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Heat loss through the window frames of buildings

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Abstract. The object of investigation is window frames of buildings since they are critical zones in terms of thermal insulation. It was studied how the properties of window frame affect the change in heat flow and temperature fields. It was analyzed the heat loss that depends on a range of structural features of a window frame, such as geometrical, thermal and physical properties of walls, windows, lintels, and joints. An experiment was designed, computer simulation and laboratory tests were conducted. Eight different types of frame units were analyzed. Their finite-element models in the ELCUD software was developed. The laboratory tests proved the adequacy of finite-element models. The comparative results obtained from tests and numerical models were in consistency. We conducted a full factorial experiment and excluded insignificant factors using statistical analysis. Mathematical models of the joint effect of these factors were developed. A detailed analysis of the join effect of factors on the heat loss through the window frame was performed. The results can be used for the energy classification of buildings in use.

1. Introduction

Attention to ecologically safe and energy-efficient technologies, particularly in the field of construction and design, has increased under the conditions of escalating tensions in the economy of certain regions, which is now a global tendency, and urgent environmental problems related to the emission of oxide compounds, caused by heat and energy production [1–7]. This paper describes a new aspect that makes it possible to reduce energy consumption by reducing heat release into the environment. The research focuses on window frames, which are significant boundary zones related to heat losses.

Window frames are one of the most important elements of a building envelope that are thermally and technically non-uniform. Unlike outer corners, and joints between walls, floors, and ceiling, inner walls can have the lowest temperatures [8–12].

Many researchers [8–14] have proved that it is important to take into account these zones when determining the reduced total thermal resistance. Some researchers [8, 10, 14] point out the most significant factors that affect the heat flow through a window frame unit.

It was established in [14, 15] that the thicker the wall, the greater the extra losses through a window frame. It allows us to conclude that the thickness of thermal insulator and the heat transfer coefficients of wall and insulation materials also affect the heat flow through a window frame unit. If the window frame is moved to the inner wall, heat losses through window frames decrease, but the wall temperature on the inner wall near the window falls [8, 9, 14, 15]. The paper [10] suggests shifting the window frame to the wall center in order to solve the problem of great heat losses through the window frame.

According to the calculations in [14], the location of the window has the following effect on heat losses through window frames: compared to a blind brick wall, there is an increase in heat losses of 18, 14, and 16 %, when the distance between the window frame and the outer wall side is 120, 250, and 380 mm, respectively.

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It was established in [13] that insulation of the inner frame negatively affects thermal and physical properties of the envelope. The window frame remains in the cold zone, and the insulator prevents the window frame from warming. As a result, there is condensation and accumulation of moisture in the insulator. The research confirmed the result described in [13], therefore this factor will not be considered in further studies.

It was established in [12] that if a joint is filled with a more thermally conductive material, the density of the heat flow increases, leading to increased heat losses.

According to [14], the thicker the window frame, the lower extra heat losses through the window frame. It is logical to assume that the coefficient of thermal conductivity of the window profile will also affect the heat flow.

However, the reviewed studies did not consider the joint effect of factors.

This research aims to model the joint effect of structural features of envelope constructions in a window frame zone on thermal insulation. To achieve the goal, we solved the following tasks:

1. determined the factors that affect heat transfer through a window frame;
2. chose a method for studying the joint effect;
3. conducted a screening experiment to exclude insignificant factors;
4. conducted a full factorial experiment;
5. processed the results and verified the adequacy of the developed models;
6. developed software to facilitate the use of these models.

First, we chose the factors that affect heat transfer through a window frame unit. These factors include:

– thickness of the wall and the coefficient of thermal conductivity of wall material;

– thickness of the inner and outer insulator and the coefficient of thermal conductivity of insulator material;

– position of the window frame across the width of the window aperture;

– thickness of the window profile, its material and coefficient of thermal conductivity;

– width of the joint and the coefficient of thermal conductivity of the joint filling;

– size of the heat-insulating insert and the coefficient of thermal conductivity of heat-insulating insert material;

– height of the lintel and the coefficient of thermal conductivity of lintel material (top jamb).

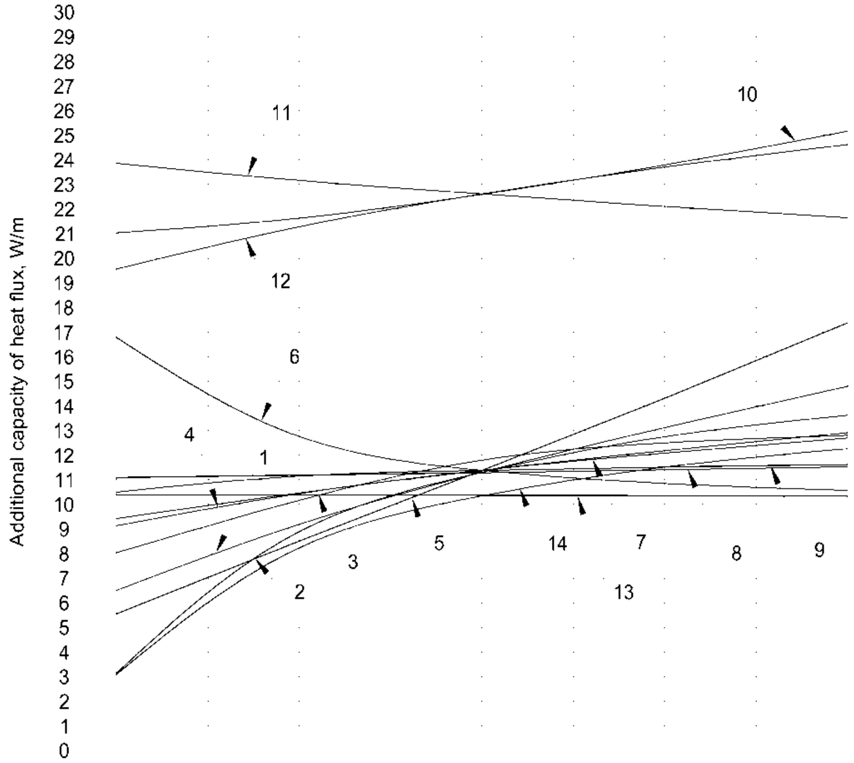
Figure 1 shows the effect of each factor on the value of heat flow through a window frame unit, obtained from the experiment described in the studies [14, 15].

The values of heat flow under varying values ranged from 3.092 W/m to 25.16 W/m. The factor "coefficient of thermal conductivity of lintel material" has the greatest effect (296.6 %), and the factor "height of the lintel" has the least effect (0.528 %).

2. Methods

Having analyzed the effect of different factors on the degree of heat insulation (Figure 1), we found out that quantitative estimates of the effect that each factor has vary significantly. To determine the joint effect of the factors, a full factorial experiment (FFE) is required. Due to a significant number of factors and complexity of their joint action, it was decided to carry out 8 independent experiments for the following boundary zones:

1. side jamb of the window structure with a PVC profile and the wall without a rabbet;
2. top jamb of the window structure with a PVC profile and the wall without a rabbet;
3. side jamb of the window structure with a PVC profile and the wall with a rabbet;
4. top jamb of the window structure with a PVC profile and the wall with a rabbet;
5. side jamb of the window structure with an aluminum profile and the wall without a rabbet;
6. top jamb of the window structure with an aluminum profile and the wall without a rabbet;
7. side jamb of the window structure with an aluminum profile and the wall with a rabbet;
8. top jamb of the window structure with an aluminum profile and the wall with a rabbet.



1-Thickness of the wall, m	0.12	0.185	0.25	0.315	0.38	0.445	0.51	0.575	0.64
2-Thermal conductivity of the wall material, W/(m*C)	0.12	0.361	0.603	0.844	1.085	1.326	1.568	1.809	2.05
3-Thickness of the insulation of outer wall, m	0.04	0.0663	0.0925	0.119	0.145	0.171	0.198	0.224	0.25
4-Thermal conductivity of the insulation material, W/(m*C)	0.03	0.0375	0.045	0.0525	0.06	0.0675	0.075	0.0825	0.09
5-Position of the window in an aperture, % of the thickness of the wall from outer edge	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100.0
6-Width of the assembly seam, m	0.01	0.0188	0.0275	0.0363	0.045	0.0538	0.0625	0.0713	0.08
7-Thermal conductivity of the assembly seam, W/(m*C)	0.02	0.0363	0.0525	0.0689	0.085	0.101	0.118	0.134	0.15
8-Thickness of the window profile, m	0.06	0.065	0.07	0.075	0.08	0.085	0.09	0.095	0.01
9-Thermal conductivity of the window profile, W/(m*C)	0.1	0.25	0.4	0.55	0.7	0.85	1.0	1.15	1.3
10-Width of the thermal filler, m	0.01	0.0275	0.045	0.0625	0.08	0.0975	0.115	0.1325	0.15
11-Depth of the thermal filler, m	0.065	0.0721	0.0793	0.0864	0.0935	0.101	0.108	0.115	0.122
12-Thermal conductivity of the thermal filler material, W/(m*C)	0.03	0.0775	0.125	0.1725	0.22	0.2675	0.315	0.3625	0.41
13-Height of lintel, m	0.065	0.13	0.195	0.26	0.325	0.39	0.455	0.52	0.585
14-Thermal conductivity of the lintel, W/(m*C)	0.06	0.309	0.558	0.806	1.055	1.304	1.553	1.801	2.05

Figure 1. Dependence of heat flow through a window frame unit on the values of the factors.

This choice is based on the fact that a top jamb differs from a side jamb and a bottom jamb (drip cap, apron) as it is influenced by additional factors (the height of the lintel and the coefficient of thermal conductivity of lintel material), as well as a wall with a rabbet compared to a wall without a rabbet. It was decided to use a heat-insulating insert for a wall with a window rabbet and apply it as the reference point for the window frame position, while the window frame position in a wall without a window rabbet is an independent factor, and heat insulation of the outer jamb is used as a heat-insulating insert. The studied PVC profiles were considered as uniform, since the values of the coefficients of thermal conductivity of main materials, i.e. PVC and air, are close to each other (0.19 W/(m·°C) and 0.15 W/(m·°C) respectively). It allowed us to vary the value of the coefficient of thermal conductivity of the profile from 0.1 to 1.3 W/(m·°C). Since the value of the coefficient of thermal conductivity of aluminum is high (221 W/(m·°C)) as compared to those of PVC and air, it is impossible to consider the aluminum profile as uniform, as it will lead to inaccurate calculations. Therefore, when studying the aluminum profile, we chose the most common construction design according to the results of analyzing design solutions and observations at construction sites. Table 1 shows the selection of factors for the eight experiments.

Table 1. Studied factors and levels of their variation.

Factor	Factor value corresponding to the level of its variation		Number of experiment							
	min (–1)	max (+1)	1	2	3	4	5	6	7	8
Wall thickness, m	0.12	0.64	X_1	X_1	X_1	X_1	X_1	X_1	X_1	X_1
Coefficient of thermal conductivity of wall material, W/(m·°C)	0.12	2.05	X_2	X_2	X_2	X_2	X_2	X_2	X_2	X_2
Outer wall insulation, m	0.04	0.25	X_3	X_3	X_3	X_3	X_3	X_3	X_3	X_3
Coefficient of thermal conductivity of the insulator, W/(m·°C)	0.03	0.09	X_4	X_4	X_4	X_4	X_4	X_4	X_4	X_4
Position of the window frame in the window aperture, % of the wall width from the outer side	0	100	X_5	X_5	–	–	X_5	X_5	–	–
Window profile thickness, m	0.060	0.100	X_6	X_6	X_5	X_5	–	–	–	–
Coefficient of thermal conductivity of the window profile, W/(m·°C)	0.1	1.3	X_7	X_7	X_6	X_6	–	–	–	–
Joint width, m	0.01	0.08	X_8	X_8	X_7	X_7	X_6	X_6	X_5	X_5
Coefficient of thermal conductivity of the joint, W/(m·°C)	0.02	0.15	X_9	X_9	X_8	X_8	X_7	X_7	X_6	X_6
Width of the heat-insulating insert, m	0.01	0.15	–	–	X_9	X_9	–	–	X_7	X_7
Depth of the heat-insulating insert, m	0.065	0.122	–	–	X_{10}	X_{10}	–	–	X_8	X_8
Coefficient of thermal conductivity of heat-insulating insert, W/(m·°C)	0.03	0.41	–	–	X_{11}	X_{11}	–	–	X_9	X_9
Height of the lintel, m	0.065	0.585	–	X_{10}	–	X_{12}	–	X_8	–	X_{10}
Coefficient of thermal conductivity of the lintel, W/(m·°C)	0.06	2.05	–	X_{11}	–	X_{13}	–	X_9	–	X_{10}

Notes:

1. X_1-X_{13} indicate the number of a specific factor in a specific experiment;

2. In experiments with a rabbeted wall (experiments 3, 4, 7, 8), the wall thickness is taken in the range from 0.38 to 0.64 m;

3. In experiments with top jambs (experiments 2, 4, 6, 8), the coefficient of thermal conductivity of the wall is taken from 0.12 to 0.99 W/(m·°C), whereas in a rabbeted wall (experiments 3, 4, 7, 8) it is taken in the range from 0.47 to 0.87 W/(m·°C);

4. In experiments with an aluminum profile window (experiments 5, 6, 7, 8), the joint width is taken in the range from 0.01 to 0.05 m.

In order to determine the joint effect of the studied factors on the thermal insulation level of an envelope fragment, we conducted an experiment using computer simulation. This experiment was carried out according to a special plan, where the value of heat loss rates through a window frame unit was used as a response function.

All possible combinations for the studied factors were studied using a complete factorial experiment. Each studied factor has two levels, therefore the number of tests within the complete factorial experiment was determined by the formula $N = 2^m$, where m is the number of factors.

Since the number of tests would be $N = 2048$, in case the number of factors $m = 11$, it was decided to conduct a screening experiment, which allowed us to reduce the number of factors and tests, and to identify the significant factors. After insignificant factors had been excluded, a complete factorial experiment was carried out with the remaining factors, which allowed us to describe the response function.

To carry out the screening experiment, we used Plackett-Burman experimental designs, because they are optimal if there are no parallel experiments. The number of experiments in these matrices is a multiple of four ($N = 4k$), and they can be used to study the effect of $(4k - 1)$ factors. As these designs are orthogonal, linear effects of the factors are determined independently from each other.

After the screening experiment, the results were statistically processed, that is, the effect of each factor was calculated and the significance of factors was verified using Student's t-test with a significance value $\alpha = 0.05$. To determine dispersion of the estimated coefficients, fake factors were used in each test.

After the screening experiment and identification of the significant factors, we performed a two-level complete factorial experiment using a linear polynomial.

$$y(k) = b_0 + \sum b_i \cdot x_i + \sum b_{ij} \cdot x_{ij} + \sum b_{ijk} \cdot x_{ijk}, \quad (1)$$

where $y(k)$ is the response function;

b_i is the linear coefficient; b_{ij} is the coefficient of double interaction;

b_{ijk} is the coefficient of triple interaction;

x_i is the coded value of the factor.

The coefficient of the joint effect of the significant factors forecast according to the model, as well as the linear coefficient and the coefficients of double and triple interaction were determined by the least square procedure.

After that, the results were statistically evaluated, that is, the significance of all coefficients was verified using Student's *t*-test with the significance value $\alpha = 0.05$, and the adequacy of the model was verified according to the Fisher criterion. To simplify the calculation, coefficients that resulted insignificant were excluded from the model. An abbreviated model was created according to all the tests.

The coefficient of the joint effect of significant factors on thermal insulation of a window frame was studied experimentally using computer simulation in the software product ELCUT, which was developed by the "Tor" company. The software has a certificate of conformance for the use in construction No. ROSS RU.SP15.N00904.

Figure 2 shows an example of the finite element model developed in the ELCUT software and the temperature field of the studied fragment.

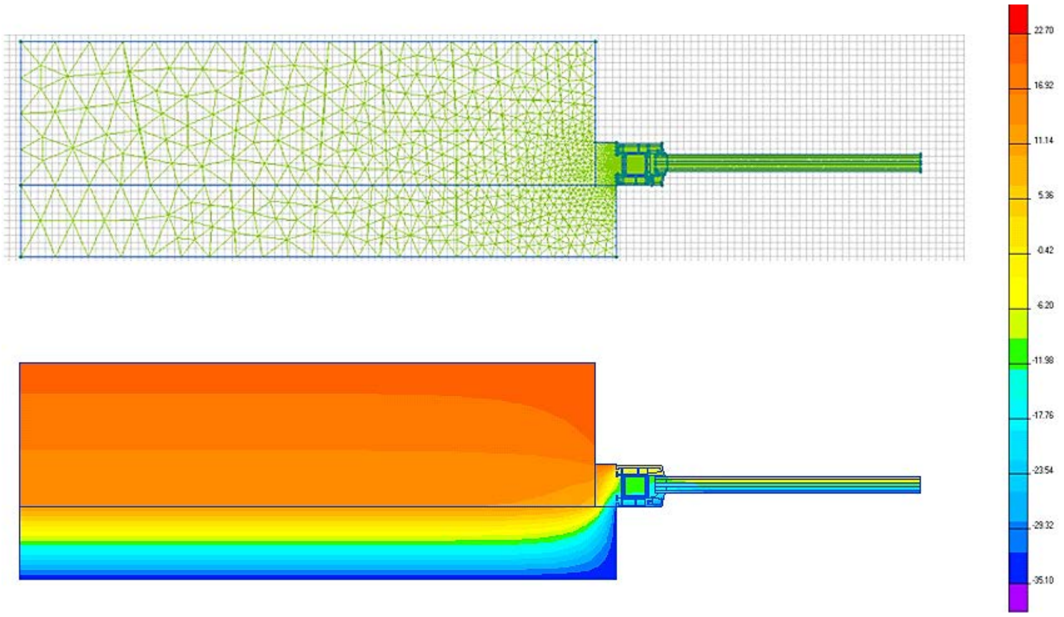


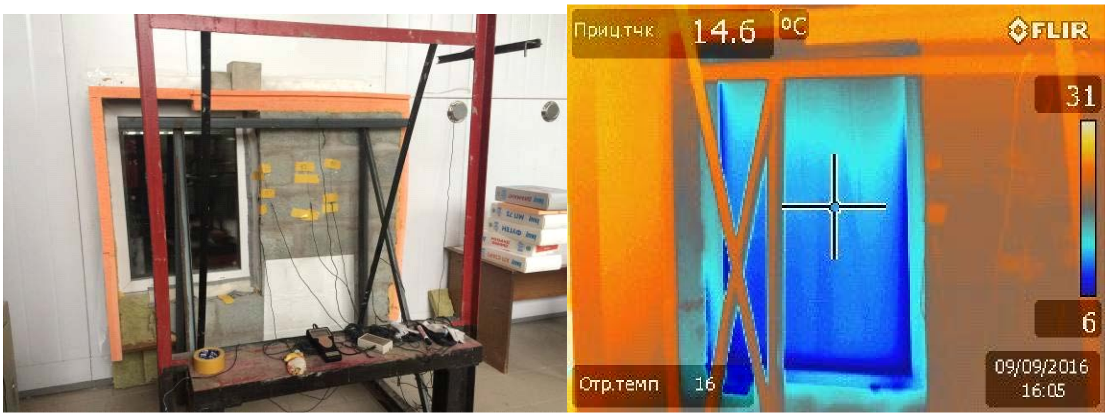
Figure 2. Example of the finite element model and the temperature field.

To confirm the adequacy of the computer calculation, the most typical defects were simulated under laboratory conditions. The tests were carried out in a certified research laboratory of the department "Construction Operations and Theory of Structures", SUSU (NRU). The research method complied with GOST 30971-2012 "Joints of connections between window blocks and wall openings".

The conditions of stationary heat flow were created with the climate chamber KKhTV-24.0 (climate chamber of cold, heat, and moisture) produced by OOO "NPO Spetsklimat" with available storage capacity of 24 m^3. A set of instrumentation included: a FLIR E60 thermographic camera; a 10-channel ITP-MG4.03.10 Flow device; a TGTs-MG4 thermohygrometer; a TEMP-3.2 thermohygrometer; an ISP-MG4 Probe thermal conductivity meter.

The study focused on a fragment of a multilayer envelope with a window (Figure 3). The fragment dimensions were the following: height – 1400 mm, width – 1600 mm, thickness – 300 (250) mm. The usable space of the fragment was 1.69 m^2. The multilayer envelope structure was made of 400×200×200 mm slag block and Isover Facade mineral wool heat insulator. The thickness of the insulator ranged from 50 to 100 mm. The slag block was laid with 15-millimeter-thick M150 cement-sand mortar. The insulation was fastened with Koelner disk-shaped dowels with steel nails of 10 mm in diameter.

The experiment was carried out in temperature conditions corresponding to the Chelyabinsk region. The laboratory temperature was 21 °C, in the climate chamber – minus 34 °C.



a ***b***

Figure 3. Studied sample:
***a* is a test bench for the laboratory experiment; *b* is the thermogram of the test structure.**

Having obtained the results of the laboratory experiment, we used the ELCUT software to develop a computer model, and evaluated the consistency of the results. The discrepancies between the results of the laboratory experiment and the computer modeling ranged from 1.01 to 9.13 % as compared to the values of the heat flow, which is less than the permissible error. Thus, the use of computer simulation in this study has been proved adequate.

3. Results and Discussion

To facilitate further analysis, all the data obtained during the study was summarized as a matrix of design and experimental results. Table 2 shows a fragment of the matrix for a side jamb of the window structure with a PVC profile and a rabbeted wall (experiment 3).

Table 2. Fragment of the matrix of the design and the results of determining the joint effect of the significant factors on the value of the heat loss rates through the side jamb unit.

No.	X_2	X_3	X_4	X_6	X_7	X_9	X_{11}	Heat loss		
								Experiment	Complete model	Abbreviated model
1	+	+	+	+	+	+	+	0.426	0.414	0.414
2	+	+	+	+	+	+	–	0.294	0.301	0.301
3	+	+	+	+	+	–	+	0.327	0.329	0.329
…	…	…	…	…	…	…	…	…	…	…
126	–	–	–	–	–	+	–	0.121	0.124	0.124
127	–	–	–	–	–	–	+	0.156	0.154	0.154
128	–	–	–	–	–	–	–	0.142	0.151	0.151

As a result of the experiment, a model of the joint effect of the significant factors on the thermal properties of the window frame was developed for each type of the frame unit, using formula (1) (Table 3).

Table 3. Models of the joint effect of the significant factors on the thermal properties of the window frame.

Experiment number	Mathematical model	Determination coefficient
1	$y(k)=0.178+0.0575\cdot x_1+0.0832\cdot x_2+0.0248\cdot x_3+$ $+0.0172\cdot x_4+0.0522\cdot x_5-0.0485\cdot x_8+0.0363\cdot x_1\cdot x_2+$ $+0.0158\cdot x_1\cdot x_4+0.0433\cdot x_1\cdot x_5+0.0152\cdot x_2\cdot x_3+$ $+0.0161\cdot x_2\cdot x_4+0.0366\cdot x_2\cdot x_5-0.0162\cdot x_2\cdot x_8+$ $+0.0171\cdot x_3\cdot x_5+0.00881\cdot x_4\cdot x_5+0.0122\cdot x_1\cdot x_2\cdot x_4+$ $+0.0355\cdot x_1\cdot x_2\cdot x_5+0.0153\cdot x_1\cdot x_3\cdot x_5+0.0108\cdot x_2\cdot x_3\cdot x_5+$ $+0.01\cdot x_2\cdot x_4\cdot x_5$	0.949
2	$y(k)=0.132+0.0531\cdot x_1+0.015\cdot x_4+0.0442\cdot x_5+$ $+0.0123\cdot x_1\cdot x_4+0.0344\cdot x_1\cdot x_5+0.0349\cdot x_1\cdot x_{11}+$ $+0.0173\cdot x_3\cdot x_5+0.0185\cdot x_4\cdot x_{11}+0.0309\cdot x_5\cdot x_{11}+$ $+0.0255\cdot x_1\cdot x_5\cdot x_{11}$	0.861

Experiment number	Mathematical model	Determination coefficient
3	$y(k)=0.258+0.0616\cdot x_2+0.054\cdot x_3-0.0264\cdot x_4+$ $+0.0204\cdot x_6-0.0216\cdot x_7+0.0145\cdot x_9+0.0289\cdot x_{11}+$ $+0.0119\cdot x_2\cdot x_3-0.00609\cdot x_2\cdot x_4+0.00184\cdot x_2\cdot x_9+$ $+0.00454\cdot x_2\cdot x_{11}+0.00328\cdot x_3\cdot x_4+0.00171\cdot x_3\cdot x_6-$ $-0.00181\cdot x_3\cdot x_7+0.01\cdot x_3\cdot x_9+0.00336\cdot x_3\cdot x_{11}-$ $-0.00644\cdot x_4\cdot x_9-0.00199\cdot x_4\cdot x_{11}-0.0182\cdot x_6\cdot x_7+$ $+0.00274\cdot x_6\cdot x_9-0.00307\cdot x_6\cdot x_{11}-0.00239\cdot x_7\cdot x_9+$ $+0.00264\cdot x_7\cdot x_{11}+0.022\cdot x_9\cdot x_{11}$	0.992
4	$y(k)=0.305+0.046\cdot x_3-0,0227\cdot x_4+0.00656\cdot x_6+$ $+0.00659\cdot x_9+0.0229\cdot x_{11}+0.24\cdot x_{13}+0.00873\cdot x_3\cdot x_4+$ $+0.00777\cdot x_3\cdot x_9+0.00232\cdot x_3\cdot x_{11}+0.0407\cdot x_3\cdot x_{13}-$ $-0.00493\cdot x_4\cdot x_9-0.0014\cdot x_4\cdot x_{11}-0.0225\cdot x_4\cdot x_{13}-$ $-0.00153\cdot x_6\cdot x_{11}+0.00145\cdot x_6\cdot x_{13}+0.0169\cdot x_9\cdot x_{11}+$ $+0.0168\cdot x_{11}\cdot x_{13}+0.00184\cdot x_3\cdot x_4\cdot x_9+0.00654\cdot x_3\cdot x_4\cdot x_{13}+$ $+0.00186\cdot x_3\cdot x_9\cdot x_{11}+0.00468\cdot x_3\cdot x_9\cdot x_{13}+0.00135\cdot x_3\cdot x_{11}\cdot x_{13}$ $-0.00116\cdot x_4\cdot x_9\cdot x_{11}-0.00322\cdot x_4\cdot x_9\cdot x_{13}+0.0125\cdot x_9\cdot x_{11}\cdot x_{13}$	0.999
5	$y(k)=0.175+0.0586\cdot x_1+0.0792\cdot x_2+0.0239\cdot x_3+$ $+0.0209\cdot x_4+0.0571\cdot x_5-0.0421\cdot x_6+0.0356\cdot x_1\cdot x_2+$ $+0.016\cdot x_1\cdot x_4+0.0422\cdot x_1\cdot x_5+0.0152\cdot x_2\cdot x_3+$ $+0.0182\cdot x_2\cdot x_4+0.039\cdot x_2\cdot x_5-0.0129\cdot x_2\cdot x_6+$ $+0.0186\cdot x_3\cdot x_5+0.01\cdot x_4\cdot x_5+0.0121\cdot x_1\cdot x_2\cdot x_4+$ $+0.034\cdot x_1\cdot x_2\cdot x_5+0.0155\cdot x_1\cdot x_3\cdot x_5+0.0113\cdot x_2\cdot x_3\cdot x_5+$ $+0.0116\cdot x_2\cdot x_4\cdot x_5+0.0085\cdot x_3\cdot x_4\cdot x_5$	0.925
6	$y(k)=0.18+0.0584\cdot x_1+0.0209\cdot x_3+$ $+0.0196\cdot x_4+0.0571\cdot x_5-0.038\cdot x_6+0.0916\cdot x_9+$ $+0.0121\cdot x_1\cdot x_4+0.0413\cdot x_1\cdot x_5+0.0396\cdot x_1\cdot x_9+$ $+0.0182\cdot x_3\cdot x_5+0.0141\cdot x_3\cdot x_9+0.00727\cdot x_4\cdot x_5+$ $+0.0176\cdot x_4\cdot x_9+0.0397\cdot x_5\cdot x_9-0.0104\cdot x_6\cdot x_9+$ $+0.015\cdot x_1\cdot x_3\cdot x_5+0.0118\cdot x_1\cdot x_4\cdot x_9+$ $+0.0313\cdot x_1\cdot x_5\cdot x_9+0.00706\cdot x_3\cdot x_4\cdot x_5+$ $+0.0124\cdot x_3\cdot x_5\cdot x_9+0.00924\cdot x_4\cdot x_5\cdot x_9$	0.954

Experiment number	Mathematical model	Determination coefficient
7	$y(k) = 0.265 + 0.062 \cdot x_2 + 0.0546 \cdot x_3 - 0.0265 \cdot x_4 - 0.023 \cdot x_5 + 0.016 \cdot x_7 + 0.0277 \cdot x_9 + 0.012 \cdot x_2 \cdot x_3 - 0.00639 \cdot x_2 \cdot x_4 + 0.0024 \cdot x_2 \cdot x_7 + 0.00478 \cdot x_2 \cdot x_9 + 0.00309 \cdot x_3 \cdot x_4 - 0.00283 \cdot x_3 \cdot x_5 + 0.0103 \cdot x_3 \cdot x_7 + 0.00339 \cdot x_3 \cdot x_9 + 0.00168 \cdot x_4 \cdot x_5 - 0.00653 \cdot x_4 \cdot x_7 - 0.00197 \cdot x_4 \cdot x_9 - 0.00463 \cdot x_5 \cdot x_7 + 0.00434 \cdot x_5 \cdot x_9 + 0.0208 \cdot x_7 \cdot x_9 + 0.00383 \cdot x_2 \cdot x_3 \cdot x_4 + 0.00124 \cdot x_2 \cdot x_3 \cdot x_7 - 0.00079 \cdot x_2 \cdot x_4 \cdot x_7 - 0.00107 \cdot x_2 \cdot x_5 \cdot x_7 + 0.0032 \cdot x_2 \cdot x_7 \cdot x_9 + 0.00233 \cdot x_3 \cdot x_4 \cdot x_7 + 0.00265 \cdot x_3 \cdot x_7 \cdot x_9 - 0.00169 \cdot x_4 \cdot x_7 \cdot x_9 + 0.00246 \cdot x_5 \cdot x_7 \cdot x_9$	0.999
8	$y(k) = 0.291 + 0.0476 \cdot x_3 - 0.0231 \cdot x_4 + 0.0117 \cdot x_6 + 0.0139 \cdot x_7 + 0.0428 \cdot x_{10} + 0.195 \cdot x_{11} + 0.00758 \cdot x_3 \cdot x_4 + 0.009 \cdot x_3 \cdot x_7 + 0.0317 \cdot x_3 \cdot x_{11} - 0.00573 \cdot x_4 \cdot x_7 - 0.018 \cdot x_4 \cdot x_{11} - 0.00257 \cdot x_7 \cdot x_{10} - 0.00212 \cdot x_7 \cdot x_{11} + 0.0735 \cdot x_{10} \cdot x_{11} + 0.00316 \cdot x_3 \cdot x_4 \cdot x_{10} + 0.00513 \cdot x_3 \cdot x_4 \cdot x_{11} + 0.00342 \cdot x_3 \cdot x_7 \cdot x_{11} + 0.0148 \cdot x_3 \cdot x_{10} \cdot x_{11} - 0.00223 \cdot x_4 \cdot x_7 \cdot x_{11} - 0.00734 \cdot x_4 \cdot x_{10} \cdot x_{11} + 0.00808 \cdot x_7 \cdot x_{10} \cdot x_{11}$	0.998

The obtained models suggest that when determining the heat loss through a window frame unit, there is a complex joint effect of factors leading to a significant change in heat loss. This allows us to conclude that separate study of each factor can be used mainly to illustrate the significance of factors and to test design solutions [16–19].

The literature review failed to find any studies of the joint effect of factors on a window frame. Earlier studies [16, 19, 20–24] considered the separate and joint effect of thermotechnical nonuniformities and defects in wall structures. In [8–14, 25–32], the temperature regimes of modern windows were studied, but the joint effect of factors on heat loss through a window frame was not studied. The study [16, 30] was based on similar methods, but focused on a different structure: a suspended facade system.

The coded values of the factors that are substituted in the formulas of the models (see Table 3) are determined by the formula:

$$X_i = \frac{\hat{X}_i - (\hat{X}_{i\max} + \hat{X}_{i\min})/2}{(\hat{X}_{i\max} - \hat{X}_{i\min})/2}, \tag{2}$$

where X_i is the coded value of the *i*-factor;

$\hat{X}_i$ is the current natural value of the *i*-factor;

$\hat{X}_{i\max}$, $\hat{X}_{i\min}$ are maximum and minimum natural values of the *i*-factor.

These models will help to determine the significant rates of heat loss through a window frame unit at construction sites without computer modeling of the unit. For calculating, Table 1 should be used to determine the number of the experiment and the factors, which should be measured. After that, the coded values of the factors in the range between –1 and 1 are defined by formula (2) and substituted in the appropriate models.

Due to possible difficulties in practical application of these models because of their awkwardness, software was developed in C# for greater convenience. The software makes it possible to calculate the rates of heat loss through a window frame, selecting the required structure parameters (type of jamb, wall and window structure) and setting the required natural values of factors determined for a specific building. The software calculates the coded values of the required factors, determines the model that is required for calculations, and displays the value of heat loss rates. This value can be used when performing thermotechnical calculations to more accurately determine the reduced total thermal resistance of the envelope structure, taking into account some thermal nonuniformities.

The developed models can be used to make specifications for installing translucent structures from the point of view of regulating the allowance for their structure according to the criterion of energy efficiency.

4. Conclusions

The experimental results are the following:

1.Eight most common types of window jambs were identified, and for each of them it is necessary to calculate the value of heat loss rates according the appropriate factors. These types include:

– Side jamb of the window structure with a PVC profile and the wall without a rabbet;

– Top jamb of the window structure with a PVC profile and the wall without a rabbet;

– Side jamb of the window structure with a PVC profile and the wall with a rabbet;

– Top jamb of the window structure with a PVC profile and the wall with a rabbet;

– Side jamb of the window structure with an aluminum profile and the wall without a rabbet;

– Top jamb of the window structure with an aluminum profile and the wall without a rabbet;

– Side jamb of the window structure with an aluminum profile and the wall with a rabbet;

– Top jamb of the window structure with an aluminum profile and the wall with a rabbet.

2. To determine the joint effect of structural features of a window frame on the value of heat loss rates for each of the eight types of jambs, we conducted an experiment. The experiment resulted in modeling joint effects, which make it possible to determine the value of heat loss rates with high accuracy and without computer simulation. The maximum discrepancy between the experimentally obtained value and the calculation according to the model was 15.2 %. The discrepancies between the results of the laboratory experiment and the computer modeling ranged from 1.01 to 9.13 %.

3. To simplify the calculation according to the models, we developed C# software that makes it possible to determine the reduced total thermal resistance of the envelope structure taking into account thermal nonuniformities.

4. The developed models can be used to make specifications for installing translucent structures from the point of view of regulating the allowance for their structure according to the criterion of energy efficiency.

5. The results can be used for the buildings in use energy classification. For EU countries, it is necessary to use the national classification of buildings for energy efficiency. The calculation results will be the same when using different Russian and European software products [33] based on the finite element method and the theory of heat transfer.

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Тепловые потери через оконные рамы зданий

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Ключевые слова: здания; окна; оконная рама; энергоэффективность; теплозащита; потери теплоты; математическое моделирование

Аннотация. Объект исследования - оконные рамы зданий, так как они являются критическими зонами с точки зрения теплоизоляции. Было изучено, как свойства оконной рамы влияют на изменение теплового потока и температурных полей. Был проведен анализ потерь тепла, которые зависят от ряда конструктивных особенностей оконной рамы, таких как геометрические, тепловые и физические свойства стен, окон, перемычек и стыков. Был разработан эксперимент, проведено компьютерное моделирование и лабораторные испытания. Было проанализировано восемь различных типов рамы. Были разработаны их конечно-элементные модели в программном обеспечении ELCUD. Лабораторные испытания подтвердили адекватность конечно-элементных моделей. Сравнительные результаты, полученные в результате испытаний и численных моделей, были согласованы. Мы провели полный факторный эксперимент и исключили незначительные факторы с помощью статистического анализа. Разработаны математические модели совместного влияния этих факторов. Был проведен подробный анализ влияния факторов влияния на потери тепла через оконную раму. Результаты могут быть использованы для энергетической классификации эксплуатируемых зданий.

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