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Method of thermotechnical uniformity coefficient evaluation by analyzing thermograms

Метод оценки коэффициента теплотехнической однородности из анализа термограмм

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Ключевые слова: энергоэффективность; коэффициент теплотехнической однородности; геометрический параметр; сопротивление теплопередаче; ограждающая конструкция здания; температурное поле; теплота; термограмма; здание; строительство

Abstract. One of the primary problems solved for increasing energy efficiency of a building is increasing of the insulating properties of the building envelope. The paper describes the method for determining the coefficient of thermotechnical uniformity by analyzing a thermogram of parts of a building envelope. The method is based on obtaining temperature distribution matrix on the surface of a building envelope fragment by thermography. Two methods for assessing the coefficient of thermotechnical uniformity are proposed. One method for determining the coefficient of thermotechnical uniformity is based on obtaining mean temperature values by numerically processing thermograms, another on numerical integration along the contour lines of temperature curves.

Аннотация. Одной из приоритетных задач, решаемой при повышении энергетической эффективности зданий, является повышение теплозащитных свойств их наружных ограждающих конструкций. В данной работе изложен метод оценки величины коэффициента теплотехнической однородности из анализа термограмм наружных ограждающих частей зданий. Метод основан на получении путем термографирования матрицы распределения температуры на поверхности фрагмента ограждающей конструкции. Предложены два способа оценки величины коэффициента теплотехнической однородности. Один способ оценки величины коэффициента теплотехнической однородности основан на получении усредненных значениях температур путем числовой обработки термограмм, другой – на численном интегрировании вдоль контуров линий температурных кривых.

Introduction

In Russian Civil Engineering, a dimensionless thermal uniformity coefficient r of the building envelope or its fragment is widely used. This coefficient is determined as $\mathrm{r} = \mathrm{R}_0^{\mathrm{rel}}/\mathrm{R}_0^{\mathrm{r}}$, where $\mathrm{R}_0^{\mathrm{rel}}$ – conventional thermal resistance of a multilayer building envelope having uniformal layers, that is calculated from $\mathrm{R}_0^{\mathrm{rel}} = \mathrm{R}_{\mathrm{si}} + \sum \mathrm{d}_{\mathrm{k}}/\lambda_{\mathrm{k}} + \mathrm{R}_{\mathrm{se}}$ (R_{si} , R_{se} – thermal resistances of the internal and the external building envelope layers, $\mathrm{m}^2 \cdot \mathrm{K/W}$; λ_{k} – thermal conductivity coefficient of the k-th uniformal layer, $\mathrm{W/(m \cdot K)}$; d_{k} – thickness of the layer, m); $\mathrm{R}_0^{\mathrm{r}}$ – reduced thermal resistance of a non-uniformal building envelope, calculated from $\mathrm{R}_0^{\mathrm{r}} = (\mathrm{t}_{\mathrm{int}} - \mathrm{t}_{\mathrm{ext}}) \cdot \mathrm{A/Q}$, where $\mathrm{t}_{\mathrm{int}}, \mathrm{t}_{\mathrm{ext}}$ – internal and external air temperatures, °C; A – surface area of a non-uniformal building envelope or its fragment, m^2; Q – total heat flux through this surface, W. The value of the total heat flux Q through the non-uniformal building envelope, containing “thermal bridges” (thermal conductive insertions, gaps, corners, etc.) is determined

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from numerical computer aided calculation of thermal fields or experimentally. Knowing the value of thermal uniformity coefficient the designer is able to perform quick evaluation of R_0^r .

Non-uniformal segments of the building envelope (so called "thermal bridges" – joints, dowels, thermal inserts, etc.) take a considerable area of the building envelope that is why they have a considerable impact on insulating properties and durability of the construction [1–3]. Looking for engineering solutions for increasing thermal uniformity of the building envelope is one of the relevant tasks solved by the modern thermal engineering. Both simplified and detailed calculation methods for determining heat transfer (thermal resistance) coefficients of building envelope are well developed and available today [4–6].

Surface thermography is performed according to Russian standards. However, the obtained thermograms due to random impacts of side effects are qualitative. The procedure for thermogram procession has several parameters, providing for alterations in temperature and color match. The core parameters are surface radiation coefficient of the construction – a measure of radiation, emitted by the object, compared to the ideal black body and apparent reflected temperature – a parameter, used to compensate radiation of other bodies [7, 8].

Thermographic analysis is a useful tool for evaluating energy performance a building. It also may be used to verify the presence of air seepage, moisture or water leaks. It is difficult to understand in details all the parameters that influence the thermal scene, that’s why infrared thermography is not commonly used for quantitative diagnosis [9, 10].

Most studies involving infrared thermography in building monitoring leads to qualitative results. The technology of infrared cameras has advanced and thermal maps generated by the latest models offer a lot of information in terms of image definition. Better quality of the IR sensors makes the information more accurate. The software for image processing has advanced the most, in terms of graphics management of the pictures: a single shooting makes it possible to make many more evaluations, changing the parameters, to locate homogeneous areas and make very precise calculation of the average values of temperatures. A complete methodology based on the infrared thermovision technique has been developed to reach quantitative data of thermal transmittances of building envelopes [11].

In practice [12] analysis of infrared thermography measurements on a multi-layered wall is a handy tool for thermal monitoring of the walls of a building with tenants. Estimating unknown parameters in the modeling in order to determine the thermal resistance of the wall. Identification is achieved by solving the corresponding inverse problem formulated in the least-squares sense.

In [13] a study is presented to calculate the U-value in building envelopes starting from IR thermography. The absolute deviation between the notional and the measured U-values for IR thermography is found to be at an acceptable level, being in the range of 10 % – 20 %.

The objective of the study presented by [14] is to calculate the sensible heat flux from the exterior surface of buildings using time sequential thermography, based upon an appropriate simplification of the building model. The authors analyzed the thermograms, dividing them into zones by constructing polygons and according to temperature, shape, material and position.

The authors of [15] wished to define a methodology to determine the level of thermal insulation in old buildings through spot measurements of thermal resistance and planar infrared thermography. Currently, the available approaches to evaluate the U-value in existing buildings are: non-destructive methods using heat flux sensors or infrared thermography or destructive methods.

The authors of [16] presented a method to calculate the U-value with IR. To validate their method, they compared IR results with measurements using a heat flux apparatus to obtain the wall heat fluxes and surface temperatures, and U-values were calculated using Fourier’s law, taking into account radiation and convection phenomena.

The proposed method is based on the fact that the temperature distribution field, obtained by the thermography, may be corrected ("calibrated") using the values of temperatures, measured by sensors, placed in several specified points. Thus, a qualitative thermogram is transformed into a numerical array of quantative data on temperature distribution across the outer surface of the building envelope.

Methods

Determining the coefficient of thermotechnical uniformity for a fragment of the building envelope

Stage one is selecting (using thermography) of thermally uniformal sections of the building envelope (the reference areas). Next, via contact method, temperature is measured in the selected points of the internal surface of the uniformal fragments of the building envelope, using temperature sensors.

Thermograms are processed using specialized software provided by the thermovisors manufacturers (for example ThermaCAM, FLIR systems). Using the parameters specified above thermograms is calibrated according to the temperature measured by the sensors in the selected points. In this way we achieve equality of temperatures measured by the sensors and obtained from thermography. Then thermograms are digitized and processed using a software tool created in MATLAB. [17–20].

For each building envelope fragment, three types of elements are selected: surface, linear and point. Surface elements are "smooth" parts of the building envelope fragment, having uniform heat flow density. Linear elements – panel joints, window and door esconsons – elements that have one dimension significantly smaller than the other one and insignificant compared to the examined element of the building envelope. Point elements – metallic panel connections, dowels, pins etc. – are elements, with insignificant dimensions of their projection on the surface of the fragment of the building envelope. The coefficient of thermotechnical uniformity of the building envelope fragment containing linear and point thermal non-uniformities is determined from the equation:

$$r = \frac{1}{1+R_0\cdot\left(\sum\frac{L_j}{A}\cdot\Psi_j+\sum\frac{N_k}{A}\cdot\chi_k\right)}, \quad (1)$$

where $R_0,\cdot m^2K/W$ – conditional thermal resistance of the building envelope fragment;

$\Psi_j = \Delta Q_j/(t_{int} - t_{ext})$ – specific heat loss through the j-th linear thermal non-uniformity, $W/(m\cdot K)$ (linear heat transfer coefficient);

ΔQ_j – additional heat loss through linear thermal non-uniformity, W/K;

t_{int}, t_{ext} – the temperature of the internal and external air respectively, $℃$;

L_j/A – ratio of the total length L_j, m of the j-th linear element to the total area of the fragment $A,\cdot m^2$;

χ_k – specific heat loss through the k-th point thermal non-uniformity, W/K (point or volumetric heat transfer coefficient);

$n_k = N_k/A$ – the ratio of average number of point elements N_k to the total area of the fragment $A,\cdot m^2$.

The first method for assessing the coefficient of thermotechnical uniformity value is based on the average temperature values, obtained by numerical procession of the thermograms:

$$r = \frac{1}{1+\left(\sum\frac{L_j}{A}\cdot b_j^{mean}\cdot\Delta_j+\sum\frac{N_k}{A}\cdot A_k^{mean}\cdot\Delta_k\right)}, \quad (2)$$

where,

$$\Delta_k = \frac{\tau_k^{mean}-\tau_0^{mean}}{\tau_0^{mean}-t_{ext}}, \quad (3)$$

τ_k^{mean} – average temperature of the surface of the building envelope fragment, determined from the thermogram analysis, $℃$;

τ_0^{mean} – average temperature of the uniformal part (reference area) of the external surface of the building envelope, $℃$;

b_j^{mean} – average width of a linear thermal non-uniformity of the j – kind of the external surface of the building envelope, m;

A_k^{mean} – average area, with a point thermal non-uniformity of the k – kind, m^2.

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The second method for determining the coefficient of thermotechnical uniformity is based on numerical integration along the contour lines of temperature curves.

The value of $\Psi, W/(m \cdot K)$ in the equation (1) is determined from the ratio

$$\Psi = \frac{q^L - q_0 \cdot d}{(t_{int} - t_{ext})}, \quad (4)$$

where $q^L - q_0 . d, W/m$ – additional heat loss through linear thermal non-uniformity; $q^L = \int_0^d q(x)dx \approx \sum_{i=1}^n q_i \cdot x_i, \frac{W}{m}$ – numerical integral of heat flow density along the line, having length of d, m, perpendicular to the linear non-uniformity; $q_0, W/m$ – value of the heat flow density through the uniformal reference area.

Value of specific heat loss through the point non-uniformity $\chi, W/m$ in the equation (1), may be calculated by integrating the volume along the temperature curve contour, obtained from a thermogram:

$$\chi = \frac{\Delta Q}{\Delta t} = \frac{\pi \cdot \int_0^{qmax} f^2(q)dq}{(t_{int} - t_{ext})} = \frac{\pi \cdot \sum x_i^2 q_i}{(t_{int} - t_{ext})}, \quad (5)$$

where $q_i = \alpha_{ext}(\tau_{ext,i} - t_{ext}), W/m^2$ – value of the heat flow density through the external surface of the building envelope fragment; $\tau_{ext,i}$ – the temperature in the i-th point of the external surface of the fragment ℃, determined from thermograms as well as by direct measurements in several reference points; $\alpha_{ext}, W/(m^2K)$ – surface coefficient of heat transfer, determined from measurements.

The coefficient of thermotechnical uniformity of the entire building envelope sample is calculated as the weighted average of the fragments:

$$r = \sum A_i r_i / \sum A_i, \quad (6)$$

If beside the temperature sensors a calorimeter for measuring the heat flow is placed in the reference points of the building envelope, it gives an opportunity to determine the surface coefficient of heat transfer of the internal surface allowing determining the value of the thermal resistance of the building envelope fragment.

Results and Discussion.

Let us evaluate the coefficient of thermotechnical uniformity of a panel based on the thermograms shown on Figure 1.

The area of opaque part of the panel equals $A = 5.6 \cdot 2.8 - 1.2 = 14.5 \cdot m^2$; $b_1^{mean} = 1.1 \cdot m$; $L_1 = 5.6 \cdot m$; specific geometric parameter is $L_1/A = 0.38 \cdot m^{-1}$; average temperatures, obtained from analysis of several dozens of similar areas from different thermograms of the same building: $\tau_1^{mean} = -6.5 \cdot °C$; $\tau_0^{mean} = -7.2 \cdot °C$; average external air temperature is $t_{ext} = -7.6 \cdot °C$. The coefficient of thermotechnical uniformity of the panels of the examined building equals: $r = \frac{1}{1 + \left(\frac{5.6}{14.5}\right) \cdot 1.1 \cdot \frac{(-6.5+7.2)}{(-7.2+7.6)}} = 0.57$

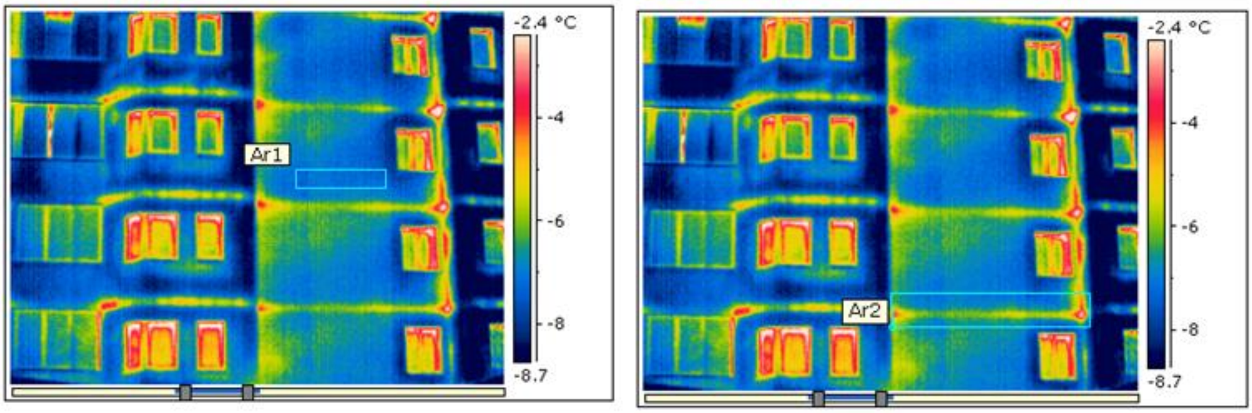

Figure 1. Results of processing data from thermograms of a panel building, obtained under field conditions

Let us evaluate the coefficient of thermotechnical uniformity of a balcony based on the thermograms shown on Figure 2. Geometrical parameters of the balcony are $A = 3.1 \cdot 2.8 - 2.5 = 6.2 \cdot m^2$; $b_1^{mean} = 0.3 \cdot m$; $L_1 = 3.1 \cdot m$; specific geometrical parameter is $L_1/A = 0{,}50 \cdot m^{-1}$. Average temperatures, obtained from the thermogram analysis for this building are: $\tau_1^{mean} = -6.9 \cdot$ °C; $\tau_0^{mean} = -8.4 \cdot$ °C; average external air temperature is $t_{ext} = -8.8 \cdot$ °C; the coefficient of thermotechnical uniformity equals: $r = \frac{1}{1+\left(\frac{3.1}{6.2}\right)\cdot 0.3\cdot\frac{(-6.9+8.4)}{(-8.4+8.8)}} = 0.64$

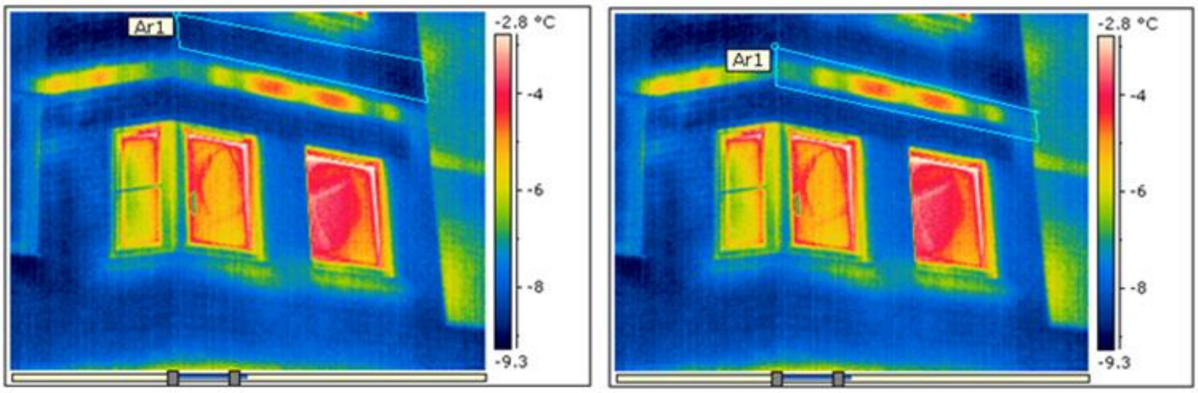

Figure 2. Results of processing data from thermograms of a panel building

Let us evaluate the coefficient of thermotechnical uniformity of the place where the window unit fits the panel (Figure 3). Geometrical parameters are $b_1^{mean} = 0.2 \cdot m$; $L_1 = 4.4 \cdot m$; $A = 3 \cdot 2.5 - 1.2 = 6.3 \cdot m^2$; specific geometrical parameter is $L_1/A = 0.69 \cdot m^{-1}$; average external air temperature is $t_{ext} = -6.4 \cdot$ °C; average temperatures obtained from thermogram analysis are $\tau_1^{mean} = -2.8 \cdot$ °C; $\tau_0^{mean} = -6.0 \cdot$ °C. The coefficient of thermotechnical uniformity equals: $r = \frac{1}{1+\left(\frac{4.4}{6.3}\right)\cdot 0.1\cdot\frac{(-2.8+6.0)}{(-6.0+6.4)}} = 0.69$

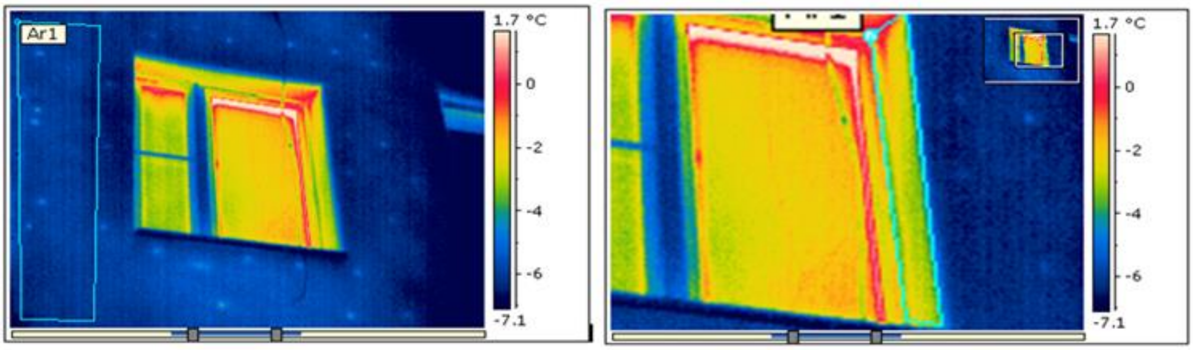

Figure 3. Results of processing data from thermograms of a panel building

Let us evaluate the coefficient of thermotechnical uniformity caused by metallic pins (Figure 4). Average number of pins within $1 \cdot m^2$ is 5; the area of the point thermal non-uniformity is $A_k^{mean} = 7.85 \cdot 10^{-3}$; average external air temperature is $t_{ext} = -9.9 \cdot$ °C; average temperature in the vicinity of a point thermal non-uniformity caused by a metal pin is $\tau_1^{mean} = -7.3 \cdot$ °C; average temperature of the reference area is $\tau_0^{mean} = -9.6 \cdot$ °C. The coefficient of thermotechnical uniformity of a fragment of a building envelope, containing metal pins equals: $r = \frac{1}{1+5\cdot 7.85\cdot 10^{-3}\cdot\frac{(-7.3+9.6)}{(-9.6+9.9)}} = 0.76$

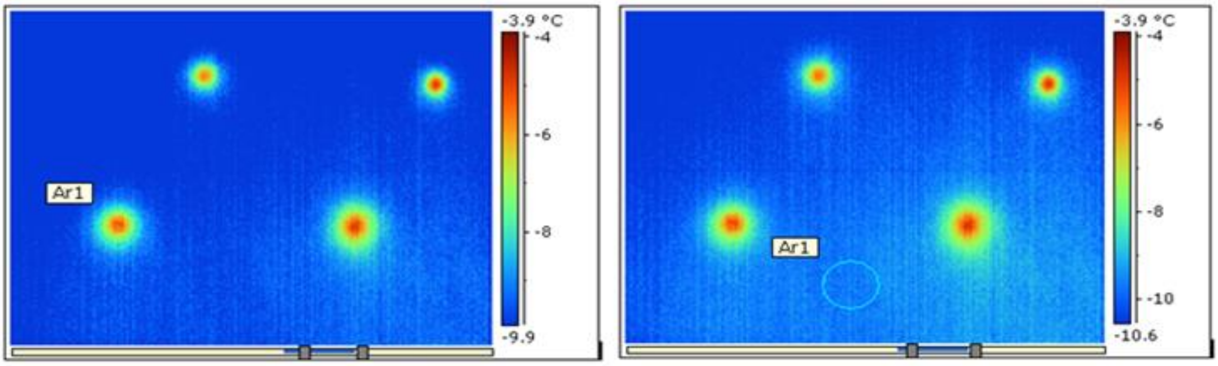

Figure 4. Results of processing data from thermograms of a panel building

Figure 5 contains thermograms showing linear thermal non-uniformity caused by the gaps between mineral wool panels and point thermal non-uniformity, caused by the metal pins. Values the coefficient of thermotechnical uniformity calculated using equations (5), (4) and (1) equal $r = 0.94$ (for gaps between panels) and $r = 0.81$ for metal pins.

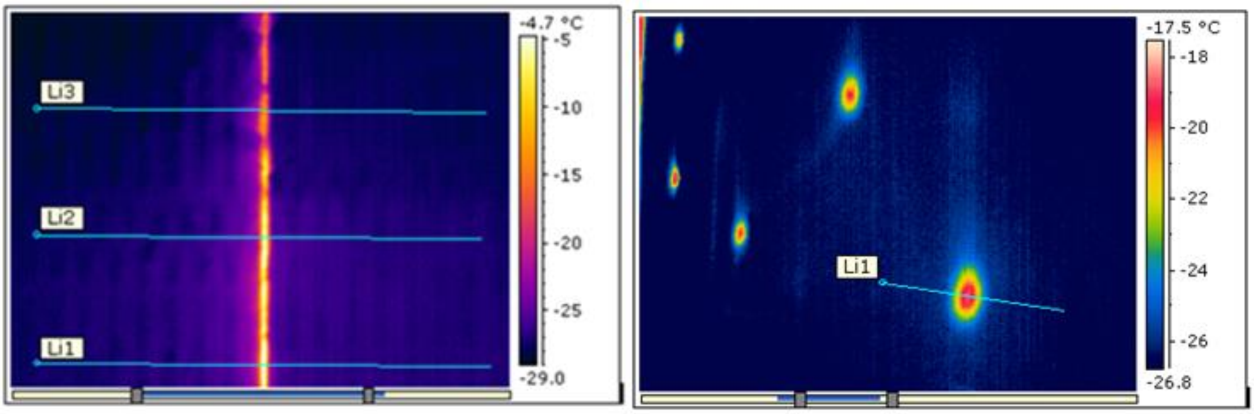

Figure 5. Thermograms, showing linear (left) and point (right) thermal non-uniformities of the external surface of samples tested in a climatic chamber

Conclusion

The proposed method is an efficient way to assess the thermal insulation quality of a tenanted building. It allows to:

- assess the thermotechnical uniformity coefficient of a fragment of building envelope under the field conditions;

- locate under the field conditions flawed elements having thermotechnical uniformity coefficient significantly lower than the average value for similar constructions which in turn provides an opportunity to study the insulation quality of said fragments.

The paper presents analytical equations allowing to evaluate the value of the coefficient of thermotechnical uniformity by analyzing thermograms.

A more detailed analysis of design decisions may be carried out based on this method to further improve them and reduce the impact of heat conductive elements on the overall performance of the fragment.

Several examples of processing thermograms obtained in the field conditions using the abovementioned equations are shown.

The described method of determining the coefficient of thermotechnical uniformity and thermal resistance of building envelope fragments tested in a climatic chamber may be used in addition to methods, described in Russian standards, allowing to reduce the testing time. The method is based on combining measuring of the temperature of the uniform building envelope fragments with analyzing temperature fields obtained by thermography.

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The coefficient of thermotechnical uniformity is determined by dividing the difference between the internal air temperature and mean temperature of a uniform building envelope fragment by the difference between the internal air temperature and mean temperature of a non-uniform building envelope fragment.

If in addition to the temperature the heat flow density is measured in the chosen spots, it is possible to calculate the surface coefficient of heat transfer for the interior surface. This allows evaluating thermal resistance of the fragment, based on the thermogram.

A software piece for data analysis was developed to determine the value the coefficient of thermotechnical uniformity and thermal resistance of a building envelope fragment based on temperature fields, obtained from thermograms.

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