results, as in works [5, 6], confirm the lowering of the peak temperatures of glazing in the summer season and the limitation of the amount of heat flux transmitted through the glazing to the adjacent room. The authors of the considered configuration noted a decrease by 2.7°C and 5.4°C temperature of the inner surface of glass in the summer season and to reduce the heat flux density penetrating respectively 16.7% and 28%.

Most of the scientific papers describing the thermal work of PCMs cooperating with transparent partitions refer only to the modernization of glass packages. It is also possible to effectively use the thermal capacity of phase-change materials, for example in internal window blinds. In papers [8–9] the author presented the results of field testing of mobile window insulation, which is the subject of patent application EP.15461528.0. In the above solution, one side of the blind was covered with black matte paint to increase the absorption capacity of solar energy. The author, being aware of the influence of: the shape of aluminum profiles, containing PCM, the intensity of their heating and thermal conditions occurring in the vicinity of the profiles, the actual amount of energy needed to completely melt the PCM used, decided to conduct laboratory tests to determine the relationship between the above-mentioned sizes. In order to reduce costs and shorten the research time, it was decided to perform them in accordance with the incomplete experience plan. This plan and statistical analysis were also used in the work [10–12]. The author, guided by the criteria of implementation, information and efficiency, decided on the choice of the poly-selective plan, orthogonal, described in more detail in [13].

2 Materials and Method

2.1 Phase-change material

As part of these studies, commercial phase change material RT 28 (paraffin mixture) was used, manufactured by Rubiterm GmbH, with a melting and solidification enthalpy value between $\Delta H_{\text{fus}} = 220\text{--}225 \text{ J/g}$, melting point = 28°C and freezing point = 21°C

2.2 Aluminum samples

For making samples, 25 cm sections of aluminum pipe with a wall thickness of 2 mm and an outside diameter of 40 mm were used. We made ten samples, two times for two samples with the following ratio of the length of the ellipse axis :1.00; 0.910; 0.500; 0.393; 0.089.

To protect samples from loss of PCM, each of them was sealed from the bottom with epoxy resin Epidian 6, using hardener Z2.

2.3 Measuring apparatus

- Climatic chamber ESPEC;
- 16-channel recorder, Comet MS6D;
- energy consumption meter Volcraft 4000;
- temperature sensors PT 1000;
- camera Creative HD 720p.

2.4 Research position

The test stand was a climatic chamber, within which there were two identical, cylindrical tanks. In each of the two tanks there were identical electric heaters with a power of 1,000 W, connected to energy consumption meters and thermoregulators as well as samples of aluminum profiles. One of the tanks contained a sample containing phase-changing material, while in the other one an identical, empty reference sample. To monitor the temperature changes of aluminum samples and containers with water, PT 1000 sensors connected to the Comet MS6D recorder were used. In order to monitor and record the degree of phase change occurrence of samples containing PCM, a Creative HD 720p mobile camera was mounted.

The station constructed in this way allowed the author to record the amount of energy needed to keep the container in a constant temperature and melt PCM contained in the sample, and to compare the above value of energy consumed with that registered in the reference container. The difference in the energy consumption values between the PCM container and the reference container was the actual amount of energy needed to completely melt the PCM under the given conditions.

Photographs of the test stand and samples tested are presented in Figures 1–2.

Fig. 1. Photography of laboratory position.

Fig. 2. Photograph of tested aluminum profiles.

2.5 Plan of the research

The poly-selective, orthogonal plan, was made using the STATISTICA 12 program, using the finite element method. The solution of the above plan will be the function of the object with the general formula (1):

$$z = b_0 + b_1x_1 + \dots + b_k \dots x_k + b_{12}x_k \dots x_1x_2 + b_{13}x_1x_3 + \dots + b_{k-1}x_{k-1} + b_{11}x_1^2 + \dots + b_kx_k^2$$

(1)

The above plan was made for the input and output data presented in table 1. The scope of variability of individual input quantities were determined by the author based on the conducted field tests described [8–9].

Table 1. The scope of variability of individual input quantities.

Input value	Output value
air temperature ∈ [12; 20] temperature of water ∈ [30; 60] shape factor ∈ [0.393; 1.0]	Real amount of heat

The minimum number of test systems was determined based on the formula [13], for three input variables ($i = 3$) and one output one was designated as 15 and additionally two reference ones. Table 2 presents standardized and real values of independent variables.

Table 2. Experience plan.

Normed values of independent variables				Actual values of the independent variables			
	Air temp.	Water temp.	shape factor		Air temp.	Water temp.	shape factor
1	-1.00000	-1.00000	-1.00000	1	-1.00000	-1.00000	-1.00000
2	-1.00000	-1.00000	1.00000	2	-1.00000	-1.00000	1.00000
3	-1.00000	1.00000	-1.00000	3	-1.00000	1.00000	-1.00000
4	-1.00000	1.00000	1.00000	4	-1.00000	1.00000	1.00000
5	1.00000	-1.00000	-1.00000	5	1.00000	-1.00000	-1.00000
6	1.00000	-1.00000	1.00000	6	1.00000	-1.00000	1.00000
7	1.00000	1.00000	-1.00000	7	1.00000	1.00000	-1.00000
8	1.00000	1.00000	1.00000	8	1.00000	1.00000	1.00000
9	-1.00000	0.00000	0.00000	9	-1.00000	0.00000	0.00000
10	1.00000	0.00000	0.00000	10	1.00000	0.00000	0.00000
11	0.00000	-1.00000	0.00000	11	0.00000	-1.00000	0.00000
12	0.00000	1.00000	0.00000	12	0.00000	1.00000	0.00000
13	0.00000	0.00000	-1.00000	13	0.00000	0.00000	-1.00000
14	0.00000	0.00000	1.00000	14	0.00000	0.00000	1.00000
15 (C)	0.00000	0.00000	0.00000	15 (C)	0.00000	0.00000	0.00000
16 (C)	0.00000	0.00000	0.00000	16 (C)	0.00000	0.00000	0.00000
17 (C)	0.00000	0.00000	0.00000	17 (C)	0.00000	0.00000	0.00000

3 Results

After performing 17 experimental setups, the obtained results were supplemented with the set experimental plan. The arrangement of the plan along with received results was presented on fig. 3.

	1 Air temp.	2 Water temp.	3 shape factor	4 absorbed heat
1	12.00000	30.00000	0.393000	13
2	12.00000	30.00000	1.000000	59
3	12.00000	60.00000	0.393000	15
4	12.00000	60.00000	1.000000	27
5	20.00000	30.00000	0.393000	14
6	20.00000	30.00000	1.000000	35
7	20.00000	60.00000	0.393000	15
8	20.00000	60.00000	1.000000	37
9	11.58749	45.00000	0.500000	16
10	22.41251	45.00000	0.500000	23
11	17.00000	24.70310	0.500000	19
12	17.00000	65.29690	0.500000	21
13	17.00000	45.00000	0.089326	11
14	17.00000	45.00000	0.910674	39
15	17.00000	45.00000	0.500000	21
16	17.00000	45.00000	0.500000	20
17	17.00000	45.00000	0.500000	21

Fig. 3. Arrangement of the polyselection orthogonal plan supplemented with received results.

The evaluation of effects, individual independent variables and their correlation on the value of the object's function, is presented in Figures 4–5.

	Effect	Standard error	t(2)	p	-95. % Lim. conf.	+95. % Lim. conf.	Factor	Standard error	-95. % Lim. conf.	+95. % Lim. conf.
Aver./const.	26.41552	0.324431	81.4210	0.000151	25.01960	27.81143	26.41552	0.324431	25.01960	27.81143
(1)Air temperature (L)	-0.38437	0.339694	-1.1315	0.375250	-1.84596	1.07721	-0.19219	0.169847	-0.92298	0.53860
Air temperature (Q)	-1.88408	0.439369	-4.2881	0.050314	-3.77453	0.00638	-0.94204	0.219685	-1.88727	0.00319
(2)Water temperature (L)	-5.28973	0.340209	-15.5485	0.004111	-6.75354	-3.82593	-2.64487	0.170105	-3.37677	-1.91297
Water temperature (Q)	-2.51620	0.455056	-5.5294	0.031185	-4.47415	-0.55825	-1.25810	0.227528	-2.23707	-0.27912
(3) shape factor (L)	20.47359	0.278406	73.5385	0.000185	19.27570	21.67147	10.23679	0.139203	9.63785	10.83574
shape factor (Q)	2.13141	0.266253	8.0052	0.015249	0.98582	3.27700	1.06571	0.133126	0.49291	1.63850
1L rel. 2L	8.30620	0.404754	20.5216	0.002365	6.56468	10.04771	4.15310	0.202377	3.28234	5.02385
1L rel. 3L	-4.28663	0.326542	-13.1274	0.005753	-5.69162	-2.88163	-2.14331	0.163271	-2.84581	-1.44082
2L rel. 3L	-7.16005	0.327663	-21.8519	0.002088	-8.56987	-5.75023	-3.58002	0.163831	-4.28493	-2.87511

Fig. 4. Evaluation of the effects of independent variables and their correlation on the value of the output variable.

Fig. 5. Pareto chart for 95% confidence level for independent variables and their correlation.

Based on the results of the analysis presented in Figures 4–5, it was found that two ingredients, Air temperature (Q) and (L), are statically irrelevant to the assumed significance level of 5%. In the next analysis, these components were included in the error component. Next, it was found that the next two components Water temperature (Q) and Shape factor (Q) are below the assumed level of significance. Other statistically significant components of analyzes are presented in Figures 6–7.

	Effect	Standard error	t(2)	p	-95, % Lim. conf.	+95, % Lim. conf.	Factor	Standard error	-95, % Lim. conf.	+95, % Lim. conf.
Aver./const.	26.00757	0.143665	181.0299	0.000031	25.38943	26.62571	26.00757	0.143665	25.38943	26.62571
(2)Water temp. (L)	-5.28973	0.340209	-15.5485	0.004111	-6.75354	-3.82593	-2.64487	0.170105	-3.37677	-1.91297
(3) shape factor (L)	20.00505	0.270349	73.9970	0.000183	18.84183	21.16827	10.00252	0.135175	9.42092	10.58413
1L rel. 2L	8.30620	0.404754	20.5216	0.002366	6.56468	10.04771	4.15310	0.202377	3.28234	5.02385
1L rel. 3L	-4.35195	0.323494	-13.4530	0.005480	-5.74384	-2.96007	-2.17598	0.161747	-2.87192	-1.48003
2L rel. 3L	-7.16005	0.327663	-21.8519	0.002088	-8.56987	-5.75023	-3.58002	0.163831	-4.28493	-2.87511

Fig. 6. Evaluation of the effects of statistically significant independent variables and their correlation on the value of the output variable.

Fig. 7. Pareto chart for statistically significant independent variables and their correlation.

Table 3 presents the answer planes with the function models describing them, made for statistically significant input variables and their correlation.

Table 3. The answer planes.

<div>Chart of absorbed heat from the air and water temperature</div> <div></div> <div>$z=-19,38-0,24\cdot y+0,043\cdot xy-2,93\cdot 0,592471\cdot x-0,94\cdot 0,59\cdot y+75,87$</div>	<div>Chart of absorbed heat from the shape factor and air temperature</div> <div></div> <div>$z=-19,38+128,05\cdot y+0,043\cdot 45\cdot x-2,93\cdot xy-0,94\cdot 45y-10,67$</div>
<div>Chart of absorbed heat from the aspect ratio and temperature of water</div> <div></div> <div>$z=-19,38-0,24x+128,05y+0,043\cdot 16,53x-2,93\cdot 16,53y-0,94xy$</div>	<div>Chart of absorbed heat from air temperature and shape factor</div> <div></div> <div>$z=-19,37+128,05x+0,043\cdot 45y-2,93yx-0,94\cdot 45x-10,67$</div>
<div>Chart of absorbed heat from the air and water temperature</div> <div></div> <div>$z=-19,38-0,24\cdot x+0,042\cdot yx-2,93\cdot 0,59y-0,94\cdot 0,59x+75,87$</div>	<div>Chart of absorbed heat from water temperature and shape factor</div> <div></div> <div>$z=-19,38-0,23y+128,05x+0,043\cdot 16,53y-2,93\cdot 16,53x-0,94yx$</div>

Figure 8 shows the calculated values of pure error, total error and variance for the analysis performed

Figure 9 presents the calculated regression coefficients for individual input variables and their correlation for the conducted analysis

	SS	df	MS	F	p
(2)Water temp. (L)	80,585	1	80,585	241,755	0,004111
(3) shape factor (L)	1825,186	1	1825,186	5475,557	0,000183
1L rel. 2L	140,379	1	140,379	421,136	0,002366
1L rel. 3L	60,327	1	60,327	180,982	0,005480
2L rel. 3L	159,168	1	159,168	477,505	0,002088
Lack adjust	233,917	9	25,991	77,972	0,012725
clear error	0,667	2	0,333		
Total SS	2433,765	16			

Fig. 8. A comparison of the calculated values of pure error, total error and variance for the conducted analysis.

	Regression coefficient	Standard error	t(2)	P	-95, % Lim. conf.	+95, % Lim. conf.
Aver./const.	-19,3767	1,349687	-14,3564	0,004817	-25,1839	-13,5694
(2)Water temp. (L)	-0,2371	0,043630	-5,4348	0,032228	-0,4248	-0,0494
(3) shape factor (L)	128,0528	2,889976	44,3093	0,000509	115,6182	140,4873
1L rel. 2L	0,0425	0,001951	21,7881	0,002100	0,0341	0,0509
1L rel. 3L	-2,9307	0,132497	-22,1190	0,002038	-3,5008	-2,3606
2L rel. 3L	-0,9379	0,042165	-22,2430	0,002015	-1,1193	-0,7565

Fig. 9. List of calculated values of regression coefficients for the conducted analysis.

4 Conclusions

Based on the examinations and analyzes, the author obtained the approximation polynomial formula, describing the relationship between the selected input quantities and the output value. For this polynomial, all independent variables and their statistically significant correlations were determined. Obtained results clearly showed that for the above configuration and given variability intervals, independent variables, the most important variable is the shape factor of aluminum profiles. The results of the above analysis can be used to build more complex models used to describe the thermal functioning of mobile window insulation.

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