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Study of Thermal Processes in Envelope Structures of Heating Boiling operating on biofuel Using Methods of Infrared Diagnostics.

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ABSTRACT

Infrared diagnostics is one of the main methods of testing of equipment and materials consuming and producing thermal energy. Methods of infrared control are used in construction, medicine, manufacturing and aerospace industry. Also, those methods are often non-destructive and non-contact. The main purpose of the presented study is calculation of real values of loses of thermal energy by envelope structures of a heating boiler during its operation. In order to achieve that goal the simplest methods of evaluation of thermal losses through wall of a boiler with non-contact and fast measurement features are developed.

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

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INTRODUCTION

Demand for energy resources is steadily increasing all over the world. For 2014 world production of energy resources were 13,768 Mtoe [1], which is 1.1% more than in 2013 and 37.2% than in 2000. Thus, production of primary energy resources (PER) is increasing, which are used for production of the secondary, the most widely used energy resources: thermal and electric energy. For example, production of electric energy in 2014 increased by 1.5% and reached 23,636 TW·h, and total consumption of electric energy was 20,302 TW·h; in other words, 14% are losses of electric energy during transmission from generating facilities to consumers.

Processes of production, transmission and consumption of resources cause serious influence on environment; at that, their effects are different. In order to decrease negative influence it is necessary to improve technologies, implement modern and smart equipment and increase efficiency of energy consumption at all stages from production to final consumption.

Therefore, issues of increase of efficiency of use of PER play important role in any branch of industry, as well as for residents, which are, along with industry main consumers of energy resources. During operation of buildings, structures and facilities, generally, secondary energy resources are used, in particular, thermal and electric energy.

In any space thermal balance is maintained, and in order to keep temperature and parameters of internal a required level it is necessary to compensate all thermal losses. According to [2], thermal losses through wall, in average, amount for 32% of loses, through doors and windows – 29%, through roof and related structures – 24%, due to air exchange – 9%, losses through foundation – about 6%. That distribution of thermal losses in buildings is presented in Figure 1. As the result, problems of energy saving and minimization of losses of thermal energy by means of decrease of leaks of thermal energy into environment through envelope structures of buildings become topical.

Compensation of thermal losses is usually carried out by means of heating – 82%, insolation (inflow of heat with solar radiation) – 12% and so-called living-related inflow of heat (due to various equipment, lamps, people and animals) – 6%.

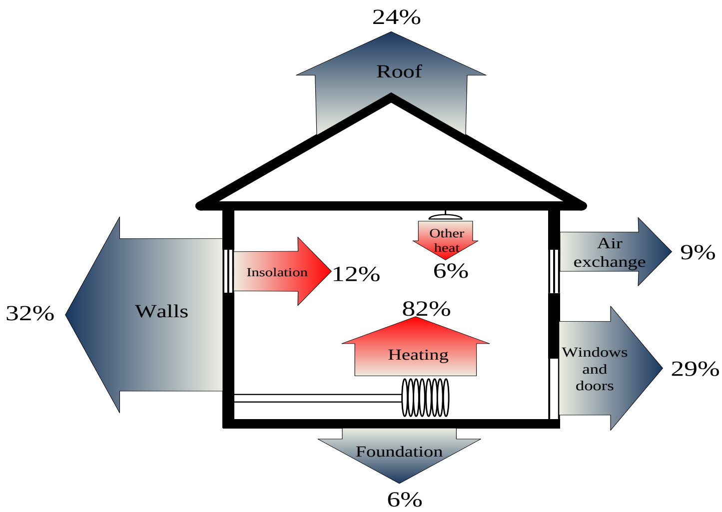

Fig.1. Thermal losses and inflow of thermal energy into buildings.

In the majority of cases, main losses in buildings are related to walls, roof and windows and doors. Depending on object, distribution of thermal losses can be different, because purpose of buildings, environment, type and amount of glazing of enveloping structures and some other parameters have a certain influence. Also, in cases of residential buildings, identification of actual thermal energy balances and assessment of actually consumed thermal energy for heating, conditioning and ventilation is problematic.

Walls, windows and doors in general are easier to inspect visually and by means of instruments, which allows to use various diagnostics methodologies for evaluation of condition of the normal protection, including methods of thermal non-destructive testing.

Background

Non-destructive testing is a method of control of properties and parameters of an object, which doesn't compromise serviceability of an object. Thermal control is based on measurement, monitoring and analysis of temperatures of controlled objects [3]. The main condition of application of thermal non-destructive testing is presence of thermal flux in the tested object. Process of transfer of thermal energy, emission and consumption of heat leads to change of temperature of an object as compared to temperature of environment [4]. Temperature distribution along surface of an object is the main parameter in the thermal control, because it carries information on feature of process of thermal transfer, regime of operation of an object, its internal structure and presence of hidden internal defects [5]. Methods of thermal control are often used in construction [6,7,8,9].

Main problems of construction thermal non-destructive testing are as follows [10,11,12]:

- need to combine a number of methods in order to decrease number of mistakes and inaccuracy, which leads to increase of material and time expenses;
- absence of practical methodologies and algorithms for identification of parameters of thermal transfer, thermophysical characteristics (TPC) of envelope structures and other materials at real structure in operating conditions with reproducible results and low inaccuracy, which have low material and time expenditures;
- limited number of high quality software for processing of thermographic images and absence of software for application of thermal imaging for purposes of identification of TPC of envelope structures and other materials;
- low availability of educational programs and limited number of specialists in the field of thermal non-destructive testing as method for wide-scale control and evaluation of thermal losses, identification of defects of envelope structures and main TPC of materials.

In order to maintain temperature of internal air at a required level with the lowest possible expenditure it is necessary that envelope structures have high energy efficiency. An additional factor increasing energy efficiency of heating is calculation and regulation and thermal balances of residential buildings. It is possible by means of control and processing of actual information about obtained thermal energy from its sources, about amount and structure of used thermal energy and condition of thermal protection of residential building and structures. One of the main modern problems of thermal methodologies of non-destructive testing is development of methodologies for rapid evaluation of TPC of materials, including external construction envelope structures and generation equipment for individual and collective distribution of thermal energy.

As it can be seen from Figure 1, the main resource compensating thermal losses through envelope service life is heating. Heating in residential houses can be centralized (from a generating station, which is common for a group of users) and individual (personal generation, which is often based on various kinds of fuels, including renewable energy sources and electric energy).

Often for individual heating systems electric, gas, liquid fuel and solid fuel heating boilers are used, which are working on natural gas, biogas, oil, coal, wood, fuel granules (pellets) and other kinds of natural and artificial kinds of fuels. Granulated biofuel if produced from wastes of lumber industry (wood of coniferous species, wood chips, sawdust and bark) agriculture (hay, straw, sunflower seeds' shells, cane, corn wastes). Use of granulated biofuel allows to: utilize various kinds of wastes; produce ecologically clean high-energy fuel; consume wastes of a main production technology and make it ecologically clean; decrease expenses for transportation and storage of fuel as compared to lumber wastes (soft and solid) or firewood; increase production standards and acquire additional income from selling of granulated biofuel.

Pellet boilers are a type of heating equipment, which is popular in Europe and which becomes increasingly popular in Russia due to the following advantages: independence from central sources of energy, and, therefore, energy tariffs, ecological cleanness, wide opportunities for automation and economic efficiency [13,14]. Capacity of pellet boilers, which are installed not only in separate residential buildings, but also in production facilities, is from 10 kW to 2 MW. Required capacity of a boiler room working on pellets is calculated on the basis of thermal balance of building, which is similar to other kinds of fuel. For boiler rooms of small capacity, which are used in residential houses, there are empirical formulas for approximate calculation of required capacity of a boiler room, which consider a number of parameters: level of thermal insulation, total heated area or volume, coefficient of glazing, presence of cold bridges, infiltration of outside air etc.

In the majority of cases boilers are small structures, which can be controlled directly during their operation. Heating boilers are divided into the following zones: zone of combustion of fuel (combustion chamber, burner), zone of heating of heat carrier and zone of ejection of combustion products. Also, heating systems, which can include one or several boilers, can be installed both indoors and outdoors, taking into account measures of thermal insulation and ejection of thermal pollution into environment.

MAIN PART

Process of thermal transfer through envelope structures of a heating boiler can be simulated on a basis of analysis of distribution of temperature on surfaces of walls of a heating boiler installed indoors. Also, calculation of losses of thermal energy by walls of heating boiler allows to quantitatively evaluate thermal energy, which remained in a room (or thermal energy, which was released into environment, if a boiler is installed outdoors). On the basis of calculation it is possible to make conclusions about reasonable method and zones of thermal insulation, which would provide desirable temperature in a room, in other words, avoid unnecessary high temperatures in a room and decrease thermal pollution of environment. Those measures allow to increase efficiency of heating of other rooms and to decrease consumption of fuel, which is used for heating of a building.

Because a heating boiler consumes energy resources for generation of thermal energy, its energy efficiency parameters are very important. Along with efficiency, effective system of burning control and amount of burned fuel, characteristics of thermal insulation of all surfaces, which are used for transfer of thermal energy to heat carrier, are very important for a heating boiler. Thus, it is necessary to solve a problem of calculation of amount of thermal energy, which is radiated by envelope surfaces of a heating boiler. It will allow to select effective layer of thermal insulation for each type of boiler, as well as to calculate power of thermal energy flux originating from a heating equipment, which is necessary for maintaining parameters of microclimate in a room. If a heating boiler is installed outdoors or in a ventilated space, that study can significantly increase efficiency of a boiler and decrease thermal pollution of atmosphere.

Envelope structures of a heating boiler in the majority of cases can be considered as plane-parallel wall. Process of transfer of thermal energy on a surface of an envelope consists of thermal fluxes by radiation and convection (Figure 2). Each of those processes is described by their own laws. For radiation it is Stefan-Boltzmann law, for convection – Newton's law of cooling. In a volume of an envelope transfer of thermal energy is carried out mainly by means of conductance, and for that case Fourier law is used.

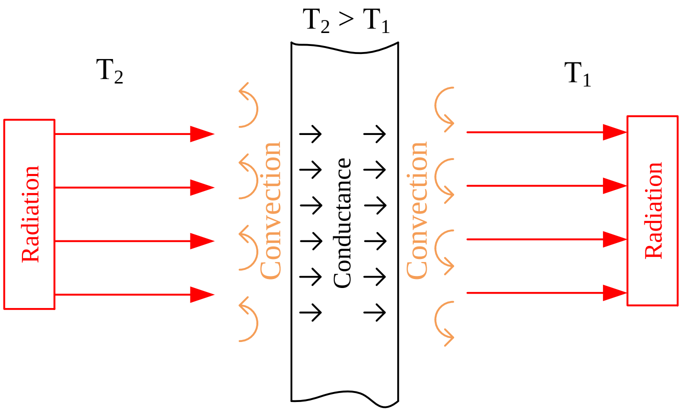

Fig.2. Process of transfer of thermal energy through plane-parallel wall.

Conductance is a type of heat transfer from more heated parts of a body to less heated ones. Density of thermal flux in steady-state mode is defined by Fourier law [15, 16, 17]:

$$q = -\lambda\left(\frac{\partial T}{\partial x}\right)$$

where λ – thermal conductivity coefficient, W/(m·K). For example, for air the coefficient is equal to 0.023-0.030 W/(m·K) (in calculation 0.028 is generally used), for reinforced concrete – 1.69 W/(m·K), for steel 47 W/(m·K) and for cast iron – 56 W/(m·K); T – temperature, which is changing along axis x, K.

From the law it can be seen that value of thermal flux depends on properties of materials and difference of temperatures in measured points. It is worth mentioning that Fourier law doesn't take into account inertia of thermal conductivity process, in other words, according to that model change of temperature in a certain point momentarily spreads for a whole body. Fourier law is useful for description of high-frequency processes (thus, these are processes, which expansion in Fourier series has significant high-frequency harmonics). Examples of these kinds of processes are propagation of ultrasound, shock waves etc. Inertia in equation of transfer was firstly introduced by Maxwell [18], and in 1948 Cattaneo proposed variant of Fourier law with relaxation member [19].

Expenditure of thermal energy through envelope structures of a heating boiler Q can be calculated using surface integral:

$$Q = \iint_{S=n\cdot m} q_{nm}\,dndm; \quad (1)$$

where q_{nm} – thermal flux in each point of a surface. n and m – dimensions of the measured surface.

Equalization of temperature in an envelope structure and surrounding space leads to establishment of steady-state thermal transfer mode. For that case process of transfer of thermal energy through an envelope structure (wall) of a boiler is presented in Figure 3. In stationary mode of thermal transfer [20,21] thermal flux trough a flat wall is constant value (q = const) and temperature doesn't change with time and depends only on coordinates. In that case on a condition of constant thermophysical properties temperature in a flat wall is changed according to linear law [22, 23, 24].

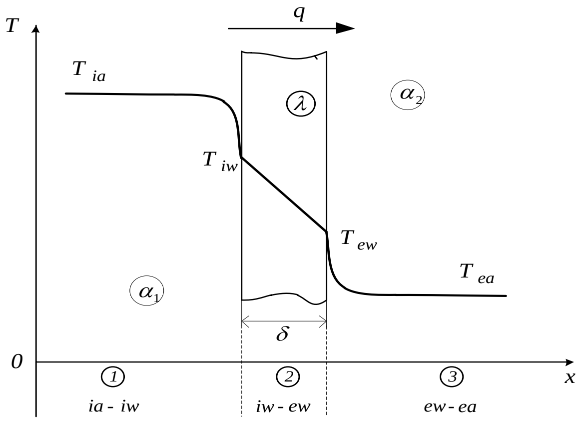

Fig.3. Direction of thermal fluxes in envelopes depending on temperatures on surfaces. $T_{iw} > T_{ew}$**;**

Where:

δ – thickness of flat wall;
α_i – coefficient of thermal emission from air inside a room to a wall;
α_e – coefficient of heat emission from a wall to external air;
T_{ia} – temperature of internal air, K;
T_{iw} – temperature of internal wall, K;
T_{ew} – temperature of external wall, K;
T_{ea} – temperature of external air, K;

Temperature of media inside a boiler is measured by installed sensor, which can operate at high temperatures. Those sensors can be also used as instruments for a system of automated control of burner and boiler itself. Thus, measurement temperature of media inside a boiler and temperature of air in a room near a heating boiler, allow to obtain difference between temperatures, which is necessary for calculation of thermal flux at surfaces of walls.
Using Fourier law for steady-state temperature inside a burner and a heating boiler it is possible to obtain the following expression for thermal flux:

$$q = \lambda\left(\frac{T_{iw} - T_{ew}}{\delta}\right) = \frac{T_{iw} - T_{ew}}{R_T} \quad (2) \qquad \text{or } q = \frac{T_{ia} - T_{ea}}{R}, \quad (3)$$

where $R = \frac{1}{\alpha_e} + \frac{\delta}{\lambda} + \frac{1}{\alpha_i} = \frac{1}{\alpha_e} + R_T + \frac{1}{\alpha_i}$ (4)

– full thermal resistance of a wall with consideration of thermal transfer processes at internal and external surfaces of a wall, $m^2 \cdot K/W$;

$$R_T = \frac{\delta}{\lambda} \text{ – thermal resistance of wall itself, } m^2 \cdot K/W;$$

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

$$q = \alpha_e (T_{ea} - T_{ew}) = (\alpha_{insol} + \alpha_{conv})(T_{ea} - T_{ew}) \quad (5)$$

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According to [25], for vertically oriented surfaces in a room, at external surface of a wall of a heating boiler convective heat emission coefficient α_{κ} can be calculated as follows:

$$\alpha_{conv} = 1.66(T_h - T_c)^{1/3}, \qquad (6)$$

where T_h – temperature of a hot object;

T_c – temperature of cold environment.

Convection is transfer of thermal energy by moving flows of matter. It leads to mixing of cold and hot layers of gas or liquid. Convection is observed in liquid and gaseous matters, as well as between liquid or gaseous media and surface of a solid body. Thus, convection takes place at internal and external surfaces of envelope surface of a heating boiler [26].

According to that law thermal energy is transferred from a more heated body to a less heated body. At that, direction of thermal flux can change if temperature of media is higher than a body's temperature. Coefficient of heat emission in that case describes not only material, but also interaction of two heterogeneous medias, and it depends on their geometry.

After studying of the relationship α_{conv} from $(T_h - T_t)$ it can be concluded that significant increase of coefficient of convective heat emission is observed for differences of temperature from 0 to 2 ºC, in other words, for minor difference of temperatures of media and measured surface. After that growth is decelerated, but not stopped and becomes close to linear. For large differences of temperature between surfaces of a wall, the equation (5) accurately describe characteristic of thermal interaction between wall and air in a room with maximum accuracy.

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

$$q = \varepsilon\sigma (T_h^{\ 4} - T_c^{\ 4}) = \alpha_{insol}(T_h - T_c)$$

where ε – reduced radiation coefficient;
σ – Stefan-Boltzmann constant,
$\sigma = 5.67 \cdot 10^{-8}$ W·m^{-2}· K^{-4};
T_h – temperature of hot object;
T_c – temperature of cold environment;
α_{insol} – coefficient of heat emission by radiation,
$\alpha_{insol} = \varepsilon\sigma (T_{ea}^2 + T_{ew}^2)(T_{ea} + T_{ew})$ (7).

Thermal radiation is flux of quantum of electromagnetic radiation, which appears due to internal energy of a body. That process is characteristic for all bodies, which temperature is higher than absolute zero (T > 0 K).

Thermal radiation is a very complicated phenomenon, which is related with the fact that process starts with transformation of thermal energy into radiation of electromagnetic waves (emission), then it continues with movement of photons and, finally, it ends with absorption of electromagnetic oscillations by absorbing media or body (absorption). Thermal radiation is discussed as process of propagation of transversal electromagnetic waves, which are emitted by a body. Those electromagnetic waves are transformed into heat again, when they are absorbed by another body.

Each surface of a body, depending on its temperature, emits energy in form of waves of various length. Length of electromagnetic waves of visible light varies in the range of 0.38-0.74 µm. For the majority of temperatures maximum of emissivity is observed in infrared part of spectra. Only for T ≥ $5 \cdot 10^3$ K maximum belongs to visible part of spectra. Infrared radiation occupies spectral range between red end of visible light (from 0.74 µm) and microwave radiation (approximately 800-1,000 µm).

Infrared radiation, when passing through atmosphere, changes power and spectral composition due to dissipation and absorption by molecules of gases and weather phenomenon, such as rain, snow, fog etc. Dissipation of radiation by particles leads to change of spatial distribution of transmitted energy, at that, the main role in that process is played by particles with sizes, which are comparable with wavelength. Molecules of water, ozone and carbon dioxide have main absorbing capacity. Also, turbulence in atmosphere can influence dissipation of IR radiation.

On the basis of studies it was established that atmosphere has so-called "transparency windows", in which dissipation and losses of power of infrared radiation are minimal. On the basis of transparency windows two main ranges are used in measurement equipment: from 3 µm to 5 µm and from 8 µm to 14 µm. For normal conditions of atmosphere without strong precipitation and weather phenomenon effects of attenuation of signal can be neglected. Another important point is correct selection of viewing angle during thermography [27].

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

$$\alpha_e = \alpha_{insol} + \alpha_{conv} = 1.66\left(T_{ew} - T_{ea}\right)^{1/3} + \varepsilon\sigma\left(T_{ea}^2 + T_{ew}^2\right)\left(T_{ea} + T_{ew}\right) \quad (8)$$

RESULTS

In order to achieve the main goal of the study it is necessary to derive the formula for calculation of thermal flux at surface of external wall and transform thermal flux in quantity of lost heat in a unit of time from the whole surface of a heating boiler.

In a course of process of heat exchange of a wall of a boiler with environment thermal energy, which is passing through a wall, is dissipated at external surface of a wall into environment. For the reason that walls of a heating boiler are manufactured from materials, which have high thermal conductivity (for example, steel or cast iron), a massif of wall reaches saturation quite fast. In other words, thermal fluxes at surface inside a wall, inside an envelope structures and at external surface rapidly reach steady-state mode. Thus, it is possible to equalize thermal fluxes by thermal conductivity (1) at a surface of a wall and thermal fluxes by radiation and convection (5):

$$\alpha_e (T_{ea} - T_{ew}) = \frac{T_{ia} - T_{iw}}{R_T}$$

Therefore, it becomes possible to calculate thermal resistance of R_T an envelope:

$$R_T = \frac{\delta}{\lambda} = \frac{1}{\alpha_e} \cdot \left(\frac{T_{iw} - T_{ew}}{T_{ew} - T_{iw}} \right); \quad (9)$$

Substitution of (9) into the formula (5) allows to evaluate surface density of thermal flux q at external surface:

$$q = \frac{T_{ia} - T_{ea}}{\frac{1}{\alpha_e}\left[\frac{T_{iw} - T_{ew}}{T_{ew} - T_{iw}}\right] + \frac{1}{\alpha_i}} \quad (10)$$

Coefficient of thermal exchange at internal surface in that case will tend to infinity: $\alpha_i \to \infty$, in other words, member 1/$\alpha_в$ can be neglected.

Thus, substitution of the expression (8) for total coefficient of thermal transfer at a surface of wall of a heating boiler in the formula (10) and use of the criteria described above allows to obtain final expression for calculation of thermal flux density through a wall:

$$q = \frac{(T_{ia} - T_{ea})(T_{ew} - T_{iw})(1.66(T_{ew} - T_{iw})^{1/3} + \varepsilon\sigma(T_{ea}^2 + T_{ew}^2)(T_{ea} + T_{ew}))}{T_{iw} - T_{ew}} \quad (11)$$

On the basis of thermal flux calculated by means of the expression (11) thermal energy, which is lost by a wall of a heating boiler at a unit of time is calculated. For that it is necessary to evaluate area for a surface, which distribution of temperatures and thermal flux are calculated. Substitution of the obtained values in the formula (1) allows to obtain value of quantity of thermal energy, which is lost by surface of a whole boiler:

$$Q = \iint_{S=n\cdot m} \frac{(T_{ia\_nm} - T_{ea\_nm})(T_{ew\_nm} - T_{ew\_nm})(1.66(T_{ew\_nm} - T_{ew\_nm})^{1/3} + \varepsilon\sigma(T_{ea\_nm}^2 + T_{ew\_nm}^2)(T_{ea\_nm} + T_{ew\_nm}))}{T_{iw\_nm} - T_{ew\_nm}} \times dndm$$

In the majority of problems related with thermal control it is necessary to preliminary evaluate thermophysical parameters of envelope structures. It is necessary for more accurate calculation of thermal balances and prognosis of amount of thermal energy, which must be generated to heat rooms.

Thermophysical parameters (TPP, in some type of technical documentation they are specified as thermophysical characteristics – TPC) characterize intensity of thermal processes occurring in envelope structures; they significantly influence thermal and air regimes of buildings of various purpose. Thus, operation of systems of heating, ventilation and air conditioning also depends of TPC of envelope materials, and, therefore, these parameters influence energy efficiency of buildings and structures.

One of main subproblems is identification of TPC, which seriously influence thermal regimes, and identification of those TPC, which can be identified in actual operation.

The main TPC are as follows:

R_T – thermal resistance, $m^2 \cdot K/W$;
λ – thermal conductivity coefficient of material, $W/(m \cdot K)$.
Instantaneous thermal resistance can be calculated according to the formula (8).

From the same formula by means of Fourier law coefficient of thermal conductivity of an envelope structure can be calculated using the equation:

$$\lambda = \frac{\delta}{R} = \delta \cdot \alpha_i \cdot \left(\frac{T_{ia} - T_{iw}}{T_{iw} - T_{ew}} \right) \quad (11)$$

Conclusion

Existing technologies of production of thermal energy in small-seized boiler rooms and residential houses require large amounts of primary fuel, which leads to use of expensive imported fuel, which quality can decrease during long-term transportation; that increases its cost and expenditures for generation of thermal energy, decreases reliability and efficiency of a boiler's operation. Control of thermal insulation of boilers and quantitative estimation of thermal energy, which is emitted into environment, allow to more efficiently use methods of generation of thermal energy with implementation of any kinds of boilers.

Nowadays there are several main methods of accounting if thermal energy, which is lost by envelope structures of various purpose. They can be divided into two classes for convenience: theoretical methods and measurement methods. Completely theoretical calculation of t through envelope structures of a boiler belongs to the first class. Disadvantages of that class are high inaccuracy, because it is impossible to evaluate thermal flux at a surface of an envelope structure without measurement of temperatures. Application of that class of methods doesn't allow to efficiently and reasonably use boiler equipment.

Methods, which include application of contact thermometers on surfaces of envelope structures and thermal flux sensors, belong to the class of measurement methods. Disadvantage of those methods is that they measure parameters in a certain point, but not at a whole surface of a tested envelope structure. In a case of measurement of thermal flux at a surface of walls of a heating boiler it is impossible to install temperature sensors at surfaces of a wall inside a boiler (however, readings of embed high-temperature sensor can be used). Also, it is impossible to use widely-spread systems for measurement of thermal flux and temperature at a surface of an external wall, because sensors of these systems are not designed for high-temperature applications. Thus, it is reasonable to use non-contact methodologies for measurement of temperature at surfaces of tested objects. In addition, implementation of thermal non-destructive testing and non-contact methodology of control allows to evaluate and analyze current condition of walls of a heating boiler.

Thus, in order to achieve required results the measured input data will be as follows:

- Temperatures of internal and external air, as well as temperatures of surfaces of envelope structures;
- Speed of wind near an envelope;
- Sizes of envelope.
- Finally, the following results were acquired:
- Required input data was defined;
- Physical and mathematical justification of calculations was carried out;
- Formula for calculation of surface density of thermal flux was obtained;
- On the basis of the carried out study it is possible to develop algorithm for rapid evaluation of thermal losses and creation of thermal model of an envelope structure.

If distribution of temperatures along surface of external envelope structures is obtained, as well as temperatures of external and internal air, it is possible to evaluate reduced thermal resistance of certain elements of envelope structures, and calculate amount of thermal energy, which is emitted from surface of these elements.

Theoretical studies, which are presented in the paper, are based on simple physical processes with assumptions, which significantly simplify calculations. In a case of application of modern measurement equipment, inaccuracy of measurement and obtained results will be minimal. On the basis of that study it is possible to develop simple, and, at the same time, complete and highly accurate methodology, which allows to capture data in contact and non-contact manner and rapidly evaluate thermal losses through envelope structures.

Application of these solutions in time will allow to create dynamic thermal model of a heating boiler, which can be used for further simulation of behavior of a boiler, condition of its envelope structures, as well as to effectively control thermal losses of a boiler, and, therefore, heat a space to required temperature. That mechanism can be implemented using thermal insulation as regulating element.

Application of these solution will allow to increase energy efficiency of boiler equipment, engineering systems and decrease harmful impact on environment.

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