Information-measuring Technology for Buildings Enclosing Structures Thermal Resistance Control

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Abstract

Improvement the heat-protective properties of the enclosing structures of buildings conducted mainly by introducing new building and heat-insulating materials and products that meet the increased regulatory requirements compliance with which allows minimize the level of heat losses. For calculation of heat losses one of the main informative characteristics is thermal resistance. Information-measuring technology for buildings enclosing structures thermal resistance control proposed which based on a combination of thermal imaging of the surface temperature for quality analysis and quantitative contact measurements of surface temperature and heat flux values. Shown advantages of this technology such as reduced the influence of the subjective factor on the control process, ability to identify local defects in thermal insulation, carry out control of enclosing structures that have a complex design, numerical thermal resistance values of the enclosing structures with accordance to metrological requirements. Presented practical application of information-measuring technology for control the thermal resistance of the buildings enclosing structures.

Keywords [1]

Information-measuring technology, thermal resistance, temperature and heat flux sensors

1. Introduction

The growth of energy production and consumption in the conditions of constant depletion of relevant resources brings to the fore questions about their rational use and wide implementation of resource-saving measures. Currently the one of the ways for solve this problem is to improve the heat-protective properties of the enclosing structures of buildings mainly by introducing new building and heat-insulating materials and products that meet the increased regulatory requirements compliance with which allows minimize the level of heat losses. For calculation of heat losses one of the main informative characteristics is thermal resistance [1].

For qualitive analysis used method based on thermal imaging technology. This method is regulated in standards ISO 6781 [2] and EN 13187 [3]. Thermal imaging method allows to identify local defects in thermal insulation by comparing the surface temperature of different sections but does not make possible to determine the numerical values of the thermal resistance of the enclosing structures and the heat losses of the building as whole.

For buildings enclosing structures heat losses numerical analysis used methods based on the principle of heat balance [1] and on contact measurements of heat flux [4-6].

First one [1] allows determine the total transmission loss through the building enclosure constructions but in same time not reveal defective or poorly insulated areas of enclosing structures.

The method based on contact measurements [4-6] of heat flux through the building enclosure and the temperatures provides the numerical thermal resistance values of the enclosing structures. Disadvantages of the method are difficulty to detect local defects and large labor costs for fixing primary sensors on surfaces of various sections which manifested in the inspection of large buildings enclosing structures with large heat exchange surfaces and thermal fields that are non-uniform in space. Based on contact method proposed different approaches for calculation of thermal resistance [7-9].

Also important to analyze systems for measuring the thermal characteristics of buildings and structural elements based on contact measurements [4-6]. For this task we compare five measurement systems by such well-known firms as Hukseflux (TRSYS01 High-accuracy building thermal resistance measuring system with two measurement locations)

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[10]; Green TEG AG (gO Measurement-System for the assessment of U-value, humidity and further parameters) [11]; FluxTeq (FluxTeq R-value measurement System) [12] and Information-measuring system created by scientists group of NASU [13]. Technical characteristics presented in table 1. The disadvantage for measuring systems were considered the use the heat flux sensors one type and size, which makes it impossible to conduct studies of various elements of the building and small number of measuring channels, which limits the number of control zones, does not allow monitoring of complex form building enclosures.

The aim of the work is to create an information-measuring technology for control the thermal resistance of the buildings enclosing structures of any scale and configuration. Analyze approach for metrological characteristics determination and verification. Check practical application of information-measuring technology for control the thermal resistance of the buildings enclosing structures.

Table 1.

SYSTEMS FOR MEASURING THE THERMAL CHARACTERISTICS OF BUILDINGS AND STRUCTURAL ELEMENTS

	TRSYS01 Hukseflux (Netherlands)	**FluxDAQ (USA)**	**Heat Flux Meter (USA)**	**gOMS greenTEG AG (Switzerland)**	**NASU (Ukraine)**
Number of channels	6	8	8	5	8 … 160
Measuring zones	2	2	2	2	2 … 40
Type of heat flux sensors	HFP01	PHFS-01e	HFP01	No information	with thermal correction
Range of heat flux values, W/m²	1 … 2000	1 … 150	1 … 2000	No information	1 … 2000
Relative error of heat flux measuring, %	± 3 %	± 3 %	± 3 %	± 3 %	± 1.5… ± 3%
Temperature sensors	Thermo-couples	Thermo- couples	Thermistor	No information	Thermo-couples, Pt100
Range of temperature values, °C	-30 … +70	-50 … +120	-30 … +70	-30 … +70	-30 … +100
Absolute error of temperature measurement, K	1	1	1	1	0.5 … 1
Method of research	ISO 9869	ISO 9869	ISO 9869	ISO 9869	ISO 9869

2. Theoretical basis and methodology for determining thermal resistance through the enclosing structures

For realization information-measuring technology required a set of measurement methods and hardware-software modules integrated for the purpose of collecting, processing, storing and using measurement information. Also important part is metrological analysis determination and verification of sensors used in systems [14]. Constituent elements of information-measuring technology is presented in figure 1.

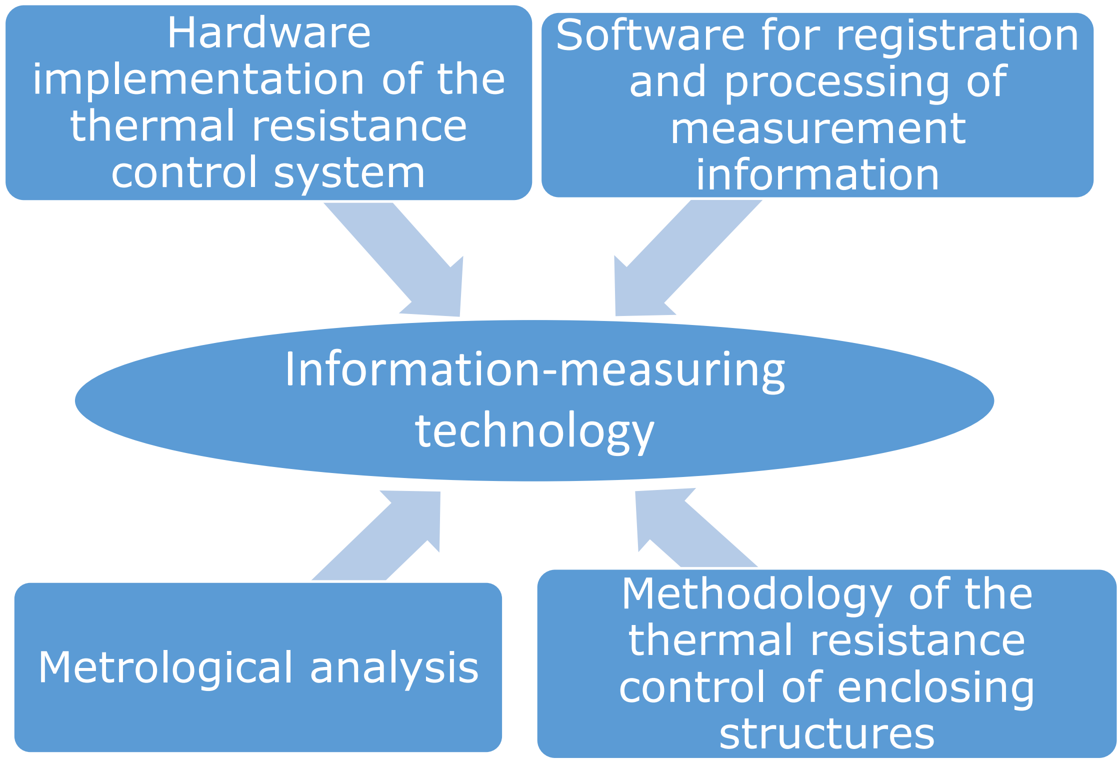

Figure 1: Constituent elements of information-measuring technology

Methodology of the thermal resistance control of enclosing buildings proposed to base on a combination of thermal imaging of the surface temperature of enclosing structures which provides qualitive information according to ISO 6781 and with numerical contact measurements of surface temperature and heat flux values in accordance with ISO 9869 [6]. This gives possibility to identify local defects in thermal insulation by comparing the surface temperature of different sections and make possible to determine the numerical values of the thermal resistance of the enclosing structures and the heat losses of the building. In figure 2 presented Methodology of the thermal resistance control of Enclosing Structures (ES). The methodology demonstrates a step-by-step control procedure. For each stage, the input data necessary for carrying out the relevant procedures at a certain stage are shown. In particular the conditions of conducting the experiment and the applied instrumentation. Also, the output obtained at each stage are shown.

The thermal imaging survey of the entire building is carried out in accordance with ISO 6781 [2]. This makes it possible to identify the features of the internal structure and composition of the fragments of the enclosing structure being examined (the presence of areas with unequal technical characteristics, heat-conducting inclusions, assemblies, butt joints, hidden manufacturing defects, etc.) which lead to thermal heterogeneity. Thus, representative areas are defined and areas with anomalous temperature distribution for this type of design.

At the second stage, in representative areas, measurements are carried out with the use of temperature and heat flux sensors. This allows us to obtain a quantitative estimate of local heat losses, as well as to calculate the thermal resistance of the enclosing structures.

When installing heat flow sensors at the appropriate location of the object being inspected, the following rules must be followed:

- the location of the installation of heat flow sensors must be selected in the area corresponding to the one-dimensionality of the measured heat flow at a distance from units that have high thermal susceptibility (eg metal mortise parts, ventilation system elements, etc.);
- the surface at the location of the heat flow sensors must be cleaned prior to removal of appreciable roughness and free from curvature;
- there must be no air in the plane of contact with the object;
- heat flow sensors must be shielded from any external influences that cause a temperature gradient to appear on the surface of the heat flow sensors;

- emissivity coefficient of the heat-sensing surface of the heat-flow sensors must be close to the degree of blackness of the surface being examined. Its value should not differ from the value of the blackness of the surveyed surface by more than ± 0,03.

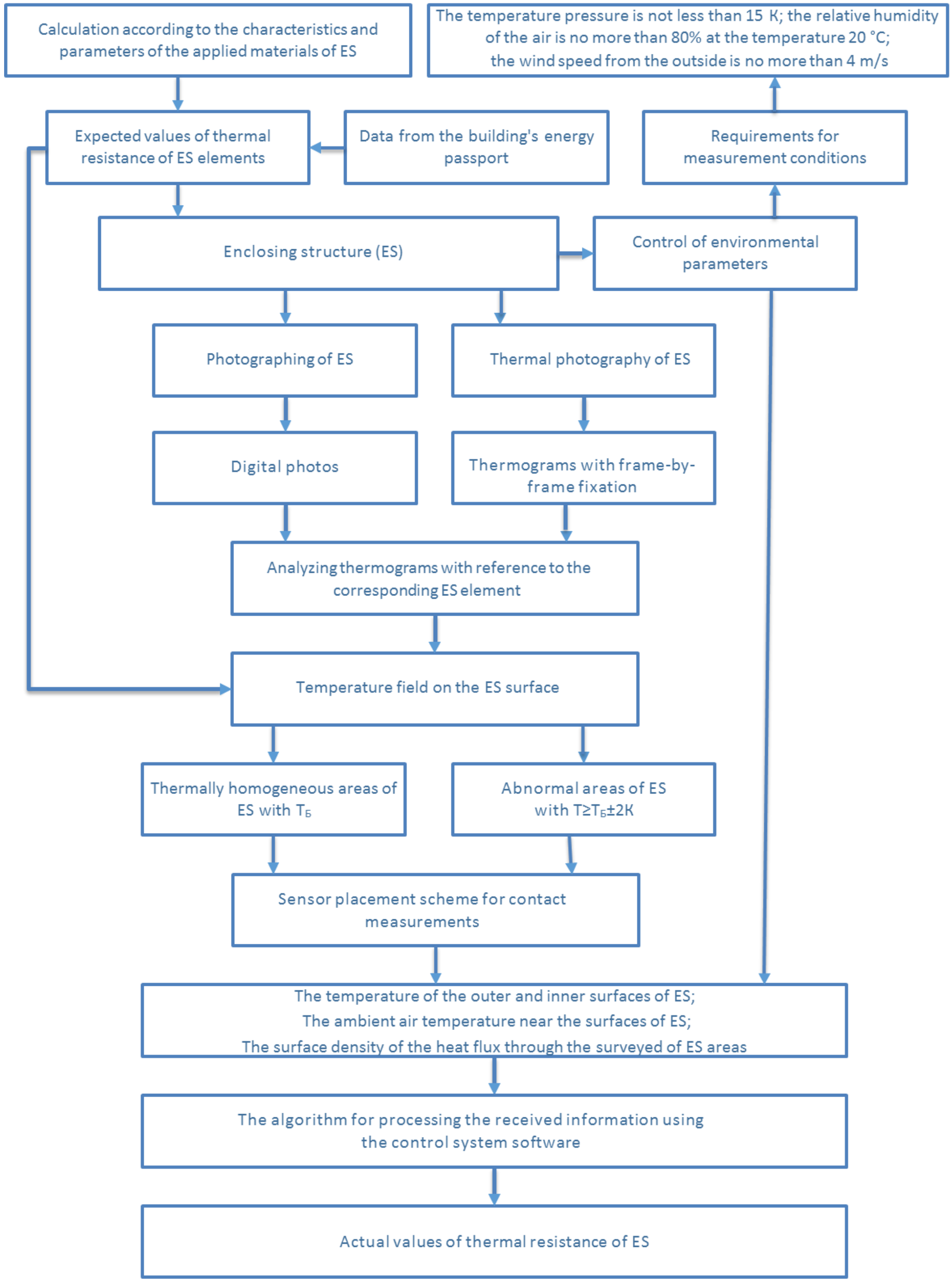

Figure 2: Methodology of the thermal resistance control of Enclosing Structures (ES).

For processing of measurement information used next method based on [1,15,16,17].

The current values of the measured heat flux density q_i (W/m^2) by the secondary measuring devices, is calculated as a product of current readings of measured the signals of heat flux sensors E_i (mV), with calibration coefficient of heat flux sensors K_{sensor} (W/(mV·m^2)) by the formula:

$$q_i = K_{sensor} \cdot E_i \, , \tag{1}$$

According to the results of measuring the current values of heat flux q_i, the temperature of surfaces T_{i_i} and T_{e_i}, the air near them $T_{i_i}^{\mathrm{Air}}$ and $T_{e_i}^{\mathrm{Air}}$ for each *n*-type zone of the *N* obtained by the contact method and calculate averaged over a period of time values.

These values are averaged over a single full day (24 hours) or over several full days. For the averaged of the listed values, the arithmetic means of the current values of each quantity, measured at regular intervals, should be taken. Also, possible to apply wavelet analysis [18].

Next, for each *n*-type zone of the *N* surveyed calculate for all-averaged values of the measured values, the averaged values of such parameters:

- the temperature difference by the formula:

$$\Delta \overline{T}_{\mathrm{structure}_n} = \overline{T}_{i_n} - \overline{T}_{e_n} \, ; \tag{2}$$

where n = 1, 2, …, N;

- the temperature head by the formula:

$$\Delta \overline{T}^{Air} = \overline{T}_{i_n}^{Air} - \overline{T}_{e_n}^{Air} \, ; \tag{3}$$

- the temperature difference between the environment and the adjacent surface of the zone, i.e. at the corresponding boundary layer, by the formulas:

$$\Delta \overline{T}_{internal_n} = \overline{T}_{i_n}^{Air} - \overline{T}_{i_n} \, , \tag{4}$$

$$\Delta \overline{T}_{external_n} = \overline{T}_{e_n} - \overline{T}_{e_n}^{Air} \, . \tag{5}$$

For each *n*-type zone of the *N* surveyed, the average values of the basic thermal characteristics of the enclosing structures are calculated, namely the thermal resistance, based on formulas (2) and (1):

$$\overline{R}_{structure_n} = \Delta \overline{T}_{structure_n} / \overline{q}_n \, , \tag{6}$$

Given the known average values of the coefficients of heat transfer α_i, α_e and thermal resistance $\overline{R}_{structure_n}$, the average value of the resistance to heat transfer $\overline{R}_{\Sigma_n}$ through the n-type section is calculated by the formula:

$$\overline{R}_{\Sigma_n} = 1/\alpha_i + \overline{R}_{structure_n} + 1/\alpha_e \, . \tag{7}$$

For specific types of enclosure structures, as known values of heat transfer coefficients α_i and α_e, as a rule, its take regulatory data: α_e = 23 W/(m^2·K) and α_i = 8 W/(m^2·K).

Scheme of determining thermal resistance through the enclosing structure is shown on figure 3.

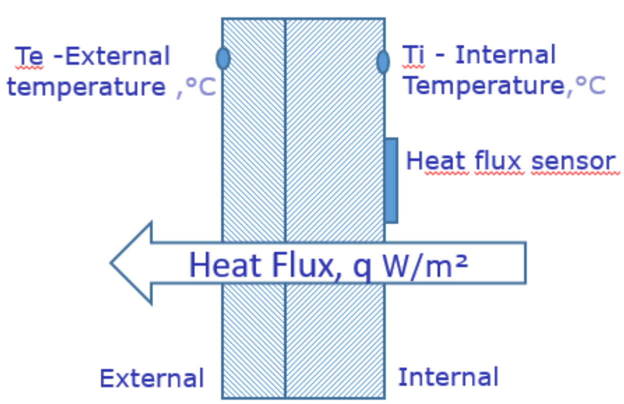

Figure 3: Scheme of determining thermal resistance through the enclosing structure.

According to standard [15,16,17], for each of the building components of the building enclosing, the thermally homogeneous areas that make up their structure must be indicated (for example, for a building wall fragment, these are brickwork, reinforced concrete floors, panels, joints of panels, etc.). The following information should also be provided:

- the total area of zones of each type $\sum_{n=1}^{N} A_n$,
- the total length of all heat-conducting inclusions $\sum_{m=1}^{M} l_m$,
- the total area of all surveyed building elements A_O.

If, for any characteristic zone, measurements are made at several points (for example, three in the height of the room), the average arithmetic values of thermal resistance and heat transfer resistance are recorded.

The average values of the reduced thermal resistance and the reduced thermal transfer resistance through the building elements of the building envelope must also be calculated:

- the average value of the reduced thermal resistance calculated for a thermally non-uniform building element of a building envelope containing N types of characteristic thermally homogeneous sections is calculated by the formula:

$$\bar{R}_{avg} = \sum_{n=1}^{N} A_n \Big/ \sum_{n=1}^{N} \left(A_n \big/ \bar{R}_{structure_n} \right), \tag{8}$$

- the average value of the reduced resistance to heat transfer through a thermally inhomogeneous enclosure structure (or inhomogeneous envelope element) containing N types of characteristic thermally homogeneous sections is calculated by the formula:

$$\bar{R}_{\Sigma_{avg}} = \sum_{n=1}^{N} A_n \,/\, \sum_{n=1}^{N} \left(A_n \,/\, \bar{R}_{\Sigma_n} \right), \tag{9}$$

- the average value of the reduced resistance to heat transfer through an inhomogeneous enclosure structure, which contains in addition to N types of characteristic thermally homogeneous sections of M linear thermal conductive inclusions with known values of the linear coefficients of heat transfer $\bar{U}_{l\,m}$, calculated by the formula:

$$\bar{R}^{rr}_{\Sigma_{ПР}} = A_O \Big/ \left[\sum_{n=1}^{N} \left(A_n \,/\, \bar{R}_{\Sigma_n} \right) + \sum_{m=1}^{M} \left(\bar{U}_{l\,m} \cdot l_m \right) \right]. \tag{10}$$

Additionally calculate the value of the reduced heat flux density through a thermally inhomogeneous zone containing in addition to N types of characteristic thermally homogeneous sections of M linear thermal conductive inclusions:

$$\bar{q}^{rr}_{f_{avg}} = \frac{\Delta \bar{T}^{Air}}{A_O} \left[\sum_{n=1}^{N} \left(A_n \big/ \bar{R}_{\Sigma_{avg\,n}} \right) + \sum_{m=1}^{M} \left(l_m \cdot \bar{U}_{l\,m} \right) \right]. \tag{11}$$

According to these estimates, as needed the following values can be further calculated the average value of the transmission coefficient of heat transfer through the enclosing structures of the building (structure) by the formula:

$$\bar{U}_{tr} = \bar{q}^{rr}_{f_{avg}} \big/ \Delta \bar{T}^{Air} = \left[\sum_{n=1}^{N} \left(A_n \,/\, \bar{R}_{\Sigma_{avgn}} \right) + \sum_{m=1}^{M} \left(l_m \cdot \bar{U}_{l\,m} \right) \right] \Big/ A_O\,; \tag{12}$$

3. Metrological characteristics studding

For studding metrological characteristics of control system by the heat flux density used a radiation comparator [14] at two values of normalized surface density of heat flux: (250 ± 10) W/m^2 and (500 ± 20) W/m^2. The advantage of using radiation comparator is ability to study sensors in any shape but condition is ensuring the same emissivity of the heat-sensing surfaces of the investigated and reference sensors. The results were obtained by comparison of the output signals of the investigated sensors with the signal of the reference sensor [14]. The maximum values of the heat flux density measurement errors are given in Tables 2 and 3. The main relative error when measuring the surface heat flux density does not exceed a limit of ± 3%.

Table 2.
Results of experimental studies of the metrological characteristics of the developed system in the mode of measurement of heat flux at a heat flux density ≈250 W/m^2.

Channel, sensor number, designation	Conversion coefficient [W/(m²·mV)]	Heat flux density measured by the reference sensor [W/m^2]	Heat flux density measured by the studied sensor [W/m^2]	Relative error of heat flux measurement [%]
25, №16793, q1	1.60	249.7	246.2	–1.40
26, №16794, q2	1.78	249.5	251.6	0.84
27, №16795, q3	1.58	249.6	251.8	0.88
28, №16796, q4	1.52	249.8	247.5	–0.92
29, №16797, q5	1.59	249.4	246.9	–1.00
30, №16798, q6	1.99	249.3	246.1	–1.28
31, №16799, q7	1.66	249.6	247.2	–0.96
32, №16800, q8	1.73	249.7	247.1	–0.99

Table 3.
Results of experimental studies of the metrological characteristics of the developed system in the mode of measurement of heat flux at a heat flux density ≈500 W/m^2.

Channel, sensor number, designation	Conversion coefficient, [W/(m²·mV)]	Heat flux density measured by the reference, sensor [W/m^2]	Heat flux density measured by the studied sensor [W/m^2]	Relative error of heat flux measurement [%]
25, № 16793, q1	1.60	495.7	493.1	–0.56
26, № 16794, q2	1.78	496.0	493.2	–0.56
27, №16795, q3	1.58	495.8	497.1	0.26
28, №16796, q4	1.52	495.7	497.8	0.42
29, №16797, q5	1.59	495.6	497.5	0.38
30, №16798, q6	1.99	495.7	495.2	–0.11
31, №16799, q7	1.66	495.6	493.1	–0.50
32, №16800, q8	1.73	495.5	495.8	0.06

Metrological characteristics of 22 thermoelectric temperature sensors (thermocouples) of the system was determined by comparing temperature values obtained by the corresponding channels of the developed system with the working standard: RTD thermocouple Pt-100 in U2C ultra thermostat. The absolute value of the temperature measurement error was performed at two temperature values: 0 °C and +50 °C. The absolute error of temperature measurement in 22 channels of the developed system was experimentally determined. The values of the temperature measurement errors are presented in Tables 4 and 5.

The absolute error of temperature measurement does not exceed the set limit of ± 1 °C.

Table 4.
Results of experimental studies of the metrological characteristics of the developed system in the temperature measurement mode at ≈0 °C.

Channel, sensor number, designation	Temperature measured by the working reference thermal-resistance sensor Pt-100 №1332 [°C]	Temperature measured by the studied sensor [°C]	Absolute temperature measurement error [°C]
1, №2893, T1	0.5	0.8	–0.3
2, №2894, T2	0.5	0.37	0.13
3, №2895, T3	0.5	0.58	–0.08
4, №2896, T4	0.5	0.65	–0.15
5, №2897, T5	0.5	0.91	–0.41
6, №2898, T6	0.5	0.82	–0.32
7, №2899, T7	0.5	0.74	–0.24
8, №2900, T8	0.5	0.7	–0.2
9, №2901, T9	0.5	0.47	0.03
10, №2902, T10	0.5	0.67	–0.17
11, №2903, T11	0.5	0.83	–0.33
12, №2904, T12	0.5	0.63	–0.13
13, №2905, T13	0.5	0.36	0.14
14, №2906, T14	0.5	0.72	–0.22
15, №2907, T15	0.5	0.45	0.05
16, №2908, T16	0.5	0.63	–0.13
17, №2909, T17	0.5	0.77	–0.27
18, №2910, T19	0.5	0.56	–0.06
19, №2911, T19	0.5	0.43	0.07
20, №2912, T20	0.5	0.59	–0.09
21, №2913, T21	0.5	0.83	–0.33
22, №2914, T22	0.5	0.8	–0.3

Table 5.
Results of experimental studies of the metrological characteristics of the developed system in the temperature measurement mode at ≈50 °C.

Channel, sensor number, designation	Temperature measured by working reference thermal-resistance sensor Pt-100 №1332, [°C]	Temperature measured by the studied sensor, [°C]	Absolute temperature measurement error, [°C]
1, №2893, T1	49.92	49.72	0.2
2, №2894, T2	49.92	50.14	–0.22
3, №2895, T3	49.92	49.62	0.3
4, №2896, T4	49.92	49.55	0.37
5, №2897, T5	49.92	50.06	–0.14
6, №2898, T6	49.92	49.82	0.1
7, №2899, T7	49.92	50.11	–0.19
8, №2900, T8	49.92	49.74	0.18
9, №2901, T9	49.92	50.03	–0.11
10, №2902, T10	49.92	49.81	0.11
11, №2903, T11	49.92	50.05	–0.13
12, №2904, T12	49.92	49.79	0.13
13, №2905, T13	49.92	49.99	–0.07
14, №2906, T14	49.92	50.02	–0.1
15, №2907, T15	49.92	49.83	0.09
16, №2908, T16	49.92	50.1	–0.18
17, №2909, T17	49.92	49.68	0.24
18, №2910, T19	49.92	49.82	0.1
19, №2911, T19	49.92	50.01	–0.09
20, №2912, T20	49.92	49.62	0.3
21, №2913, T21	49.92	49.72	0.2
22, №2914, T22	49.92	50.14	–0.22

4. Practical application of information-measuring technology for control the thermal resistance of the buildings enclosing structures

The study of a sixteen-storey residential building was conducted.

The building structure is a precast concrete frame with precast ceilings and precast foundation slab. The exterior walls of the building are made of reinforced concrete 100 mm thick, expanded clay concrete 200 mm thick, and 100 mm thick plaster layer. The attic and technical floor are cold. There is piping in the attic. Translucent structures (windows, balcony doors) made of double-glazed windows in wooden dividing frames. The building has water heating, hot water supply, which is connected to the district heating system. The total number of apartments is 112. The total height of the house is 52.605 m, the height of the basement is 2.7 m. The building has one stairwell and two lifts. The heated area of the building is 9021 m^2. The heated volume of the building is 27064 m^3. The total area of external envelopes is 7065 m^2.

At the first stage, a thermal imaging survey of the entire building is carried out according to ISO 6781 [2] and EN 13187 [3]. Thermal imaging allowed to obtain qualitative detection of thermal irregularities in building envelopes [2] and locate areas with uniform temperature distribution where temperature and heat flux sensors can be placed.

The photographs and thermal images of the building envelope are presented below. Line and dot markers represent areas with a higher temperature than the entire wall. These are heat loss zones that require special attention. A dot marker also indicates the area with normal surface temperature.

Figure 4 shows the zones of significant thermal heterogeneity of the side wall.

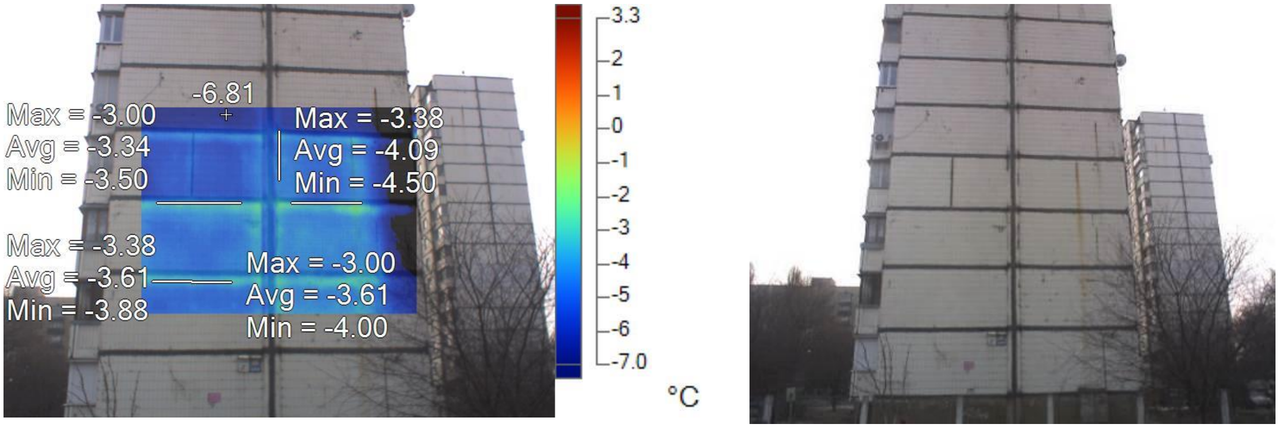

Figure 4: Thermal image of the side wall of a 16-storey building

In Figure 4 the joints of floors and walls are marked with the increased heat losses in the area of the panel perpendicular to the facade.

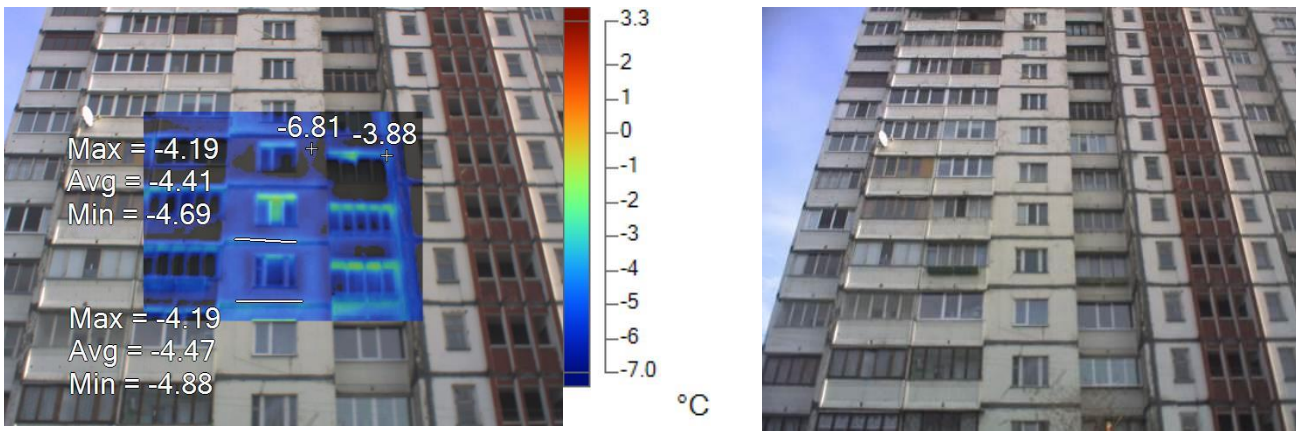

Figure 5: Thermal image of joints of the 16-storey building facade

In Figure 5 shown cold bridges on joints witch requires attention. Figure 6 shows that the envelope, which is perpendicular to the building facade, is a cold bridge and requires insulation.

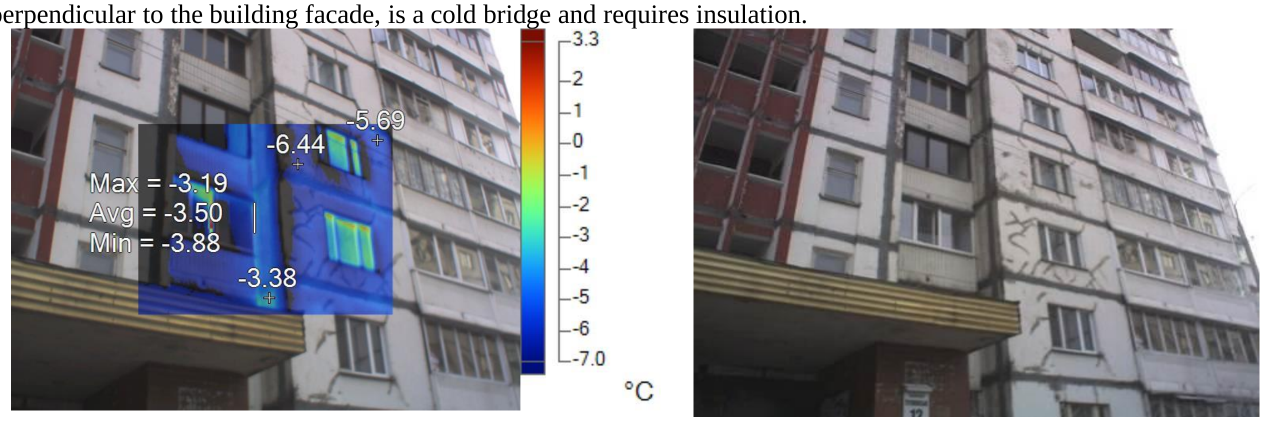

Figure 6: Thermal image of the face-wall of the 16-storey building

The thermal image in Figure 7 shows the areas with high heat losses at the entrance to the building.

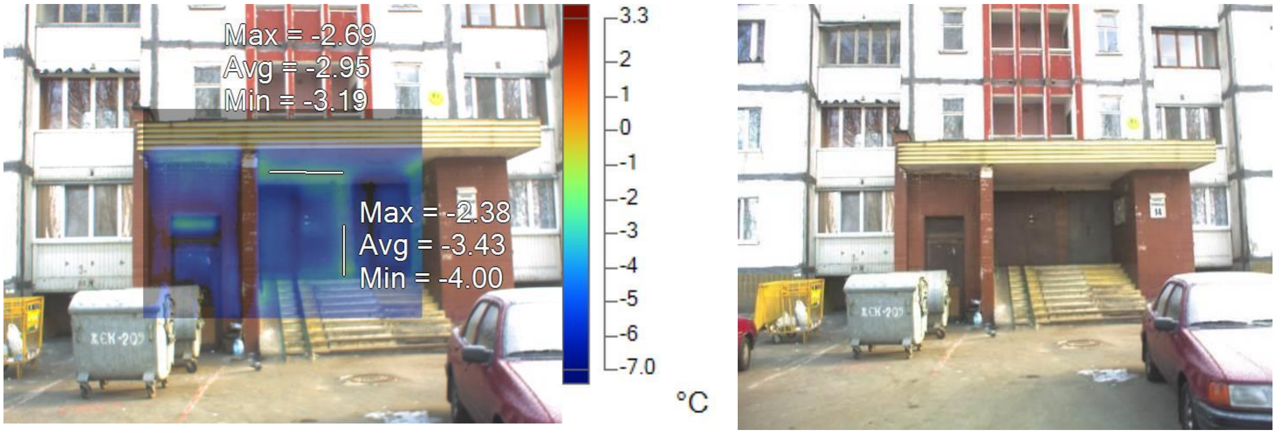

Figure 7: Thermal image of the building entrance

The thermal image shown in Figure 8 markers indicate the areas where heating appliances (heating system radiators) are located. As it can be seen from the temperature indicators the lack of thermal insulation in these zones leads to increased heat losses.

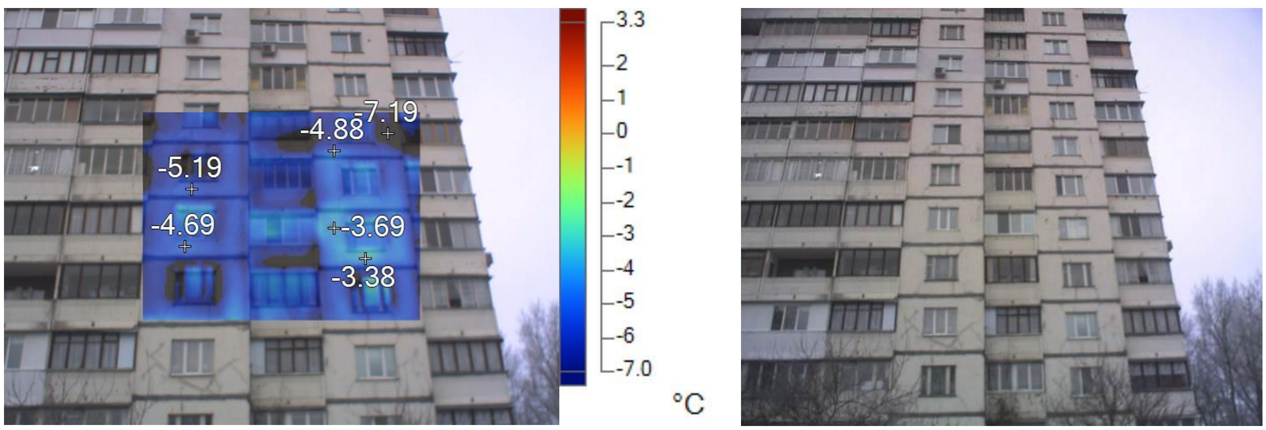

Figure 8: Thermal image of zones with high heat losses

At the second stage, the measurements with the use of temperature and heat flux sensors are carried out according to ISO 9869 [6]. This allows us to obtain a quantitative estimate of local heat losses, as well as to calculate the thermal resistance of the envelope structures.

Not all required building envelope elements, for example such as overlapping of the 16th floor, overlapping of the ground floor, can be studied with in-situ measurement of thermal resistance. For these envelope elements representative samples were taken and thermal conductivity was measured with the device described in [13]

The third stage is calculation of thermal resistance based on obtained results. The results of determining the geometric and thermal characteristics of the envelope structure according to [6] are shown in table 6.

By using thermal imaging of the surface temperature of envelope structures in accordance with ISO 6781 we managed to detect local structural defects and identify certain location of the installation of heat flux sensors, making the measurement process more effective.

During the experiments up to 8 zones were monitored simultaneously using the measurement units connected via RS-485 and radio frequency modules which made it possible to monitor whole buildings in the same conditions. If we used a monitoring system with only two measurement zones for this task, it would lead to a significant increase in measurement time.

Table 6.
The results of determining the geometric and thermal characteristics of the building envelope

Building envelope element	Area of elements of the envelope structure, m^2	Thermal resistance (R)
Facade walls	2699	0.81
Windows	303	0.3
Loggias, including:		
- external panel	1106	0.24
- loggia glazing	1567	0.18
- the inner wall	1792	0.81
- internal glazing	883	0.42
Technical floor:		
- outside walls	325.9	0.81
- roofing	648	0.26
- overlapping of the 16th floor	648	0.44
Underfloor:		
- outside walls	139.7	0.81
- overlapping of the ground floor	648	0.4
- envelope on soil	784.7	4.2

5. Conclusions

Information-measuring technology for buildings enclosing structures thermal resistance control proposed which based on a combination of thermal imaging of the surface temperature for quality analysis and quantitative contact measurements of surface temperature and heat flux values. Advantages of this technology are: reduced the influence of the subjective factor on the control process; ability to identify local defects in thermal insulation; carry out control of enclosing structures that have a complex design; numerical thermal resistance values of the enclosing structures with accordance to metrological requirements.

Presented practical application of information-measuring technology for control the thermal resistance of the buildings enclosing structures on example of sixteen-storey residential building. It is shown that the modular construction of the system gives possibility to carry out control of enclosing structures that have a complex design.

6. References

[1] ISO 6946, Building Components and Building Elements – Thermal Resistance and Thermal Transmittance – Calculation Method, ISO, Geneva, Switzerland, 2007.

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