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AUTOMATIC CONTROL OF THE BOILER HEAT POWER BASED ON CHANGING HYDROCARBON FUEL'S CALORIFIC VALUE

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This paper is devoted to the development and research of an advanced approach to automatic control of the heat output of the boiler when compensating the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture. The proposed approach gives the opportunity to design the boiler's automatic control system (ACS) with the possibility of creating the conditions for the formation and determination of the current calorific value of the gases mixture, which corresponds to the current heat load of the boiler, as well as determining the flue gas flow and temperature in the boiler. The implementation of the developed approach of the boiler's load control allows for providing a constant nominal flue gas flow at any level of heat output. The fuel composition control process consists of mixing certified and non-certified hydrocarbon gases, which ensures maximum efficiency and compliance with environmental emission standards. The effectiveness study of the proposed approach is carried out in the development of the heat output ACS for the GM-50 boiler and conducting a computational experiment of operating at a power different from the nominal one. The obtained results fully confirm the high efficiency of the developed approach, as well as the expediency of its application for boilers of various types and capacities when operating at a power different from the nominal one.

Keywords: boiler, automatic control system, artificial combustible gases, gas calorific value, flue gas flow.

Introduction

In connection with the global world policy of energy efficiency and energy independence, as well as the dynamic change in prices for the extracted hydrocarbon resource of certified quality, today the issue of using gas hydrocarbon raw materials at thermal power plants that have not passed quality certification is particularly relevant [1–3]. As a rule, this segment of the hydrocarbon market includes secondary energy resources, which include non-certified fuels. Moreover, great prospects have recently opened up for the use of fuel mixtures at thermal power plants, industrial and heating boiler houses equipped with steam and especially hot water boilers for the overall reduction in the cost of energy carriers [4].

At the same time, the use of different types of fuel together in one mixture significantly increases the requirements for the functional characteristics of automatic control systems (ACS) for thermal power facilities [5]. Such ACSs must control technological processes both when using certified and non-certified hydrocarbon fuels. In turn, modern automatic control systems in most cases cannot provide an acceptable quality of control if both internal and external disturbances occur simultaneously, for example, a change in the heat load and a change in the composition of the fuel. This causes a significant problem when it is necessary to compensate for the disturbance from the heat load that has arisen at the consumer. This problem can be solved quite successfully by controlling the composition of the combusted hydrocarbon fuel to provide the set characteristic of the calorific value of the gaseous fuel mixture when regulating the boiler's heat output. Such regulation of a combustible fuel mixture, which is a mixture of certified and non-certified hydrocarbon fuels, with the aim of its most efficient use, determines the relevance of this study.

This paper proposes an advanced approach to automatic control of the heat output of the boiler when compensating for the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture. The rest of the paper is organized as follows. Section 1 presents a brief literature review of the studied area and the statement of the research problem. The development of the mathematical model of the boiler, in which changing the gas calorific value is considered as the disturbance, is presented in section 2. Section 3, in turn, describes in detail the proposed approach to automatic control of the boiler's heat output. Section 4 shows the effectiveness study of the automatic control system for a specific steam boiler designed based on the proposed approach. Finally, section 5 concludes the work and suggests directions for future studies.

1. Related works and problem statement

The problem of optimal fuel combustion in the scientific literature has always received great attention. Herewith, the combustion control system is one of the main boiler's control systems. During the use of boilers equipment, a large number of control schemes for various types of fuel (solid, liquid and gaseous) have been developed and have already become standard. However, when developing equipment and ACSs for it, it is assumed that during operation the composition of the fuel will change in a small, predetermined range.

Conventional methods of heat load control are discussed in detail in [6, 7]. In turn, in the considered ACSs, the control task is to maintain the predetermined pressure of the superheated steam in the control mode or the predetermined flow rate of the superheated steam when the boiler is operating in the basic mode. Such control systems, as a rule, are implemented in two modifications: (a) with a fuel consumption signal, when liquid or gaseous fuel with a constant calorific value is supplied to the burner devices, and (b) with a heat release signal in the combustion chamber, when the qualitative composition of a liquid or gaseous fuel is not constant.

In the first method (with a fuel consumption signal), the task can be implemented only when the boiler is operating in a steady mode and the regulation can be provided when disturbances are applied within a certain regulation range. In turn, with a significant change in the load of the boiler or a change in the calorific value of hydrocarbon fuel, it is necessary to reconfigure the task for the load (pressure) controller. With a decrease in load, the heat flows are redistributed in the volume of the furnace and gas ducts, which leads to an indefinite decrease in efficiency. Therefore, this method of controlling the heat output in boilers is not used when combusting hydrocarbon fuel of a random composition that changes over time [6].

In turn, the change in the calorific value is typical for solid fuels. Therefore, the load ACSs with a «heat» signal are used for the power boilers that operate on solid fuels [7]. One of the information signals in such ACSs is the rate of pressure change in the boiler drum. Therefore, the use of such control systems for water heating boilers operating on gaseous fuels is rather difficult due to the invariance of the water pressure in the boiler.

Despite the long enough experience of operation of a large number of steam boilers, the research and improvement of their control systems continue. Particular attention is paid to load regulation [8, 9]. Also quite relevant is saving resources and improving the energy efficiency of enterprises both for the economy as a whole [10] and in its sectors [11]. In particular, Richard Heinberg in his book [12] shows that alternative energy so far cannot ensure the development of industrial production. The main problem with renewable energy sources is the high losses during conversion from one type of energy to another, and the fact that most of the energy produced in this way cannot be stored.

In turn, currently, secondary energy resources (SER) are rather widely used in production processes. They include thermal, overpressure and combustible SERs [13]. The first two types should be attributed to the field of increasing energy efficiency of production. They are used in the form in which they are received and, as a rule, at the place of receipt. This is certainly important, but it cannot be the basis for reducing the energy intensity of production where such resources are not available. The situation with combustible renewables is different. At the moment, they are also usually used at the place of their production. Most often and in the largest volumes, they are produced in the gaseous form: blast furnace gases, open-hearth gases, gases from coke-chemical processing of coal, oil refining, gases after mine degassing, landfill gases, etc. [13]. These are universal energy carriers and in this form, they can be used in standard equipment (without significant additional financial costs) and to produce the types of energy that are needed in a given place or at a given time. They are easily transported without changing their energy characteristics (using pipelines). They can be burned in standard boilers to produce hot process water and steam, which is what happens at metallurgical plants. They can be used as fuel in engines (pistons or turbines) to generate electricity, etc. In addition, combustible SERs have a low or even zero cost, since all costs for the feedstock and the technological process that results in their formation are attributed to the main product. Thus, the use of combustible SERs can be considered the best option for reducing the energy intensity (in terms of cost) of the output.

Papers [14–17] summarize methods for calculating the composition of combustion products, which allows the modeling of almost all organic compounds that burn in the air atmosphere. This makes it possible, despite the wide variety of combustibles, to describe the process of formation of combustion products and determine their temperature using a uniform model.

The work [18] considers the ACS of the thermal load of a drum boiler with random changes in the flow rate of blast furnace and coke oven gases and the control effect only on the flow rate of natural gas. It is envisaged to use a compensator for the main disturbance — blast-furnace gas consumption. Also, the simulation results under the action of random disturbances in blast-furnace gas consumption are presented. Moreover, in the given paper, the method for controlling the thermal load of a drum boiler for burning combustible artificial gases is described. To improve the heat load control system with a heat signal, using artificial gas as a fuel, a compressor is used, which, by increasing the gas pressure, increases the mass flow and thus compensates for the low density of the hydrocarbon gas and the calorific value.

The ACS of the thermal load of a drum boiler during the joint-separate combustion of blast furnace, coke and natural gases with random changes in their consumption is given [5, 19]. To increase the efficiency of this system, it is proposed to introduce devices for compensating random disturbances in the flow rates of these gases in addition to a typical ACS using the «heat» signal. The results of the study of the combined system are presented and its efficiency is shown under different operating modes of the boiler.

However, this method only partially solves the problem, since it makes it possible to regulate the boiler load when using hydrocarbon gas, which is non-certified but has a constant composition over time. The above method provides a technical implementation of the supply of non-certified gas to the burner, but not for the method of regulating the heat output of the boiler. Moreover, providing a given mass flow rate of combustible gas through the burner devices at elevated pressure immediately leads to throttling of this flow, which ultimately, with a constant flow area of the boiler, leads to an increase in the flue gas velocity and an increase in their temperature at the outlet of the boiler, which leads to a sharp decrease in thermal efficiency.

These shortcomings of the known automatic control systems lead to the impossibility of obtaining a constant flow of flue gases in the boiler furnace with a change in the heat output (load) of the boiler. The main technological problem is that with a proportional change in flue gas flow in cases of using certified or non-certified hydrocarbon gases, the flue gas velocity in the boiler furnace decreases, which leads to a decrease in the heat transfer coefficient and practically makes it impossible to regulate at low values of the heat output [20].

Thus, the purpose of this work is the development and study of the advanced approach to automatic control of the heat output of the boiler when compensating the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture to provide the necessary characteristic of the calorific value of the fuel.

The obtained results of the study will make it possible to implement the boiler's load control at any level of the heat output and to ensure a constant nominal flue gas flow rate regardless of the current power level. The fuel composition control process is to ensure the current value of the calorific value by mixing certified and non-certified hydrocarbon gases while maintaining a constant nominal flue gas flow, that will ensure maximum efficiency and meeting environmental standards for emissions.

To do this, the following tasks should be solved.

1. Development of the mathematical model of the boiler, in which changes in the gas calorific value act as disturbances, while ensuring the constancy of the flue gas flow in the boiler furnace.

2. Development of the system's structure for the automatic control of the heat output of the boiler by the calorific value of hydrocarbon gas when the boiler is operating at a power different from the nominal one.

3. Carrying out the computational experiment of the developed ACS with the determination of the control quality indicators.

2. Mathematical model of the boiler with the disturbances in the form of the calorific value of the fuel

To achieve the set purpose, first of all, it is necessary to improve the mathematical model of the combustion of non-certified gaseous fuel by taking into account the nonlinear change in the amount of heat supplied to the combustion device and taking into account the change in heat transfer conditions with significant fluctuations in the flow of flue gases.

To study the static and dynamic characteristics, the GM–50 steam boiler was chosen, as it is the most common in the communal economy of district boiler houses.

The boiler's mathematical model structure (Fig. 1) consists of 6 components (1', 1, 2', 2, 3, 4) that are described by certain differential equations [21]. In turn, the outputs of the previous components are the inputs for the subsequent components of the model. Components 1 and 2 describe the heat exchange processes related to radiation and convective heating surfaces. Components 1' and 2' describe the auxiliary differential equations relating the input data to heat release by radiation and convection. Component 3 describes the processes that take place in the boiler drum. Component 4, in turn, describes the pipeline.

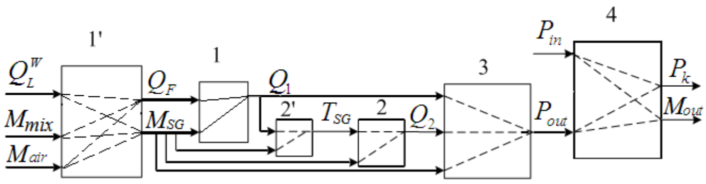

Fig. 1

In Fig. 1 and the next equations, the following notations are adopted: Q_L^W is the lower calorific value of the working mass of fuel; M_{mix} is the consumption of a mixture of hydrocarbon fuels; M_{air} is the airflow; Q_F is the amount of heat released during the fuel combustion; M_{SG} is the flue gas flow; Q_1 is the amount of heat transferred to the working fluid by radiant heat exchange; Q_2 is the amount of heat transferred to the working fluid by convective heat exchange; T_{SG} is the flue gas temperature; P_{in} is the boiler inlet pressure; P_{out} is the pressure in the boiler drum; P_k is the boiler outlet pressure; M_{out} is the steam flow at the boiler outlet.

First, it is advisable to clarify the model of heat release during the combustion process.

It is known that the heat released during combustion can be calculated using the equation (1)

$$Q_F = M_{mix} Q_L^W . \tag{1}$$

Since the combustion model is considered in deviations, we linearize (1) and represent the expression in deviations in the following form:

$$\overline{Q}_F + \Delta Q_F = (\overline{M}_{mix} + \Delta M_{mix})(\overline{Q}_L^W + \Delta Q_L^W). \tag{2}$$

After opening the brackets and taking into account the expression (2), it is possible to write:

$$\Delta Q_F = \overline{M}_{mix}\Delta Q_L^W + \overline{Q}_L^W \Delta M_{mix}. \tag{3}$$

Usually, the second term is rejected as having the second order of smallness. However, since the deviation of the calorific value of the biogas is so large, in this case, the calculation in the model is carried out according to expression (3).

Next, we consider and clarify the model of heat transfer by convection. A change in the ratio of excessive air α in the region of sufficiently large excesses has little effect on Q_F but can have a strong impact on the distribution of heat contribution between individual heating surfaces. The change in α is associated with a change in the specific amount of flue gases, and as a result, the gas temperature θ_G in the furnace, which, as is known, strongly affects the heat transfer by radiation. Corresponding changes in heat transfer, but of the opposite sign, occur in convective heating surfaces.

Next, we consider the mathematical model of a convective gas duct.

Mathematical model of a convective gas duct. In [22, 23] the derivation of differential equations and the coefficients included in them is given. Therefore, only the resulting relations are given here. The amount of heat that is transferred from the flue gases to the coolant can be described by the system of equations (4)–(6).

In turn, the heat balance on the side of the heating gas is calculated as follows:

$$m_{SG}c_{SG}\frac{d\vartheta_{SG}}{dt} + Q = M_{SGin}c_{SGin}\vartheta_{SGin} - M_{SGout}c_{SGout}\vartheta_{SGout}, \tag{4}$$

where M_{SG} is the consumption of flue gases; m_{SG} is the mass of gas in the element; c_{SG} is the specific heat capacity of gases; ϑ_{SG} is the gas temperature; Q is the heat flow from the gas to the wall. Herewith, the indices «in» and «out» denote the corresponding quantities at the inlet and outlet of the gas duct.

The balance of substance on the flue gas side (with no accumulation of flue gas mass) is presented by the expression (5)

$$M_{SGout} = M_{SGin}. \tag{5}$$

The deviation of the amount of heat ΔQ_2 in the «heating gas-pipe» system by the convection is as follows

$$\Delta Q_2 = 0,33k_4\overline{M}_{SG}^{0,33}\frac{\overline{\vartheta}_{SGin} + \overline{\vartheta}_{SGout} - 2\theta_m}{2\overline{M}_{mix}}\Delta M_{SG} + 0,5k_4\overline{M}_{SG}^{0,33}(\Delta\vartheta_{SGin} + \Delta\vartheta_{SGout}), \tag{6}$$

where θ_m is the pipe's metal temperature; k_4 is the proportional gain.

The dependence of the amount of heat on the consumption of flue gases and the temperature of the gases in time is described by the differential equation (7)

$$T_2\frac{dQ_2}{dt} + \Delta Q_2 = a_2\Delta M_{SG} + b_2\frac{dM_{SG}}{dt} + c_2\Delta\vartheta_{SGin}, \tag{7}$$

Where coefficients T_2, a_2, b_2 and c_2 are calculated based on expressions (8)–(11).

$$T_2 = \frac{c_{SG}m_{SG}}{k_4\overline{M}_{SG}^{0,33} + 2c_{SG}\overline{M}_{SG}}; \tag{8}$$

$$a_2 = c_{SG}\frac{0,33(4\overline{\vartheta}_{SGin} - \overline{\vartheta}_{SGout} - 3\theta_m)}{1 + \frac{2c_{SG}}{k_4}\overline{M}_{SG}^{0,33}}; \tag{9}$$

$$b_2 = c_{SG}\frac{0,33m_{SG}(\overline{\vartheta}_{SGin} - \overline{\vartheta}_{SGout} - 2\theta_m)}{\overline{M}_{SG}\left(1 + \frac{2c_{SG}}{k_4}\overline{M}_{SG}^{0,33}\right)}; \tag{10}$$

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$$c_2 = \frac{1}{\dfrac{1}{k_4 \overline{M}_{SG}^{0,33}} + \dfrac{1}{2c_{SG} \overline{M}_{SG}}}. \qquad (11)$$

Next, we consider the mathematical model of the combustion process of the hydrocarbon gaseous fuel.

Mathematical model of the combustion process of the hydrocarbon gaseous fuel. The combustion air flow rate, flue gas flow rate and fuel combustion calorific value can be calculated based on the stoichiometric equations of combustion chemical reactions. In the proposed model, this is carried out according to the expressions (12)–(26).

In turn, the theoretically required air volume is calculated as follows:

$$V^0 = 0,0476\left[0,5\mathrm{CO} + 0,5\mathrm{H}_2 + 1,5\mathrm{H}_2\mathrm{S} + \sum\left(m + \frac{4}{n}\right)\mathrm{C}_m\mathrm{H}_n - \mathrm{O}_2\right], \qquad (12)$$

where m and n are the numbers of carbon and hydrogen atoms, respectively, in a molecule of a pure hydrocarbon substance.

The flue gas volume is determined in the following way. With the complete combustion of fuel under theoretical conditions the combustion products are formed, which are a gas mixture consisting of CO_2, SO_2, N_2 and H_2O. The carbon dioxide and sulfur dioxide are usually combined and called «dry triatomic gases», denoting through RO_2 i.e.

$$\mathrm{RO}_2 = \mathrm{CO}_2 + \mathrm{SO}_2. \qquad (13)$$

Herewith, the theoretical volume of nitrogen in combustion products is calculated by equation (14)

$$V_{\mathrm{N}_2}^0 = 0,79V^0 + 0,01\mathrm{N}_2. \qquad (14)$$

The presence of water vapor in the combustion products is due to the combustion of hydrogen and the evaporation of the moisture contained in the fuel, as well as moisture coming with air. When combusting gaseous fuels, the theoretical volume of triatomic gases is

$$V_{\mathrm{RO}_2}^0 = 0,01\left[\mathrm{CO}_2 + \mathrm{CO} + \mathrm{H}_2\mathrm{S} + \sum m\mathrm{C}_m\mathrm{H}_n\right]. \qquad (15)$$

In turn, the theoretical volume of water vapor is

$$V_{\mathrm{H}_2\mathrm{O}}^0 = 0,01\left[\mathrm{H}_2 + \mathrm{H}_2\mathrm{S} + \sum \frac{n}{2}\mathrm{C}_m\mathrm{H}_n + 0,124 d_{GF}\right] + 0,0161V^0, \qquad (16)$$

where d_{GF} is the moisture content of gaseous fuel, referred to as 1 m^3 of dry fuel, g/m^3.

In real combustion chambers, for economical combustion of fuel, it is necessary to supply more air than is theoretically necessary. The excess air ratio α that is the ratio of the actual amount of air V^R supplied for combustion to the theoretically required amount of air V^0 is calculated by the expression (17)

$$\alpha = \frac{V^R}{V^0}. \qquad (17)$$

Then the total volume of combustion products V_{SG} taking into account the above equations is

$$V_{SG} = V_{\mathrm{RO}_2}^0 + V_{\mathrm{N}_2}^0 + V_{\mathrm{H}_2\mathrm{O}}^0 + 1,0161(\alpha - 1)V^0. \qquad (18)$$

The heat of combustion of gaseous fuel is determined in the following way. For analytical calculations of the heat of combustion of all types of solid and liquid fuels, the formula of D.I. Mendeleev (kJ/nm^3) is used:

$$Q_L^W = 358{,}18CH_4 + 637{,}48C_2H_6 + 912{,}3C_3H_8 + 1186{,}46C_4H_{10} + 1460{,}77\times \\ \times C_5H_{12} + 126{,}44CO + 107{,}6H_2 + 358{,}18CH_4 + 586{,}99C_2H_4 + 231{,}11H_2S. \quad (19)$$

In calculations of fuel combustion, conventional units of gas volume are used, reduced to normal conditions (0°C and 101,325 kPa), denoted by «nm^3».

These dependencies are used to calculate the combustion process of both one type of fuel and when burning a mixture of combustible gases. In general, even natural gas is a mixture of combustible gases, the composition of which is considered constant. Then the admixture of some artificial gas, such as blast furnace gas, simply changes the composition of the main gas. Therefore, simple ratios can be used to determine the characteristics of a mixture of gases.

Thus, the calorific value of the mixture Q_{Lmix}^W is calculated by the expression (20)

$$Q_{Lmix}^W = \frac{Q_{LNG}^W M_{NG} + Q_{LAG}^W M_{AG}}{M_{NG} + M_{AG}}, \quad (20)$$

where Q_{LNG}^W and Q_{LAG}^W are the calorific values of the natural gas (NG) and artificial gas (AG), respectively; M_{NG} and M_{AG} are the consumption values of NG and AG.

The specific flow of the flue gases V_{SGmix} is calculated as follows;

$$V_{SGmix} = \frac{V_{SGNG} M_{NG} + V_{SGAG} M_{AG}}{M_{NG} + M_{AG}}, \quad (21)$$

where V_{SGNG} and V_{SGAG} are the flow values of the natural gas and artificial gas, respectively.

The specific amount of air V_{mix}^0 required for combustion is determined as

$$V_{mix}^0 = \frac{V_{NG}^0 M_{NG} + V_{AG}^0 M_{AG}}{M_{NG} + M_{AG}}, \quad (22)$$

where V_{NG}^0 and V_{AG}^0 are the specific amount of air required for combustion of the natural gas and artificial gas, respectively.

However, when modeling, no specific values are used, but deviations from absolute ones. Therefore, expressions (20)–(22) must be multiplied by the consumption of gas supplied to the combustion.

Thus, the amount of heat Q_F released during fuel combustion is

$$Q_F = Q_{Lmix}^W (M_{NG} + M_{AG}) = Q_{LNG}^W M_{NG} + Q_{LAG}^W M_{AG}. \quad (23)$$

The flow of the flue gases M_{SG} is calculated as follows;

$$M_{SG} = V_{SGmix}(M_{NG} + M_{AG}) = V_{SGNG} M_{NG} + V_{SGAG} M_{AG}. \quad (24)$$

The air consumption G_{air} required for combustion is determined as

$$G_{air} = V_{mix}^0 (M_{NG} + M_{AG}) = V_{NG}^0 M_{NG} + V_{AG}^0 M_{AG}. \quad (25)$$

Thus, the deviation of the flue gas flow ΔM_{SG}, which is included in equations (6) and (7), is described by the dependence (26)

$$\Delta M_{SG} = M_{mix}\alpha\Delta V^0_{mix} + M_{mix}V^0_{mix}\Delta\alpha + \alpha V^0_{mix}\Delta M_{mix} + \\ + M_{mix}\Delta V^0_{mix}\Delta\alpha + \alpha\Delta M_{mix}\Delta V^0_{mix} + V^0_{mix}\Delta M_{mix}\Delta\alpha. \quad (26)$$

Based on the above mathematical description, a static calculation of the GM–50 boiler was carried out for various load values and various ratios of the main fuel (natural gas) and low-calorie fuel (blast furnace gas or biogas). The calculation results are summarized in Table 1.

The analysis of data given in Table 1(Calculation results of the boiler operating modes for a fuels mixture) shows that by forming a mixture of basic (high-calorie) and artificial (low-calorie) fuels, it is possible to achieve a reduction in boiler power at a constant flue gas flow rate. However, the higher the calorific value of artificial fuel is, the greater the lower power limit to which the load can be reduced without a significant reduction in flue gas flow.

So, for biogas, this is generally not possible due to the lower specific volume of flue gases. Namely, the decrease in the calorific value of the fuel mixture is compensated by a decrease in the volume of flue gases with a slight increase in fuel consumption. For blast-furnace gas, it is possible to reduce the power to 75–70% without a significant reduction in flue gas consumption.

Table 1

The content of artificial gas in natural		**Load**	**Steam flow**	**Power**	Q_L^W	**Fuel consumption**	**Volume of combustion products**	**Flue gases consumption**
Fuel type	**%**	**%**	**kg/s**	**MW**	**MJ/m^3**	**m^3/s**	**m^3/m^3**	**m^3/s**
Estimated fuel	0	100	13,89	32,92	37,56	0,96	11,67	11,24
	0	85	11,81	27,98	37,56	0,82	11,67	9,96
	0	75	10,42	24,69	37,56	0,72	11,67	8,79
	0	55	7,64	18,11	37,56	0,53	11,67	6,16
Biogas, Q^W_L=20,63 MJ/m^3	60	75	10,42	24,69	27,42	0,99	8,80	9,07
	80	75	10,42	24,69	24,02	1,13	7,84	9,22
	100	75	10,42	24,69	20,63	1,32	6,88	9,42
Blast-furnace gas Q^W_L = 4,11 MJ/m^3	17	85	11,81	27,98	31,93	0,96	9,99	10,03
	100	85	11,81	27,98	4,11	7,48	1,69	12,64
	28	75	10,42	24,69	28,17	0,96	8,87	8,90
	50	75	10,42	24,69	20,71	1,31	6,64	9,05
	100	75	10,42	24,69	4,11	6,60	1,69	11,44
	50,5	55	7,64	18,11	20,66	0,96	6,63	6,64
	100	55	7,64	18,11	4,11	4,84	1,69	8,39

Next, consider the proposed authors' advanced approach to automatic control of the heat output of the boiler when compensating the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture

3. Approach to automatic control of the heat output of the boiler by regulating the composition of the combusted hydrocarbon fuel mixture

According to the proposed approach, the automatic control system for the boiler's heat output in terms of the calorific value of the gas different from the nominal one should include 3 main control subsystems:

— ACS for the thermal load of a drum boiler — for maintaining a set flow rate of superheated steam in stationary mode using a stabilizing fuel flow controller and maintaining a set value of steam pressure in the line in a regulating mode using a corrective heat load controller;

— ACS for the fuel economy — for maintaining such a ratio between the supply of fuel and air, which ensures maximum efficiency of the combustion process;

— calorific value ACS — for maintaining the required calorific value of the fuel mixture to provide the necessary heat output of the boiler and ensuring the specified parameters of the heat carrier at a constant flue gas flow rate, which corresponds to the flow rate when burning certified hydrocarbon fuel at nominal load.

In view of the foregoing, to implement the developed approach, the control system of the boiler's heat output should be designed based on the structure shown in Fig. 2. The Structure of the ACS for the boiler's heat output by the calorific value of the gas when operating at a power different from the nominal is shown in Fig. 2 as well. In turn, in Fig. 2 the following notations are adopted: 1 is the boiler furnace; 2 is the boiler burner; 3 is the boiler heat exchange surface for heating the coolant; 4 is the boiler air heating heat exchange surface; 5 is the boiler drum; 6 is the duct fan; 7 is the smoke extractor; 8 is the pipeline of certified hydrocarbon gas; 9 is the pipeline of uncertified hydrocarbon gas; 10 is the air supply pipeline; 11 is the gas pipe from the boiler to the smoke extractor; 12 is the flow measuring transducer for certified hydrocarbon gas; 13 is the flow measuring transducer for non-certified hydrocarbon gas; 14 is the temperature measuring transducer for gas mixture combustion; 15 is the measuring transducer for pressure in the drum of the boiler; 16 is the measuring transducer for the flow of the heat carrier heated in the boiler; 17 is the measuring transducer for the pressure of the heat carrier steam; 18 is the regulating body for the supply of certified hydrocarbon gas; 19 is the regulating body for the supply of uncertified hydrocarbon gas; 20 is the installation for determining the composition of the fuel gas during its combustion [24]; 21 is the calorific value controller; 22 is the controller with heat load setting function; 23 is the differentiator; 24 is the controller with fuel flow setting function; 25 is the correcting device; 26 is the fuel economy controller; 27 is the transmission line of the information signal for the flow of certified hydrocarbon gas; 28 is the transmission line of the information signal for the coolant pressure in the main line; 29 is the transmission line of the information signal for the flow of the coolant; 30 is the transmission line of the information signal for the steam pressure in the boiler drum; 31 is the transmission line of the information signal for the temperature in the furnace; 32 is the transmission line of the control signal for the regulating body of certified hydrocarbon gas supply; 33 is the transmission line of the control signal for the regulating body of non-certified hydrocarbon gas supply; 34 is the transmission line of the information signal for the calorific value of non-certified hydrocarbon gas; 35 is the transmission line of the information signal for the air pressure drop on the floor air heaters (air consumption); 36 is the transmission line of the control signal for the directional device of the air supply fan; 37 is the transmission line of the information signal for the flue gas pressure drop on the air heaters (flue gas consumption); 38 is the transmission line of the information signal for the change in the consumption of uncertified hydrocarbon gas; 39 is the device that sets the heat load; 40 is the device that sets the fuel consumption; 41 is the measuring transducer of the flue gases pressure drop; 42 is the pulse line for measuring the pressure of the flue gases in front of the air heater; 43 is the pulse line for measuring the pressure of the flue gases after the air heater; 44 is the pulse line for measuring the air pressure after the air heater; 45 is the pulse line for measuring the air pressure before the air heater; 46 is the air pressure drop measuring transducer; 47 is the steam pipeline; 48 is the adder; 49 is the calculating device for determining the calorific value of a mixture of gases; 50 is the information transmission line of the signal of theoretically necessary air flow for burning 1 m^3 of gas mixture; 51 is the transmission line of the information signal for the calorific value of the gas mixture; 52 is the transmission line of the correction signal from the heat load controller; 53 is the transmission line of the information signal for the rate of change of steam pressure in the drum; 54 is the transmission line of the information signal by «heat».

The proposed approach to control the heat output of the boiler by the calorific value of the gas when the boiler is operating at a power different from the nominal is implemented as follows. The pipelines of certified and non-certified gases as well as the air duct are connected to the burner 2 of the boiler and the installation 20 for determining the composition of combustible gas in the process of its combustion. The regulating bodies and the duct fan form such a flow rate of a mixture of gases and air to provide a fuel gross formula that has a calorific value and temperature mixture combusting, which will provide the current heat load of the coolant. In turn, blocks 22, 23 and 24, based on the signals of pressure in the boiler drum and at the boiler outlet as well as the coolant flow rate, form a control signal for fuel consumption to provide a given boiler load. The control signal from the fuel flow controller 24 is applied to the regulating body 19 for the supply of certified hydrocarbon gas. In turn, the calculating device 49 for determining the calorific value of the gas mixture is supplied with the measurement signals of pressure differences of air in heater 37 and the flue gases 35, the combustion temperature of the air-fuel mixture 31, flow rates of certified 27 and non-certified 38 hydrocarbon gases. The calorific value Q^{W}_{LAG} is applied to the calorific value controller 21 from the installation for determining the composition of the combustible gas 20 and the flow rates of certified and non-certified hydrocarbon gases are determined. In turn, the control signal U_{AG} from the calorific value controller 21 is applied to the regulating body of non-certified hydrocarbon gas supply 19.

The correcting device 25 and the fuel economy controller 26 are supplied with the values of the theoretically required airflow for combustion of 1 m^3 of gas mixture (by the transmission line 50) and the value of the air pressure drop across the air heater (by the transmission line 35). The control signal U_{air} is supplied from the economy controller 26, which forms the air flow rate that ensures the economical mode of the boiler operation during the combustion of the current mixture.

When the boiler load changes, the controllers form the corresponding change in the certified gas flow rate. As a result, the gross formula of the gas mixture changes.

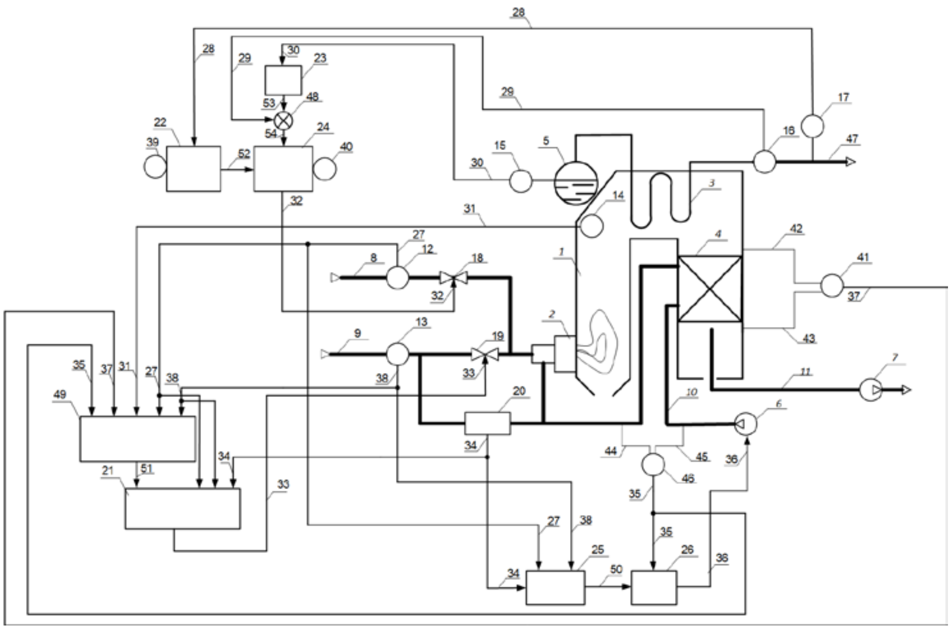


Fig. 2

To do this, the value of the current calorific value of the mixture is determined, and the calorific value controller changes the amount of supplied non-certified gas so that the resulting mixture of gases provides the calorific value to provide a new balance. If the composition of the non-certified gas deviates, the calculating device 49 determines a new calorific value of the gas mixture. By applying this signal to the calorific value controller 21, a control action is formed in the form of a certified gas flow so that in the resulting gas mixture its gross formula corresponds to such a calorific value that, when the gas mixture is combusted, the necessary energy release will be provided.

Thus, at the moment of formation of the current mixture of gases, the current calorific value of this mixture is formed. Regulation of the heat load ensures the equality between the release of heat energy after the combustion of gas of a given calorific value, the heat transfer by the formed flue gases through the heat exchange surfaces to the heat carrier and providing the heat carrier with the specified energy parameters. To ensure the constancy of the heat transfer coefficient, the flow rates of energy carriers must be constant, that is, in this case, the constancy of the speed of flue gases and coolant. To ensure the balance at a heat load less than the nominal one, such a mixture of gases is formed from certified and non-certified hydrocarbon gases, in which the enthalpy of the gross formula will correspond to such a calorific value that will ensure the release of the required amount of energy during combustion and at the same time the flue gas flow rate will remain unchanged, but there will be a change in the combustion temperature of the mixture of gases. If the energy balance is disturbed (in the event of any disturbances), the calorific value controller, based on a certain imbalance of energy flows, will calculate the new composition of the mixture and the regulating bodies will ensure the formation of this mixture of hydrocarbon gases, which will provide a new balance.

To study the effectiveness of the proposed approach, in this paper, we have developed the appropriate heat output ACS for the GM–50 boiler and carried out the computational experiment for operating at a power different from the nominal one.

4. Effectiveness study of the approach to automatic control of the boiler's heat output by regulating the composition of the fuel mixture

The dynamic properties of the boiler are described by the transfer functions connecting inputs and outputs of the boiler's model presented in Table 2 [21]. The leftmost column of Table 2 (Table of transfer functions, which connect inputs and outputs of the boiler's model) lists the main variables of the boiler's model shown in Fig. 1. Moreover, the top line of Table 2 shows the main control signals for the consumption of natural gas U_{NG}, artificial gas U_{AG}, and air U_{air}.

In turn, the following designations are adopted in Table 2: $K_Q(U_{air})$ and $K_{Qa}(U_{NG} + U_{AG})$ are the «gas flow — temperature» transmission ratios, that are functions of the flow rates; T_{QNG}, T_{QAG} and T_{air} are the «gas flow — temperature» and «air — temperature» time constants; K_{PD} and T_{PD} are the «gas flow — boiler drum steam pressure» transmission ratio and time constant; K_{PS}, T_{1PS} and T_{2PS} are the «gas flow — steam pressure at the boiler outlet» transmission ratio and time constants; K_{SG1}, T_{SG1}, T_{1FS} and T_{2FS} are the «natural gas flow — boiler steam flow» transmission ratios and time constants; K_{SG2} and T_{SG2} are the «artificial gas flow — boiler steam flow» transmission ratio and time constant; K_{SGA} and T_{SGA} are the «air flow — boiler steam flow rate» transmission ratio and time constant; $K_{SGN}(Q_W^L, U_{Air})$ and $T_{SGN}(Q_W^L, U_{Air})$ are the «natural gas flow — flue gas flow» transmission ratio and time constant, that are functions of natural gas calorific value and air flow rate; $K_{SGA}(Q_W^L, U_{Air})$ and $T_{SGA}(Q_W^L, U_{Air})$ are the «natural gas flow — flue gas flow» transmission ratio and time constant, that are functions of artificial gas calorific value and air flow rate; $K_{SG}(U_{NG}, U_{AG}, Q_{Wmix}^L)$ and $T_{SG}(U_{NG}, U_{AG}, Q_{Wmix}^L)$ are the «air flow rate — flue gas flow» transmission ratio and time constant, that are function of gases flow rates and mixture gas calorific value.

Table 2

	U_{NG}	U_{AG}	U_{air}
T_{SG}	$W(s)=\dfrac{K_Q(U_{Air})}{T_{QNG}s+1}$	$W(s)=\dfrac{K_Q(U_{Air})}{T_{QAG}s+1}$	$W(s)=\dfrac{K_{Qa}(U_{NG}+U_{AG})}{T_{QAir}s+1}$
P_{out}	$W(s)=\dfrac{K_{PD}}{T_{PD}s+1}$	$W(s)=\dfrac{K_{PD}}{T_{PD}s+1}$	$W(s)=\dfrac{K_{PD}}{T_{PD}s+1}$
P_k	$W(s)=\dfrac{K_{PS}e^{-\tau s}}{T_{2PS}^2 s^2+T_{1PS}s+1}$	$W(s)=\dfrac{K_{PS}e^{-\tau s}}{T_{2PS}^2 s^2+T_{1PS}s+1}$	$W(s)=\dfrac{K_{PS}e^{-\tau s}}{T_{2PS}^2 s^2+T_{1PS}s+1}$
M_{out}	$W(s)=\dfrac{T_{SG1}s+K_{SG1}}{T_{2FS}^2 s^2+T_{1FS}s+1}e^{-\tau s}$	$W(s)=\dfrac{T_{SG2}s+K_{SG2}}{T_{2FS}^2 s^2+T_{1FS}s+1}e^{-\tau s}$	$W(s)=\dfrac{T_{SGA}s+K_{SGA}}{T_{2FS}^2 s^2+T_{1FS}s+1}e^{-\tau s}$
M_{SG}	$W(s)=\dfrac{K_{SGN}(Q_W^L,U_{Air})}{T_{SGN}(Q_W^L,U_{Air})s+1}$	$W(s)=\dfrac{K_{SGA}(Q_W^L,U_{Air})}{T_{SGA}(Q_W^L,U_{Air})s+1}$	$W(s)=\dfrac{K_{SG}(U_{NG},U_{AG},Q_{Wmix}^L)}{T_{SG}(U_{NG},U_{AG},Q_{Wmix}^L)s+1}$

The dependence of the combustion temperature (flue gases) T_{SG} on flow rates is extreme and has a maximum value when the ratio of fuel and airflow rates is close to stoichiometric, calculated by the expressions (20)–(25). The dependence of flue gas flow rate M_{SG} on fuel and airflow rates is also nonlinear and is calculated using equations (6) and (7). Moreover, the linear part of the boiler model is calculated according to the relationships given in [21].

The transfer functions indicated in the table correspond to the general structure of the boiler model shown in Fig. 1. They are obtained in the identification process of the control plant and are used for adjusting the parameters of the controllers for the corresponding ACSs. In turn, the controllers for all ACS coordinates have the proportional-integral control law with automatic adjustment of the coefficients. This adjustment is carried out during the system's operation using devices 20, 25 and 49 (Fig. 2).

In the process of simulating the described ACS, a certain contradiction was revealed. When the boiler load decreases, the heat load controller reduces the fuel consumption which leads to a reduction of the flue gas flow. At the same time, the gas calorific value controller generates a control action to increase the consumption of non-certified gas. However, an increase in the consumption of non-certified gas leads to an increase in the calorific value of the mixture. Thus there is a so-called «race of controllers», as a result of which undesirable fluctuations in technological parameters occur in the system. To eliminate this phenomenon, it is proposed to introduce an interconnection compensator into the system which is a proportional link.

The initial data for the ACS simulation are the boiler load setpoint Q_F and the flue gas flow setpoint M_{SG} which are calculated based on the system of equations (23) and (24). As the coefficients of these equations, the calorific values of the mixture components Q_{LNG}^W, Q_{LAG}^W, and the specific flue gas flow rates V_{SGNG}, V_{SGAG} are used. The output values are the target flow rates for certified and non-certified gases. In matrix form, these equations take the form (27)

$$\begin{bmatrix} Q^W_{LNG} & Q^W_{LAG} \\ V_{SGNG} & V_{SGAG} \end{bmatrix} \cdot \begin{bmatrix} M_{NG} \\ M_{AG} \end{bmatrix} = \begin{bmatrix} Q_F \\ M_{SG} \end{bmatrix}. \tag{27}$$

When solving equation (27), it is possible to obtain negative values of flow rates, which is physically impossible. In this case, the corresponding controller is given a ban on the development of the control action. That is, the corresponding gas flow is reduced to zero and the load of the boiler is ensured by the consumption of only one of the gases. The flue gas flow, in this case, is not regulated.

The simulation results in the form of transients graphs of the boiler's ACS when operating at a power different from the nominal one are shown in Fig. 3–5. In turn, in Fig. 4, *a* and Fig. 5, *a* — without a flue gas flow regulating, in Fig. 4, *b* and Fig. 5, *b* — with a flue gas flow regulating.

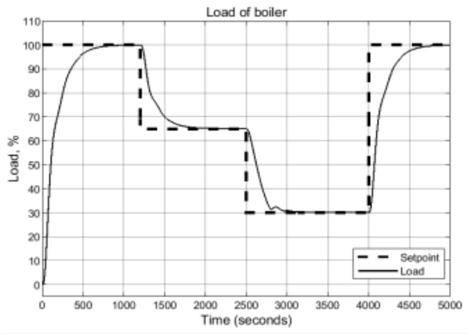
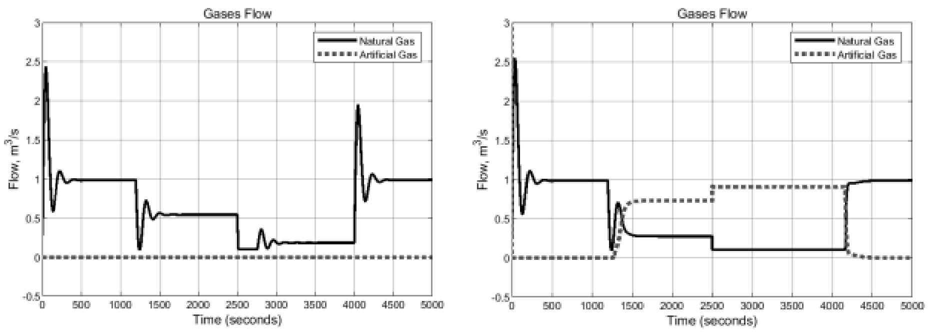
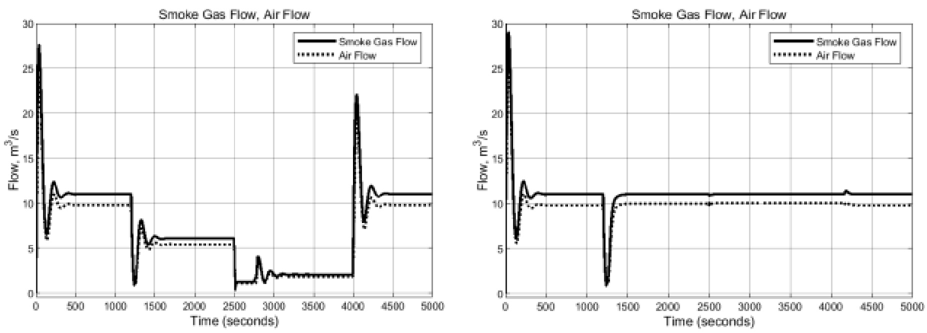


Fig. 3



a *b*

Fig. 4



a *b*

Fig. 5

The analysis of the computational experiment results shows that the control system ensures that the boiler load follows the given schedule with enough high accuracy. In this case, there are no differences between the conventional and the proposed ACS (Fig. 3).

The certified fuel consumption controller was set to the aperiodic character of transients for maintaining the set power. At the same time, some damped fluctuations in fuel consumption were observed (Fig. 4, *a*).

After including a flue gas flow controller into the circuit and introducing a cross-coupling between the controllers, it was possible to achieve an aperiodic change in the flow rates of natural and artificial gases (Fig. 4, *b*).

Following the change in fuel consumption, the flow rates of air and flue gases change, as shown in Fig. 5. Their fluctuations are observed when only natural gas is burned. When the flue gas flow controller is turned on, there are practically no fluctuations in air and flue gas flow rates (Fig. 5, *b*).

Thus, the obtained results of the computational experiment in the form of presented transients (Fig. 3–5) show that the proposed by the authors approach allows the implementation of automatic control of the boiler's heat output with sufficiently high accuracy and fuel economy when compensating the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture. This fully confirms the high efficiency of the developed approach, as well as the expediency of its application for boilers of various types and capacities when operating at a power different from the nominal one.

To further improve the accuracy and other quality indicators for the main controlled coordinates of the boiler's ACS, it is quite promising to use the control principles based on artificial intelligence [25]. In this case, fuzzy, neural network and neuro-fuzzy controllers can be applied quite successfully to control the certified and non-certified gases consumptions, as well as the calorific value [26, 27]. Moreover, bioinspired evolutionary and multi-agent methods can be used to adjust and optimize these control devices [28, 29].

Conclusion

The development and research of an advanced approach to automatic control of the heat output of the boiler when compensating the load disturbances by regulating the composition of the combusted hydrocarbon fuel mixture are presented in this paper.

The developed dynamic mathematical model of the boiler, taking into account the processes of heat transfer in the convective heating surfaces of the boiler, makes it possible to stabilize the flue gas flow in the flow path with time-varying calorific value of the combusted gas. This is achieved due to the convergence of the iterative process in determining the energy balance between the current composition of the combusted hydrocarbon gas and ensuring the specified parameters of the coolant at a constant flue gas flow. The current value of the flue gas flow corresponds to its flow during the combustion of certified hydrocarbon fuel at the nominal load of the boiler.

The development of an automatic control approach became possible due to the introduction in the ACS of the possibility of creating the conditions for the formation and determination of the current calorific value of the gases mixture, the calorific value of which corresponds to the current heat load of the boiler, determining the flue gas flow by measuring its pressure drop on the heat exchange surface and determining the temperature of flue gas formation in the boiler. The proposed approach of boiler load control at any level of heat output will provide a constant nominal flue gas flow regardless of the current power level. The fuel composition control process consists of mixing certified and non-certified hydrocarbon gases, which ensures maximum efficiency and compliance with environmental emission standards.

The computational experiment showed that the developed ACS according to the proposed approach gives the opportunity to perform fully and efficiently the assigned task. Namely, it keeps the flue flow rate constant when the boiler load changes over a wide range from 100 % to 40 %. Also, flue gas flow and boiler heat output remains unchanged when the calorific value of non-certified hydrocarbon gas changes. Moreover, in the course of the experiment, the effect of the «race of controllers» was revealed.

In particular, the controllers of heat load and calorific value of the fuel influence each other due to the dependence of the volume of flue gases on the composition of the fuel. To eliminate this phenomenon, a compensator of interconnections was introduced into the system which is a proportional link. The main function of the compensator is to set the controllers to the appropriate flow rates of certified and non-certified gases.

The possibility of operation of the proposed ACS is shown in the example of load jump compensation. Natural gas was used as the certified gas, and blast furnace gas as the non-certified gas, with the current boiler capacity of 24,69 MW, which corresponds to 75 % of the nominal capacity. Regulation of calorific value by such ACS formed a mixture of gases, which ensured the necessary value of current boiler power when compensating for a loaded jump in the range from — 20 % to + 10 % of current power. In addition, such an ACS allows compensating for a jump in the calorific value of uncertified gas, which is shown by the example of compensating the change in the calorific value from 20,63 MJ/m^3 (biogas) to 4,11 MJ/m^3 (blast gas) in a mixture with certified (natural) gas with a calorific value of 37,56 MJ/m3. This ensured the redistribution of uncertified gas consumption at an unchanged constant current boiler power of 24,69 MW and 18,11 MW, which corresponds to 75 % and 55 % of the nominal power, respectively.

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АВТОМАТИЧНЕ КЕРУВАННЯ ТЕПЛОВОЮ ПОТУЖНІСТЮ КОТЛА НА ОСНОВІ ЗМІНИ ТЕПЛОТИ ЗГОРЯННЯ ВУГЛЕВОДНЕВОГО ПАЛИВА

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Дана стаття присвячена розробці та дослідженню підходу до автоматичного керування тепловою потужністю котла при компенсації збурень навантаження шляхом регулювання складу спалюваної вуглеводневої паливної суміші. Запропонований підхід дає можливість здійснювати проєктування системи автоматичного керування (САК) котлом з можливістю створення умов для формування та визначення поточної теплотворної здатності суміші газів, яка відповідає поточному тепловому навантаженню котла, а також визначення витрати і температури димових газів у котлі. Реалізація розробленого підходу до керування навантаженням котла дозволяє забезпечувати постійну номінальну витрату димових газів при будь-якому рівні теплової потужності. Процес контролю складу палива полягає у змішуванні сертифікованих і несертифікованих вуглеводневих газів, що забезпечує максимальну ефективність і відповідність екологічним нормам викидів. Дослідження ефективності запропонованого підходу проведено при розробці САК тепловою потужністю котла ГМ-50 та проведенні обчислювального експерименту роботи на потужності, відмінній від номінальної. Отримані результати повністю підтверджують високу ефективність розробленого підходу, а також доцільність його застосування для котлів різного типу та потужності при роботі на потужності, відмінній від номінальної.

Ключові слова: котел, система автоматичного керування, штучні горючі гази, теплота згоряння газу, витрата димових газів.

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