Methodology of Calculation of Heat Losses by Envelope Structures on an Example of a Heating Boiler using biofuel.

**Ivan Pavlovich Yakushkin*, Aleksandr Viktorovich Larchikov, and
Dmitry Borisovich Rygalin.**

National Research University of Electronic Technology, Russia, Moscow, Zelenograd, Shokin square, 1, 124498.

ABSTRACT

Modern high-resolution technologies are becoming a new tendency of thermal imaging non-destructive testing. Those technologies are required for development of quick and accurate techniques and methodologies of data post-processing for thermal images. The presented methodology implements algorithms, which allow to analyze zones of thermal losses of envelope structures of heating boilers with minimal time expenditures. Also, those solutions allow to consider thermal losses with high accuracy, which allows to decrease thermal pollutions in atmosphere and increase efficiency of system, which use boiler equipment.

Keywords: Non-destructive thermal testing, methodologies of infrared diagnostics, infrared diagnostics, thermal losses, thermal losses of boiler, envelope structures, thermal protection, boiler equipment, burner, pellet boiler, pellet.

*Corresponding author

INTRODUCTION

In two recent decades, due to uncontrolled production and wasteful use of non-renewable energy resources, humanity brought closer global crisis of world fuel reserves, as well as significant worsening of ecological conditions. Experts predict that, if people will keep use resources at the current rate, world reserves of natural resources such as gas, oil and coal, will become depleted in 40-50 years. In Russia potential of energy saving is very high. Power-intensity of Russian economy is significantly higher in purchasing-power parity than that parameter of economies of the USA, Japan and developed countries of EU.

Measures aimed at the decrease of power-intensity for the period of 1998-2005 were insufficient for the decrease of dynamic growth of demand for energy resources. Increase of demand for natural gas and electric energy appeared to be higher than specified values. Total power consumption in Russia was, approximately, 990 mln tons of equivalent fuel, and losses of fuel and energy resources were, approximately, 35%. If rate of implementation of energy-saving and energy-efficient equipment will reach the values same with EU, power-consumption will decrease to 650 mln tons of equivalent fuel.

Systematic work in the field of energy-saving and increase of energy-efficiency in various industries of Russian economy started after the adoption of the Federal Law of the Russian Federation of 23.11.2009 No. 261-FZ "On energy-saving and increase of energy-efficiency and changes of certain laws of the Russian Federation". In 2010 the State Program of the Russian Federation "Energy-saving and the increase of energy-efficiency in the period to 2020" ("STEE-2020") was adopted by the decree of the Government of the Russian Federation of 27.12.2010 No. 2446-r. One of the main aims of the Program is the decrease of power consumption of GDP by 40% by 2020.

In order to achieve the goals of "STEE-2020", it is necessary to have objective data on real amount and quality of the used energy resources. That data can be obtained using instruments for measurement of used energy resources and systems on their basis. Installation of instruments is the first step in all strategies for increase energy efficiency. However, there are specific parameters, which are impossible to calculate on the basis of data from the instruments.

One of the main secondary resources, which are used by humanity, is thermal energy. Thermal energy is used for heating systems of buildings, heating of water for hot water supply system and various technological and production purposes. According to the data from the Federal Statistics Agency (Rosstat), in Russia in 2014 814.2 mln Gcal was consumed. At that the official losses of thermal energy were 127.5 mln Gcal or 15.7%.

According to Rosstat, there were 75,236 sources of heat supply in Russia in 2014. From them, approximately, 60,000 belong to small boiler rooms with power of up to 3 Gcal/hour. Also, for purposes of heat supply of personal residential houses and personal part-time farms 800,000-1,000,000 autonomous individual heat-generators – heating boilers, using various kinds of fuel, are operated. Generally, a heat generator consists of a combustion chamber with heat exchanger, burner and centrifugal and axial fans. Depending on the type of the used burner, natural gas, diesel, bio-gas, oil, coal, peat, wood, fuel granules (pellets) and other kinds of natural or artificial kinds of fuels are used in heating boilers.

Fuel granules (pellets) are a kind of bio-fuel produced by peat, wastes of lumber production and various agricultural wastes [1,2]. Heating boilers using pellets recently becoming increasingly popular, which is, generally, related to spreading of that kind of fuel and its high operational characteristics as compared with regular boilers using solid fuels. Another positive point is possibility to upgrade regular furnaces or boilers, using solid fuels, in order to use pellets. In order to further automate process of operation of a boiler, pellets are put into a bunker, from which they are fed to a boiler. Volume of a bunker depends on capacity of a boiler. Shape of the major part of boilers is parallelepiped, which simplifies their control by means of instruments and visual inspection. In order to control processes in furnace thermal technologies can be implemented [3].

For analysis of quantitative parameters of heat losses through envelope structure it is necessary to carry out complex thermal simulation of the study object [4]. Thermal simulation is the method for experimental study of thermal processes, based on physical similarity and mathematical description of processes, which are taking place in the modeled object. Generally, studies using the method of thermal

simulation are carried out in a laboratory. It is related to the fact that in operating conditions there are large numbers of occurring thermal exchange processes, which are often taken into account from physical and mathematical point of views.

The aim of the thermal simulation is mathematical description of processing, which takes place inside the measured object, and calculation of main thermophysical parameters on the basis of experimentally obtained data. In the discussed case the object of thermal simulation is a vertically oriented envelope structure, i.e. the wall of the heating boiler, which can be tested using methods of thermal non-destructive testing [5,6].

METHODOLOGY

Input data for thermal simulation are as follows: distance to object, height, width, material of wall of a boiling heater, temperature of external and internal air, temperatures of internal and external surfaces, thicknesses of materials, which belong to an envelope structure, thickness of a structure, as well as data from technical certificates and documentations on a tested object.

Thermographic camera is selected depending on design features of the tested object. For study of an envelope structure of that type the most suitable thermographic camera type is thermographic cameras recording IR-radiation in the range of 7...14 μm [7,8]. For measurement it is reasonable to use thermographic equipment with the best resolution (320x240 pixels and higher). Higher resolution of a thermographic camera allows to achieve higher accuracy, and, thus, increase accuracy of calculation of main parameters. During the testing of a surface of an envelope structure of a building using a thermographic camera temperature is registered in each point (each pixel) of a measured surface. Thus, temperature distribution for a whole surface of a tested object in a given moment of time is obtained, which in further can be processed automatically [9]. Another important point is correct selection of viewing angle during thermography [10].

Thermographic camera is equipped with complicated optical system, a simplified model of which may be represented as a single lens with a number of parameters: focal length F, etc. (Figure 1).
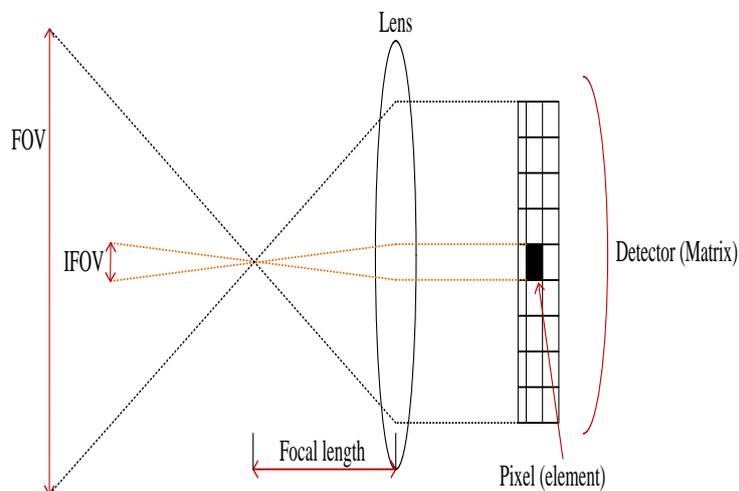

Fig.1. Scheme of simplified optical system of a thermographic camera.

If a certain object of size Y is measured by means of a thermographic camera from distance L, its image on matrix will be of size Y'. That ratio can be expressed as follows:

$$\frac{Y}{Y'} = \frac{L}{L'} ;$$

where L' is distance between image and lens.

Field of view (FOV) represents boundaries of a viewed space, which can be observed at a certain moment of time. In a case of optical devices or sensors it is a spatial angle, through which a detector is sensitive to electromagnetic radiation [11]. In optical-mechanical systems focal length of a lens and size of a sensitive detector define a fixed relationship between FOV and working distance. In matrix thermographic cameras measurement is carried out on the basis of IR radiation detectors, which are situated along rows and columns of a rectangular matrix, and, generally, they don't fell a matrix completely.

All objects, which are in FOV during testing, are recorded by matrix, and, thus, represented on a thermal image. Size of FOV and size of a detector of matrix thermographic camera directly influence resolution of image [12]. Characteristic distance of a lens in that case is distance between a lens and a tested object. Increase of fill ratio leads to increase of an image quality. In the best matrices fill ratio can reach 90% [13]. FOV of detectors defines size of the smallest object, which temperature field can be captured using a thermographic camera. That filled of view is referred as instantaneous field of view (IFOV).

Thus, knowing distance from an object L, FOV, IFOV and resolution of matrix of a thermographic camera, one can identify the following parameters of the measured object H and the smallest measured element $H_{\min}$ (Figure 2):

$$H = L \cdot tg\,\alpha = L \cdot FOV$$

$$H_{\min} = \frac{L \cdot tg\,\alpha}{B} = L \cdot IFOV$$
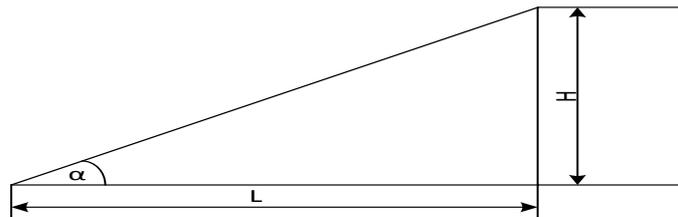
Fig.2. Ratio of distance to a tested object (L), height of frame of a thermographic camera (H) and optical FOV of a lens.

Where:
- α – optical FOV of a lens, degrees;
- B – number of vertical elements of a matrix AxB;

Surface of an envelope structure is divided into elements [14], thus, it becomes possible to carry out calculation for each element independently [15], and the obtained result can be summed or averaged in the final calculation. On the basis of the obtained data coordinate grid of the tested object is created (Figure 3).
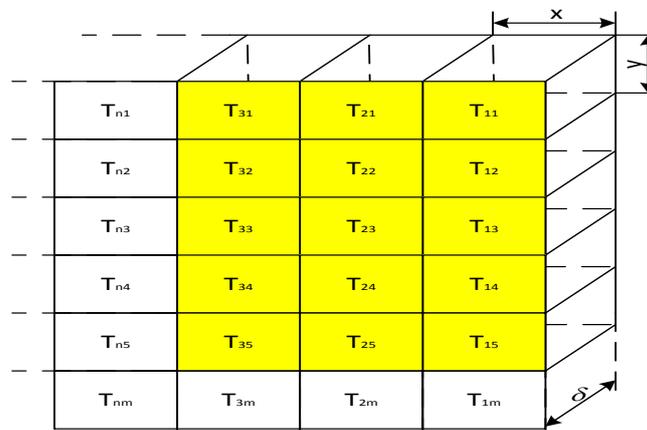
**Fig.3. Division of the measured surface into elements and creation of the coordinate grid.**

On the basis of the coordinate grid, if necessary, several thermal images can be joined in one using characteristic distributions of temperatures at edges of images. Also, it is possible to use a number of software applications, which allow to create panoramic photographs from a set of images. Generally, principle of operation of that kind of software is the same with the described above.

Simplified scheme of testing in that case is presented in Figure 4.
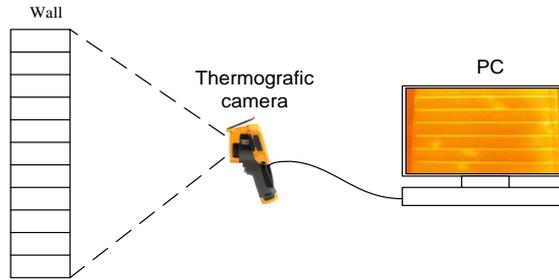
Fig.4. Simplified scheme of testing.

After required preparation thermal images of surfaces are joined into one thermal model of an envelope structure in a way that in every elementary cell of a coordinate grid of a wall temperature measured by a thermographic camera is known. For the whole length of an envelope structures thermal images are joined into one image with its own coordinate grid.

In other words, there is one-to-one correspondence, when each element of external surface of an envelope structures correspond to an element of an internal surface. For a case of a heating boiler temperature of an internal wall is measured by means of contact thermometers installed beforehand, which can carry out measurements with high accuracy at high temperature environment. That process is represented in Figure 5. Thus, there is a volumetric element, which geometry is close to parallelepiped with a square base and enclosures, which are going inside the object.
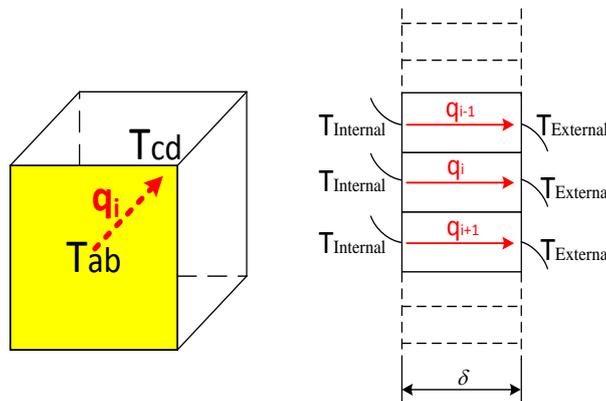
Fig.5. Connection of surfaces into one thermal model of a wall.

That method of connection has two problems, on a condition, that there is more than one contact thermometer inside a boiler. First, it is necessary to connect elements of external and internal surfaces with high precision. Second, it is necessary to connect elements of various spatial dimensions. That problem can be solved by means of harmonization of sizes of internal and external grid. Also, the situation is possible, at which several elements of one surface correspond to one element of another surface. In the case of use of one thermometer inside a boiler those problems are not topical.

After measurements computer processing of the obtained results is carried out. For that it is necessary to calculate thermal flux, which exists in each element. In calculations, it is assumed that the wall is in

thermodynamic equilibrium/saturation state, and thermal flux passing through a wall inside a room is, approximately, equal to a flux at an external surface.

According to Newton's law of cooling [16], at boundary of external media (air) and a wall thermal flux q is equal to:

$$q = \alpha_i (T_{ia} - T_{iw}) = (\alpha_r + \alpha_{conv})(T_{ia} - T_{iw}) \qquad (1)$$

Where:

α_a – coefficient of heat emission from a wall to external air;

T_{iw} – temperature of internal wall, K;

T_{ew} – temperature of external wall, K;

T_{ia} – temperature of internal air, K;

According to [17], for vertically oriented surfaces in a room, at external surface of a wall of a heating boiler convective heat emission coefficient α_{conv} can be calculated as follows:

$$\alpha_{conv} = 1.66(T_h - T_c)^{1/3}, \qquad (2)$$

where T_h – temperature of a hot object;

T_c – temperature of cold environment.

Coefficient of heat emission by radiation in that case can be calculated using Stefan-Boltzmann equation [18-19]:

$$q_r = \varepsilon\sigma(T_h^4 - T_c^4) = \alpha_r(T_h - T_c)$$

where ε – reduced radiation coefficient;

σ – Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ W/(m²·к⁴);

T_h – temperature of hot object;

T_c – temperature of cold environment;

α_r – coefficient of heat emission by radiation, $\alpha_r = \varepsilon\sigma(T_{ew}^2 + T_{ea}^2)(T_{ew} + T_{ew})$ (3).

Thus, total coefficient of heat emission from an external surface will be a sum of coefficients for convection and radiation [20]:

$$\alpha_i = \alpha_r + \alpha_{ce} = 1.66(T_{ew} - T_{ea})^{1/3} + \varepsilon\sigma(T_{ew}^2 + T_{ea}^2)(T_{ew} + T_{ea}) \ (4)$$

Substitution of the expression (4) in the expression (1) produces the final expression for calculation of thermal flux q through the wall of a heating boiler.

$$q = \alpha_i (T_{ew} - T_{ea}) = 1.66(T_{ew} - T_{ea})^{4/3} + \varepsilon\sigma(T_{ew}^4 - T_{ea}^4) \qquad (5)$$

On the basis of thermal flux calculated by means of the expression (5) thermal energy, which is lost by a wall of a heating boiler at a unit of time is calculated. The resulting heat is equal to integral along the study surface of a boiler wall: $Q = \iint\limits_{S=n\cdot m}(1.66(T_{ia} - T_{iw})^{4/3} + \varepsilon\sigma(T_{ia}^4 - T_{iw}^4))dndm$

where n and m – dimensions of the measured surface.

In the case of plane-parallel wall the integral will transform into sum of thermal fluxes along the whole studied surface:

$$Q = \sum_{S} (1.66\left(T_{ia\_nm} - T_{iw\_nm}\right)^{4/3} + \varepsilon\sigma\,(T_{ia\_nm}^{4} - T_{iw\_nm}^{4})) \qquad (6)$$

Thus, after obtaining amount of thermal energy, which is emitted by a heating boiler through an envelope structures in a second, while knowing distribution of losses at each element (pixel of a surface), it becomes possible to calculate flow of heat through walls on a basis of application of various types of thermal protection, which, finally, will increase efficiency of any boiler.

Inaccuracy

In order to identify accuracy of calculated values of thermal flux it is necessary to calculated inaccuracy of the formula (5), which is obtained used the methodology described above. In order to identify inaccuracy it is necessary to define inaccuracy of input data.

For measurements of temperature of the internal chamber of the heating boiler high-precision temperature sensors are required, which can operate at high temperature conditions and has accuracy of 0.1-1 ^{o}C. Measurements of air temperature in a room were carried out using sensors with accuracy of 0.1-1 ^{o}C. Temperature of surface of a boiler must be measured by means high-precision modern thermography equipment. Level of inaccuracy due to hardware for modern thermographic cameras is, approximately, 3-4 ^{o}C for temperatures of 300-400 ^{o}C. That inaccuracy can be minimized using special methodologies of capturing of images.

In a case of a boiler with metal walls covered with black coefficient of emission of surface will tend to maximum value. In that case value of coefficient of radiation will be, approximately, 0.97...0.99, and inaccuracy of its measurement will be minor. Thus, in further calculations coefficient of radiation ε is accepted equal to 1.

In order to calculate inaccuracy Δq the following formula must be used:

$$\Delta q = \sqrt{\left(\frac{\partial q}{\partial T_{ew}}\Delta T_{ew}\right)^{2} + \left(\frac{\partial q}{\partial T_{ea}}\Delta T_{ea}\right)^{2}}$$

$$\Delta q = \sqrt{\left((2.21(T_{ew} - T_{ea})^{1/3} + 4\sigma T_{ew}^{3})\Delta T_{ew}\right)^{2} + \left((-2.21(T_{ew} - T_{ea})^{1/3} + 4\sigma T_{ew}^{3})\Delta T_{ew}\right)^{2}} \qquad (7)$$

In order to evaluate level of influence of inaccuracy on measurement results it is necessary to simulate the obtained equation (5) and (7) with possible values of input data. Values of input data and results of calculations using the equations are presented in Figure 1. In the calculations inaccuracies in measurements of temperatures of external walls and external air, $\Delta T_{ew} = \pm 2\ ^{o}C$, $\Delta T_{ea} = \pm 1\ ^{o}C$ are considered.

Table.1. Input data and results of evaluation of inaccuracy of calculations with the formula (5).

Input data		Results		
Tew	Tea	q	Δq	%
100	20	1251.87	85.57	6.84
150	20	2490.60	114.05	4.58
200	20	4107.31	146.62	3.57
250	20	6163.57	184.69	3.00
300	20	8735.16	229.27	2.62
350	20	11909.17	281.20	2.36

From the calculations it can be seen that increase of temperature at external wall of the heating boiler, and, thus, increase of temperature in the boiler, leads to decrease of total inaccuracy of measurements. At that, for difference between temperatures of the enveloping structure and air in the room of 80 ^oC, inaccuracy of measurements is 7%, which is sufficiently accurate result.

RESULTS

For the obtained and prepared thermal images it is possible to carry out further calculation of losses of thermal energy through the wall of the heating boiler. For example, let's take randomly defined distribution (Table 2).

Table.2. Randomly defined distribution of temperatures along the surface of the tested object

146.52	146.01	148.52	141.51	154.04	151.81	146.25	144.53	150.98	141.78	157.71	165.07	119.78	142.10	158.99
154.42	131.53	138.20	149.49	136.94	149.80	152.60	147.71	150.23	146.19	161.58	137.43	158.76	165.29	167.26
136.21	158.89	145.34	153.29	154.49	138.47	151.80	151.39	133.57	175.87	151.57	147.22	148.71	144.52	138.93
160.23	160.42	143.23	157.65	151.89	150.21	157.51	164.33	152.36	166.37	149.88	157.94	147.00	138.87	157.67
158.20	149.36	159.15	141.75	166.79	138.12	151.19	150.54	141.32	151.11	135.48	143.90	150.40	149.28	151.98
139.31	145.94	163.56	147.81	149.07	153.49	137.87	145.21	160.43	146.68	154.14	143.65	148.94	160.53	155.74
132.26	147.27	159.32	151.05	141.98	154.14	153.94	163.22	162.12	135.30	160.54	137.78	147.39	126.76	146.96
141.70	159.57	143.41	167.48	154.85	154.01	156.17	157.99	164.06	157.24	179.68	152.98	145.30	149.50	150.88
167.07	160.65	144.48	151.54	149.89	147.28	138.85	137.04	147.16	170.43	150.72	136.51	153.58	135.40	142.30
146.94	142.17	152.49	141.30	152.66	145.90	137.33	154.29	153.85	142.87	174.95	159.72	139.99	133.39	144.72
141.80	145.73	134.66	157.92	143.65	153.66	142.83	133.95	140.66	134.87	164.51	141.40	151.22	149.79	164.06
160.70	141.78	147.82	142.26	148.27	132.64	143.19	144.17	151.50	161.72	143.87	158.66	157.36	140.44	149.51
140.39	157.60	149.85	145.84	130.70	141.08	141.75	145.81	162.70	148.83	147.81	146.29	147.51	138.46	146.56
155.82	125.74	146.07	164.62	152.93	156.53	168.87	155.03	161.21	137.19	155.72	152.21	141.36	155.65	143.87
149.01	128.19	153.45	141.35	151.26	152.68	164.18	166.09	133.07	141.69	149.52	155.82	146.06	155.14	143.98
154.09	156.63	146.68	128.33	142.00	126.85	158.28	147.10	157.20	141.44	140.06	141.83	148.31	161.07	151.73
154.84	148.49	139.98	154.99	144.65	144.18	131.68	143.52	159.63	148.97	149.86	161.30	135.58	163.57	136.39
139.16	145.89	131.94	147.01	161.60	151.79	148.45	143.92	154.62	157.00	155.81	168.08	141.75	141.55	159.39
155.88	147.04	146.82	141.77	157.68	165.79	151.33	141.16	161.72	163.03	146.62	141.20	143.96	161.28	155.14
143.65	157.08	152.25	133.50	156.85	153.74	149.74	153.03	135.43	133.54	144.96	141.52	147.93	151.40	139.25

Table 3 presents the results of calculation of thermal flux in any point, taking into account $T_{ew} = 20\ ^oC$. For example, we used distribution 3x4 for number of elements along lengths of sides. It corresponds to the most widely used matrices of modern thermographic cameras.

Table.3. Distribution of values of thermal flux for calculated elements

2392.63	2378.59	2448.85	2255.18	2606.59	2542.16	2385.13	2337.70	2518.46	2262.33	2713.84	2935.65	1699.78	2270.96	2751.82
2617.50	1991.59	2166.01	2476.03	2132.64	2484.90	2564.85	2425.96	2497.18	2383.46	2829.42	2145.66	2745.08	2942.48	3003.20
2113.47	2748.78	2359.85	2584.88	2619.55	2173.41	2541.96	2530.05	2044.40	3276.53	2535.24	2412.35	2454.19	2337.30	2185.63
2788.74	2794.69	2301.84	2712.00	2544.46	2496.45	2707.98	2913.07	2557.95	2975.62	2487.11	2720.58	2406.13	2183.89	2712.70
2728.26	2472.39	2756.72	2261.65	2988.52	2164.05	2524.60	2505.88	2249.88	2522.20	2094.10	2320.18	2501.99	2470.21	2547.18
2195.64	2376.74	2889.34	2428.76	2464.24	2590.46	2157.41	2356.32	2794.74	2397.17	2609.35	2313.41	2460.62	2797.91	2656.09
2010.39	2413.56	2761.67	2520.54	2267.80	2609.51	2603.51	2878.98	2845.77	2089.47	2798.19	2155.03	2416.91	1870.98	2405.04
2260.18	2769.19	2306.81	3010.03	2630.04	2605.48	2668.65	2722.14	2904.80	2699.93	3401.24	2575.94	2358.96	2476.38	2515.58
2997.17	2801.58	2336.18	2534.37	2487.56	2413.97	2183.43	2135.39	2410.61	3102.43	2510.98	2121.28	2593.25	2092.22	2276.52
2404.45	2272.98	2561.62	2249.34	2566.72	2375.64	2142.94	2613.78	2600.85	2292.10	3246.53	2773.61	2213.94	2039.75	2342.97
2262.94	2370.76	2072.78	2720.05	2313.55	2595.57	2291.05	2054.25	2232.00	2078.33	2918.50	2252.16	2525.43	2484.70	2904.82
2802.90	2262.40	2429.07	2275.37	2441.60	2020.33	2300.86	2327.76	2533.28	2833.50	2319.48	2741.99	2703.66	2226.08	2476.77
2224.85	2710.71	2486.37	2373.83	1970.43	2243.35	2261.63	2372.94	2863.44	2457.53	2428.69	2386.40	2420.45	2173.09	2393.82
2658.30	1845.49	2380.26	2921.88	2574.38	2679.00	3053.42	2635.38	2818.37	2139.23	2655.43	2553.79	2251.02	2653.35	2319.38
2462.58	1906.85	2589.38	2250.83	2526.35	2567.13	2908.45	2967.12	2031.32	2259.94	2477.09	2658.29	2379.95	2638.52	2322.36
2607.91	2682.06	2397.27	1910.20	2268.47	1873.14	2730.82	2409.07	2698.94	2253.02	2215.90	2263.73	2442.87	2813.99	2539.97
2629.80	2448.05	2213.67	2634.14	2341.06	2328.06	1995.63	2309.77	2770.92	2461.38	2486.51	2821.14	2096.80	2889.65	2118.14
2191.77	2375.22	2002.28	2406.28	2830.04	2541.54	2446.89	2320.69	2623.35	2693.00	2657.92	3028.71	2261.65	2256.24	2763.84
2660.13	2407.18	2401.19	2262.06	2713.06	2957.68	2528.46	2245.61	2833.51	2873.29	2395.50	2246.52	2321.94	2820.40	2638.45
2313.33	2695.37	2554.89	2042.55	2688.43	2597.88	2483.27	2577.14	2093.02	2043.65	2349.55	2255.43	2432.14	2530.48	2194.14

Let's calculate heat loses of the structure:

$$Q = \sum_S (q_{nm}) = 742{,}801.42 \pm 34{,}098.88 \ \text{W/m}^2$$

For the area of the structure $S = 1\,\text{m}^2$ and time of operation of the heating boiler in the given temperature regime $t = 1\,\text{h}$, heat losses for the surface of the wall are as follows:

$$Q = 0.6388 \pm 0.029\,\text{Gcca}$$

The obtained value of thermal losses is very high. For the cost of 1 Gcal of 300-400 rubles (5-6.5$), daily losses in terms of cost will be 4,500-6,000 rubles (75-100$). That loses can be avoided by means of correct adjustment of the heating boiler and effective use of thermal protection of the boiler.

For effective use of thermal protection of the envelope structures of the heating boiler it is necessary to evaluate thermal resistance R_T of the wall in every measured point. Formula for calculation of that parameter can be divided from the Fourier [21] for the case of stationary thermal transfer [22,23].

$$q = \frac{T_{ia} - T_{ew}}{R_T}$$

$$R_T = \frac{T_{iw} - T_{ew}}{q}$$

Values of thermal flux q are presented in Table 3. Thermal resistance of the wall was calculated for every independent element (Table 4). For example, difference between internal and external surfaces of wall of the heating boiler was accepted as $T_{iw} - T_{ew} = 300\ ^{o}C$.

Table.4. Distribution of values of thermal resistance for calculated elements

0.1254	0.1261	0.1225	0.1330	0.1151	0.1180	0.1258	0.1283	0.1191	0.1326	0.1105	0.1022	0.1765	0.1321	0.1090
0.1146	0.1506	0.1385	0.1212	0.1407	0.1207	0.1170	0.1237	0.1201	0.1259	0.1060	0.1398	0.1093	0.1020	0.0999
0.1419	0.1091	0.1271	0.1161	0.1145	0.1380	0.1180	0.1186	0.1467	0.0916	0.1183	0.1244	0.1222	0.1284	0.1373
0.1076	0.1073	0.1303	0.1106	0.1179	0.1202	0.1108	0.1030	0.1173	0.1008	0.1206	0.1103	0.1247	0.1374	0.1106
0.1100	0.1213	0.1088	0.1326	0.1004	0.1386	0.1188	0.1197	0.1333	0.1189	0.1433	0.1293	0.1199	0.1214	0.1178
0.1366	0.1262	0.1038	0.1235	0.1217	0.1158	0.1391	0.1273	0.1073	0.1251	0.1150	0.1297	0.1219	0.1072	0.1129
0.1492	0.1243	0.1086	0.1190	0.1323	0.1150	0.1152	0.1042	0.1054	0.1436	0.1072	0.1392	0.1241	0.1603	0.1247
0.1327	0.1083	0.1300	0.0997	0.1141	0.1151	0.1124	0.1102	0.1033	0.1111	0.0882	0.1165	0.1272	0.1211	0.1193
0.1001	0.1071	0.1284	0.1184	0.1206	0.1243	0.1374	0.1405	0.1244	0.0967	0.1195	0.1414	0.1157	0.1434	0.1318
0.1248	0.1320	0.1171	0.1334	0.1169	0.1263	0.1400	0.1148	0.1153	0.1309	0.0924	0.1082	0.1355	0.1471	0.1280
0.1326	0.1265	0.1447	0.1103	0.1297	0.1156	0.1309	0.1460	0.1344	0.1443	0.1028	0.1332	0.1188	0.1207	0.1033
0.1070	0.1326	0.1235	0.1318	0.1229	0.1485	0.1304	0.1289	0.1184	0.1059	0.1293	0.1094	0.1110	0.1348	0.1211
0.1348	0.1107	0.1207	0.1264	0.1523	0.1337	0.1326	0.1264	0.1048	0.1221	0.1235	0.1257	0.1239	0.1381	0.1253
0.1129	0.1626	0.1260	0.1027	0.1165	0.1120	0.0983	0.1138	0.1064	0.1402	0.1130	0.1175	0.1333	0.1131	0.1293
0.1218	0.1573	0.1159	0.1333	0.1187	0.1169	0.1031	0.1011	0.1477	0.1327	0.1211	0.1129	0.1261	0.1137	0.1292
0.1150	0.1119	0.1251	0.1571	0.1322	0.1602	0.1099	0.1245	0.1112	0.1332	0.1354	0.1325	0.1228	0.1066	0.1181
0.1141	0.1225	0.1355	0.1139	0.1281	0.1289	0.1503	0.1299	0.1083	0.1219	0.1207	0.1063	0.1431	0.1038	0.1416
0.1369	0.1263	0.1498	0.1247	0.1060	0.1180	0.1226	0.1293	0.1144	0.1114	0.1129	0.0991	0.1326	0.1330	0.1085
0.1128	0.1246	0.1249	0.1326	0.1106	0.1014	0.1186	0.1336	0.1059	0.1044	0.1252	0.1335	0.1292	0.1064	0.1137
0.1297	0.1113	0.1174	0.1469	0.1116	0.1155	0.1208	0.1164	0.1433	0.1468	0.1277	0.1330	0.1233	0.1186	0.1367

Average value of thermal resistance:

$$R_T = 0.123\,\text{W/(m}^2 \cdot^{o} C)$$

From Table 4 it can be seen, which elements require additional thermal insulation and degree of the required thermal insulation. The obtained distributions, the same to those presented in Figures 2, 3 and 4, for many variants of temperature allow to vary methods and types of thermal protection, as well as regimes of operation of heating boiler, in order to achieve optimal temperatures of air inside a room.

CONCLUSION

The main advantage of the developed methodology is fast control of the tested object and significant engineering accuracy. It allows to obtain at any time "clear" value of losses of thermal energy by envelope structures of a heating boiler. Moreover, the developed methodology can be applied for other types of tested objects, for example, heating appliances or heat pipes of networks; with some modifications the methodology can be used for envelope structures of buildings.

Multiple repetition of the measurement with recording of temperature and time parameters allows to create complete time-temperature model of an envelope, which can be used for complex evaluation of thermal protection for various seasons and all kinds of input data. One of advantages of the presented methodology is its versatility and applicability at various environmental conditions. For example, a heating boiler can be situated not indoors, but outdoors. In that case additional inaccuracy of measurement can be caused by weather conditions, but, if they are carefully taken into account, they do not seriously affect measurement results and accuracy.

Thus, the presented methodology allows to rapidly evaluate thermal losses by external envelope structures, which, in turn, allows to timely eliminate zones of unreasonable losses. Periodic measurements according to the presented methodology clearly demonstrated changes of condition of thermal protection and losses of an enveloping structure with time after a number of renovations and reconstructions.

ACKNOWLEDGEMENTS

REFERENCES

[1]   M. Ronnbock, M. Johansson, F. Claesson. "ERA-Net Evaluation of Development Status of Small-Scale Combustion Units Using Pellets from New Materials with a High Content of Ash". - Boras, Sweden: SP-Technical Research Institute of Sweden, 2008.
[2]   C. Porso. "The Effect of New Raw Materials on Pellets Prices". - Uppsala, Sweden: Swedish University of Agriculture Science, 2010.
[3]   P. Yu. Hudyakov, D. Dordge, B.P. Zhilkin, N.S. Zaikov, A.Yu. Kisel'nikov. "Application of Thermal Imaging Technologies for Control of Processes in a Furnace of Power Equipment", Proceedings of the 4th International Scientific and Practical Conference "Organization of Research Activities of Young Researchers: Problems, Search and Solution", pp. 37-140, 2012.
[4]   S. Lagüela, L. Díaz-Vilariño, J. Martínez and J. Armesto. "Automatic Thermographic and RGB Texture of As-Built BIM for Energy Rehabilitation Purposes", Automation in Construction, vol. 31, pp. 230-240, 2013.
[5]   V.M. Fokin, V.N. Chernishov. "Non-destructive Testing of Thermophysical Characteristics of Construction Materials: Monograph". - Moscow: Mechanical Engineering, 2004.
[6]   A. Kylili, P.A. Fokaides, P. Christou, S.A. Kalogirou. "Infrared Thermography (IRT) Applications for Building Diagnostics: A review", Applied Energy, vol. 134, pp. 531-549, 2014.
[7]   O.N. Budadin, A.I. Potapov, V.I. Koglanov et al. "Thermal Non-Destructive Testing of Products". - Moscow: Science, 2002.
[8]   J. Lloyd. "Thermal Imaging Systems". - Moscow: World, 1978.
[9]   Yu. A. Plotnikov, W.P. Winfree. "Automation of the Image Analysis for Thermographic Inspection", Proc. SPIE 3397, Nondestructive Evaluation of Aging Aircraft, Airports and Aerospace Hardware II, pp. 135-140, 1998.
[10]   P.R. Muniz, R. da Silva Magalhães, Sh.P.N. Cani, C.B. Donadel. "Non-Contact Measurement of Angle of View between the Inspected Surface and the Thermal Imager", Infrared Physics & Technology, vol. 72, pp. 77-83, 2015.
[11]   W.J. Parker, R.J. Jenkins, C.P. Butler, G.L. Abbot. "Flash Method of Determining Diffusivity, Heat Capacity and Thermal Diffusivity, Heat Capacity and Thermal Conductivity", J. Appl. Phys., vol. 32, 1961.

[12]   V.P. Vavilov. "Thermal Method of Non-Destructive Testing: Handbook". - Moscow: Mechanical Engineering, 1991.

[13]   V.P. Vavilov. "Infrared Thermography and Thermal Control (2nd ed., expanded)". - Moscow: Spektr Publishing House, 2013.

[14]   J.Y. Zhang, W. Zhang, Zh.-W. Yang, G. Tian. "A Novel Algorithm for Fast Compression and Reconstruction of Infrared Thermographic Sequence Based on Image Segmentation", Infrared Physics & Technology, vol. 67, pp. 296-305, 2014.

[15]   A. Rosenfeld, A. Kak. "Digital Picture Processing (Vol.1)". - Orlando: Academic press, 1982.

[16]   V.A. Osipova. "Experimental Study of Thermal Exchange Processes". - Moscow: Energy, 1979.

[17]   E.G. Malyavina. "Heat Losses of Buildings". - Moscow: AVOK PRESS, 2007.

[18]   A.V. Lykov, Yu.A. Mikhailov. "Theoretical Aspects of Thermal and Mass Transfer". - Moscow, Leningrad: Gosenergoizdat, 1963.

[19]   Zh. Gossorg, "IR Thermography". - Moscow: World, 1998.

[20]   R. Viskanta, R. Gross. "Heat Transfer by Simultaneous Conduction and Radiation in an Absorbing Medium", Heat Transfer, vol. 84, pp. 73-76, 1962.

[21]   N.M. Belyaev, A.A. Ryadno. "Methodology of Theory of Thermal Conductivity (Part 1 and 2)". Moscow: Higher School, 1982.

[22]   Yu. V. Vidin. "Engineering Methodologies of Calculation of Thermal Transfer", 1974.

[23]   Yu. Vidin, V.V. Ivanov. "Calculation of Temperature Fields in Solid Bodies Simultaneously Heated by Convection and Radiation". Krasnoyarsk, 1965.