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METHOD OF CONTROLLING THE VOLUME OF COMBUSTION PRODUCTS AT DIFFERENT BOILER LOADS

Purpose. Development of a method for controlling the volume of combustion products at different load of boiler equipment. Achieving the objective may allow controlling the flue gas temperature and, consequently, the efficiency to increase it.

Methodology. Control of the flue gas volume value on the basis of determining the appropriate composition of the fuel gas mixture.

Findings. The effect of flue gas temperature increase at use of fuel gases of lower calorific value and increase in ballast gases quantity is revealed. The latter can be the air used as an oxidising agent at its considerable excess. The mechanism of such an effect due to the increase in the quantity and velocity of flue gases is suggested. A parameter determining the volume of flue gases produced per unit calorific value of various fuel gases is proposed. On the basis of this parameter the method for calculating the composition of the mixture of different gases to ensure the constancy of the flue gas volume at variable load is proposed

Originality. On the example of the results of verification thermal calculation the change in flue gas temperature and efficiency value is considered. The non-standard character of their change is revealed. In contrast to the case of using fuel gas of constant composition with increasing load, the temperature of flue gases remained close to constant, and the value of efficiency increased.

Practical value. The obtained results indicate the possibility of controlling the flue gas temperature and boiler efficiency at a given load. This allows one, unlike the case of using fuel gas of constant composition, to increase the efficiency exactly at maximum load avoiding getting into the condensate mode at minimum load. There is a possibility to save fossil gas and, consequently, to reduce the greenhouse share in CO_2 emissions.

Keywords: *gas mixture, boiler efficiency, flue gas temperature, flue gas volume*

Introduction. According to the Paris Agreement [1], all countries should aim to reduce all cumulative non-food CO_2 emissions to zero by 2050.

One of the directions of international programme on decarbonisation of industry and energy is the development of renewable energy sources. "Green" energy requires substantial capital investments. Therefore, it is fully available only to a limited number of industrialised countries. But even they retain a large part of generation based on combustion of any extracted fuel to ensure the possibility of dispatching energy supplies. In addition, the preservation and even development of traditional sources of energy generation is even more observed in countries with limited financial resources.

EU countries are actively working to reduce greenhouse gas emissions. But despite the high percentage of renewable energy sources, at the same time they have started to significantly increase the import of electricity from third countries. In Germany, for example, the share of electricity from renewable sources reached 48.4 per cent in 2022. But the country has turned from an exporter into a net importer of electricity [2]. This can be interpreted as a sign of a possible capacity shortage to manage electricity flows within the EU, despite the presence of a large installed capacity in electricity generation from renewable sources. Against this background, the European Commission decided to include one of the fossil fuels, natural gas (NG), in the EU Green Taxonomy [3]. This means that this type of activity will be categorised as environmentally sustainable, despite the limitations and potential problems associated with it.

Another factor indicating the planning for the long-term use of gaseous fuels (beyond 2050) is the conclusion of long-term LNG supply contracts by leading European firms. So only two of them, Shell (Netherlands-England) and TotalEnergies (France), signed contracts with Qatar for annual receipt of 7 million tonnes of liquefied gas for 27 years starting from 2026 [4].

The current situation indicates that natural gas will be used as an important energy source in industry and power generation for a long time to come. At the same time, in accordance with the Paris Agreement [1], the task of reducing CO_2 remains relevant.

Literature review. It should be borne in mind that not all combustible gases produce CO_2, a greenhouse gas. Such gases can include secondary produced or utilised gases. For example, pyrolysis, gas generator gases from agricultural or wood waste processing, blast furnace gas (BFG), coke oven gas (COG). When using BFG and COG, CO_2 emissions as a greenhouse gas are related to the main technological process (coke production, iron smelting) and are already accounted for. For this reason, when such gases are used instead of NG, the reduction in the use of natural gas should be considered equivalent to the reduction in the emission of the corresponding amount of CO_2 as a greenhouse gas. Agricultural and wood waste can be considered as renewable sources for the production of pyrolysis and generator gases. For this reason, the CO_2 generated by their combustion is also not classified as a greenhouse gas.

Based on the above-mentioned, one of the ways to reduce the greenhouse effect from CO_2 emissions is to reduce the amount of NG used by replacing part or all of it with secondary produced or utilised gases in technological processes. The issues of determining the composition of combustion products of combustible gases are considered in many works, for example, in the work by Karp I. N., Soroka B. S., Dashevky L. D., Semernina S. D., 1967. The use of BFG and COG in mixture with each other can be considered as one of the options. Thus in [5], rational ways of replacing NG in heating devices with a mixture of BFG and COG are developed. Emphasis is placed on saving energy resources, which can also be considered as a reduction of CO_2 emissions as a greenhouse gas.

In continuation of [5], [6] proposes a method for numerical determination of consumption, energy and environmental characteristics of fuel utilisation when its type and composition are specified. Calculations are performed taking into account the *1st* and *2nd* laws of thermodynamics, equilibrium of processes and on the basis of the ideal gas equation. The complex of measures proposed in [5 and 6] makes it possible to investigate the results of using any combustible gases and their mixtures in power equipment. Emphasis is placed on the determination of combustion results and disposable energy. The possibility of using in different proportions BFG and COG in a mixture with NG and, accordingly, the influence of changing the composition of the combustible gas mixture and the amount of combustion products on the character of change of thermohydraulic processes in the gas-flue path of the equipment (boiler) was not considered. At the same time, the change in these parameters affects the temperature of flue gases, equipment efficiency and the amount of greenhouse component of CO_2 in the presence of NG in the combustible gas mixture.

Secondary produced or utilised gases can be used not only in mixture with each other, but also together with NG to regulate the power developed in high-temperature processes, e.g. in hot water and steam boilers. When using a mixture of combustible gases of variable composition, there is a problem of ensuring their interchangeability when combusted in the same burner. The incompatibility is determined by the difference of Wobbe indexes for mixtures of gases of different compositions. The solution to this problem is proposed in [7]. It consists in changing the volume flow rate of a mixture of gases by preliminary mixing a certain volume of air into it. The amount of air to be mixed in is determined by the composition of the currently used gas mixture. In [7] the case of using only two known compositions: BFG and COG of known ratio and NG as a reserve one is considered. In the case of using a variable gas composition, the ratio of its components, in addition to ensuring interchangeability, should be determined by the capacity of the gas supply path.

Another way to reduce the greenhouse effect from CO_2 emissions when using NG is to increase the efficiency of the equipment. Non-condensing boilers have an efficiency of ~ 88–93 %. Increase in this value leads to reduction of carbon dioxide emissions at given volumes of energy production. In the energy balance of boilers, the largest losses occur with flue gases (5–10 %). Therefore, the only area where a significant increase in efficiency is possible is in the reduction of these losses.

One of the possible directions is the use of condensing boiler technology. Additional increase in efficiency of such technology can be provided by adding hydrogen to combustion gases. On the one hand, it reduces the share of carbon-containing gas in the initial fuel and, consequently, the amount of formed CO_2. On the other hand, the moisture content in flue gases increases, which favourably affects the increase in efficiency. However, in [8] it is noted that the addition of a safe amount of hydrogen (20 %), in turn, reduces the boiler efficiency by 4.7 %, which can offset the advantage of using condensing technology.

The main mass of condensing boilers is concentrated in private households and small boiler houses. In [9] this is explained by the problem of condensate utilisation for large capacity boilers and additional costs for its neutralisation. As a result of the study, in [10] it is concluded that the possibility of annual fuel savings when using condensing boilers is up to 17.5 % in real operating conditions. But, at the same time, it is noted that the payback period of transition from a conventional boiler to a condensing boiler is close to or exceeds the average life of the boiler. Thus, the transition of households from a traditional boiler to a condensing boiler is economically unattractive.

Industrial power equipment of medium and large capacity, when using gaseous fuel, operates mainly in non-condensing mode. A change in the pressure load of a gas boiler causes a change in the temperature of the flue gas. Necessity of cyclic change of capacity of non-condensing boiler in the range of 40–100 % can cause a change in the temperature of flue gases in the range of ~393–473 K (120–200 °C) [11]. The maximum load corresponds to the maximum temperature and losses. The value of the minimum temperature is caused by the necessity to provide a non-condensation mode in the smoke removal process. Theoretically, in the non-condensation mode of smoke extraction, increase can be achieved in efficiency up to ~4 % at reducing the maximum temperature of flue gases to an admissibly low value. At known designs of power equipment such approach cannot be realised.

The main purpose of [12] is to describe a possible method of extending the life of industrial and heating boilers that have reached the factory set life by reducing the maximum allowable load. It is noted that in this way the average efficiency can also be increased due to the reduction of flue gas temperature at the newly installed reduced maximum allowable load. This approach is possible for end-of-life equipment but is not rational for newly installed equipment.

In [13], correction factors were determined by means of thermal measurements and tests to bring the calculation results on the basis of the mathematical model into compliance with the parameters of the operating steam boiler. A mixture of NG and blast furnace gases at different ratios was used as a combustible fuel.

From the comparison of the data given in paper [13, Table 2] it follows that at the same load the use of a larger share of less calorific gas in the fuel mixture, and, therefore, a larger amount of it and a larger excess of air (ballast) leads not to a decrease, but to an increase in the temperature of flue gases. This effect is not explained in the paper.

A similar effect is observed with NG. With increasing load and, consequently, the amount of combustion products, the flue gas temperature increases. As a consequence, the efficiency of the equipment decreases.

The analysis shows the influence of the amount of combustion products on the flue gas temperature and, consequently, on the efficiency of the equipment. At a given load, the amount of combustion products can be changed by using its mixture with less calorific secondary gases instead of NG. The use of such a mixture, on the one hand, makes it possible to reduce the greenhouse fraction of CO_2 in flue gases. On the other hand, a controlled change in the composition of such a mixture may allow for a controlled change in the amount of combustion products, control of flue gas temperature and equipment efficiency. Such control is promising from the point of view of increasing the efficiency of power equipment and, consequently, reducing CO_2 emissions.

Purpose. The purpose of the research is development of a method of controlling the volume of combustion products at different load of boiler equipment. Achievement of the goal may allow controlling the flue gas temperature and, consequently, the boiler efficiency.

In order to achieve the objective, the task was set involving:

- defining a process to influence the flue gas temperature at a given equipment load;
- definition of a parameter that allows classifying auxiliary combustion gases according to their ability to fulfil different scenarios of combustion product volume control;
- calculation of flue gas parameters under a given flue gas volume control scenario.

Methods. ***Potency.*** In gas boilers of traditional configuration and with fuel of constant composition, the output is controlled by changing the quantity of the supplied gas-air mixture. This method of regulation leads to a direct dependence of the flue gas temperature and, accordingly, the boiler efficiency, on the currently developed output. Reduction of power is accompanied by reduction of combustion products quantity, reduction of their velocity in the gas path, increase in contact time with heat-exchange surfaces. As a consequence, the flue gas temperature decreases and, accordingly, the boiler efficiency increases. The maximum output corresponds to the minimum efficiency.

The method for increasing the average efficiency value proposed in [12] provides for reducing the maximum boiler output up to 60–70 %. The dependence of efficiency on the load for the example for PTWM-30 is presented in (Fig. 1).

According to the given data, in the considered case the minimum efficiency can be increased from 92 to 94–95 % by this method. The average efficiency is increased by reducing the difference Δη between its maximum and minimum values. But the value of this difference can also be reduced while maintaining the power control range by reducing the slope of the flue gas temperature change graphs and, consequently, the efficiency. For this purpose, for example, the volume of combustion gases corresponding to the maximum power can be preserved when the power is reduced. The resulting increase in flue gas temperature and decrease in efficiency can be counteracted by increasing the area of the tail heat exchanger surfaces and thereby reducing the flue gas temperature over the entire range of boiler load variation.

Conservation of the volume of combustion products as the load decreases can be ensured by replacing part of the main combustion gas with an alternative gas of lower calorific value. In this case, this gas must have specific properties - it must produce more combustion products per unit calorific value than the main gas.

Alternative gas selection. Let us consider NG as the main combustible gas. We will assume that it consists of methane only. As alternative combustible gases consider BFG, COG, gaseous part of wood pyrolysis products and product of wood waste gasification process with air supply. These gases have a lower calorific value than NG. Let us estimate the amount of flue gases at oxidiser (air) excess ratio $\alpha = 1$, corresponding to the unit calorific value of these gases. Let us assume as air composition a mixture of 21 % O_2, 79 % N_2 (percentages are volumetric). As an example, consider BFG [5, Table 2, Fig. 2]:

- calorific value (lowest) – $Q_n = 3.4\frac{MJ}{(m_{gg})^3}$. Dimensionality $(m_{gg})^3$ marks the belonging of the quantity in question to the corresponding volume of a mixture of combustible gases;

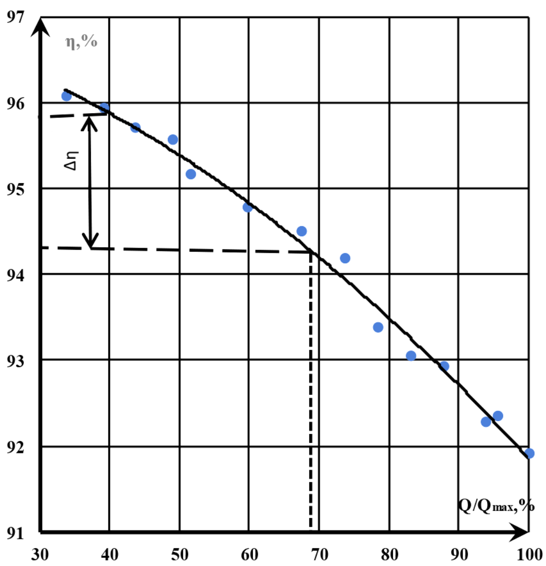

Fig. 1. Dependence of the average efficiency η on the relative load Q/Q_{max} for the PTVM-30 boiler [12, Fig. 2]

- the composition is based on a mixture volume equal to 1 m^3

$$\begin{cases} V_{H_2} = 0.036 \\ V_{CO} = 0.254 \\ V_{CO_2} = 0.195 \\ V_{N_2} = 0.515 \end{cases} \quad (1)$$

Combustion reactions of combustible components from (1) at stoichiometric ratio with air

$$0.036 \cdot H_2 + 0.018 \cdot O_2 + 0.068 \cdot N_2 = \\ = 0.036 \cdot H_2O + 0.068 \cdot N_2; \quad (2)$$

$$0.254 \cdot CO + 0.127 \cdot O_2 + 0.478 \cdot N_2 = \\ = 0.254 \cdot CO_2 + 0.478 \cdot N_2. \quad (3)$$

All elements are in the gaseous state. The coefficients before the summands represent their quantity in cubic metres (m^3). Summing up the volumes of reaction products (2–3) and the volumes of ballast CO_2 and N_2 (1) we obtain the volume of flue gases at combustion of 1 m^3 mixture (1)

$$V_{dg} = 1.51\frac{(m_{dg})^3}{(m_{gg})^3}. \quad (4)$$

Dimension $(m_{dg})^3$ marks the belonging of the corresponding value to the flue gas volume. The calorific value unit corresponds to the following flue gas volume

$$\omega = \frac{V_{dg}}{Q_n} = 0.444\frac{(m_{dg})^3}{MJ}. \quad (5)$$

Similarly, the value of ω can be estimated for NG and the alternative gases considered. The results are presented in Table 1.

From the comparison of ω values for the considered list of gases with load reduction and the given (maximum) flue gas quantity, it is possible to replace a part of NG with BFG and gas generator gas. These gases produce more flue gas per unit calorific value than NG.

Method of Calculation. Taking into account the parameter ω (Table 1), using the combination of NG with different auxiliary gases different scenarios of flue gas volume control at a given load can be developed. As an example, let us consider

Table 1

Proportion of gases in 1 $(m_{gg})^3$ of their mixture and volume of flue gases $(m_{gg})^3$ corresponding to a unit of its calorific value *MJ*

	NG	COG [5, Table 2]	BFG [5, Table 2]	pyrolysis	gas generation
CH_4	1	0.267	–	0.18	–
C_2H_4	–	0.026	–	–	–
H_2	–	0.571	0.036	0.02	0.134
CO	–	0.029	0.254	0.3	0.246
H_2O	–	–	–	–	0.085
CO_2	–	0.042	0.195	0.5	0.058
N_2	–	0.065	0.515	–	0.476
$Q_n, \frac{MJ}{(m_{gg})^3}$	35.8	17.7	3.4	15	4.57
$V_{dg}, \frac{(m_{dg})^3}{(m_{gg})^3}$	10.52	5.04	1.51	3.31	1.71
$\omega, \frac{(m_{dg})^3}{MJ}$	0.294	0.285	0.444	0.221	0.375

Table 2

Characteristics of NG + BFG mixture for different boiler load at α = 1.1

Combustible gas mixture NG + BFG				Flue gas volume, m^3 (normal conditions)				
Load factor	Volume of combustible gas mixture, m^3	% methane in the mixture	T_a, K	CO_2	H_2O	O_2	N_2	Σ
0.40	4.21	0	1,543	1.892	0.152	0.061	4.702	6.807
0.50	5.26	0	1,543	2.365	0.190	0.076	5.877	8.508
0.60	6.32	0	1,543	2.838	0.227	0.092	7.052	10.209
0.66	6.97	0	1,543	3.131	0.251	0.101	7.781	11.264
0.71	6.08	2.5	1,636	2.811	0.513	0.116	7.854	11.295
0.75	5.48	4.6	1,700	2.598	0.688	0.1258	7.903	11.316
0.80	4.58	8.7	1,796	2.279	0.951	0.141	7.977	11.347
0.85	3.69	14.9	1,894	1.959	1.213	0.156	8.051	11.378
0.90	2.79	25.1	1,991	1.639	1.475	0.170	8.125	11.410
0.95	1.90	44.7	2,083	1.320	1.738	0.185	8.198	11.441
1.00	1.00	100	2,182	1.000	2.000	0.200	8.272	11.472

the parameters of the process of combustion of a mixture of NG and BFG in the boiler KV-GM-4.65 at different load, but with keeping the flue gas volume close to constant. Let us consider the volume corresponding to the maximum volume at combustion of NG only at full load operation of the boiler. Determination of parameters is based on the normative method by means of verification thermal calculation. The calculations are performed with minor exceptions that do not affect the general character of change in the determined parameters. The comparison is made with the calculated parameters of the boiler operation when using only NG.

Results. ***Initial data***. Both for NG and for the mixture NG + BFG the calculations were performed at oxidant excess α =1.1. For NG, the adiabatic combustion temperature was determined as T_a = 2,182 K. For the mixture of NG + BFG at different load and, accordingly, different ratio of NG and BFG the value of T_a is different. In all cases the value of T_a was determined on the basis of calorific values of corresponding combustible gases, composition of their mixture using chemical enthalpies of formation of combustion product gases. Table 2 summarises the characteristics of the NG + BFG mixture for different boiler loads with flue gas composition near constant (for normal conditions).

The boiler load is shown as a fraction of the maximum load, equal to 1 (first column of Table 2). The maximum load is reached when only methane is used. When the load is reduced, a mixture of NG + BFG is used with a ratio (column 3) that allows obtaining the same flue gas volume as with NG at max. load. A constant flue gas volume can only be achieved up to a load of 0.66 of the maximum load. At this point, NG is eliminated from the mixture and further load reduction is achieved by reducing the BFG. Column 2 shows the volume of this mixture. Columns 5–8 show the volumes of the flue gas constituents and column 9 shows their total volume. The verification thermal calculation is performed with respect to 1 m^3 of combustible gas mixture (under normal conditions). The relevant initial data are given in Table 3.

Discussion of the results of the calculations. The results of calculations of efficiency and flue gas temperature are shown in Figs. 2 and 3.

Conclusions. The following results were obtained from the research.

1. The most rational at this stage of technology development method of greenhouse gas emission reduction is determined. The use of a mixture of methane and low-calorific gas – for example, a product of wood waste gasification – allows reducing the part of carbon dioxide in flue gases, which refers to greenhouse gases. In addition, given the high cost of natural gas, replacing part of it with less expensive low-calorific gas can reduce the cost of energy produced.

2. A method and model for calculating the composition of flue gases at different ratios of methane and low-calorific gases

Table 3

Flue gas composition for 1 m^3 of NG + BFG mixture for different boiler load at α = 1.1

Load factor	CO_2	H_2O	O_2	N_2	Σ
0.40	0.449	0.036	0.015	1.116	1.615
0.50	0.449	0.036	0.015	1.116	1.615
0.60	0.449	0.036	0.015	1.116	1.615
0.66	0.449	0.036	0.015	1.116	1.615
0.71	0.463	0.084	0.019	1.292	1.859
0.75	0.474	0.126	0.023	1.442	2.065
0.80	0.497	0.207	0.031	1.740	2.475
0.85	0.531	0.329	0.042	2.183	3.085
0.90	0.587	0.528	0.061	2.910	4.087
0.95	0.696	0.917	0.098	4.324	6.034
1.00	1.000	2.00	0.200	8.272	11.472

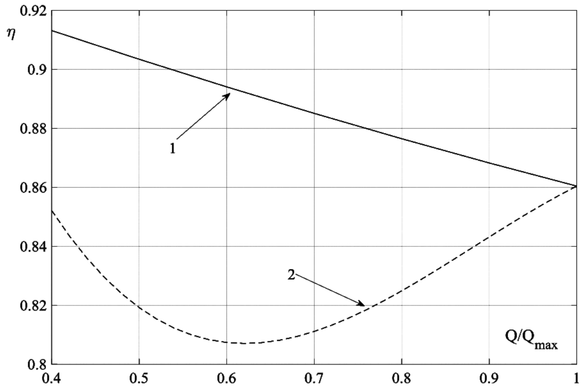

Fig. 2. Variation of efficiency for different combustible gases at changing boiler load:

1 – NG; 2 – NG + BFG of variable ratio

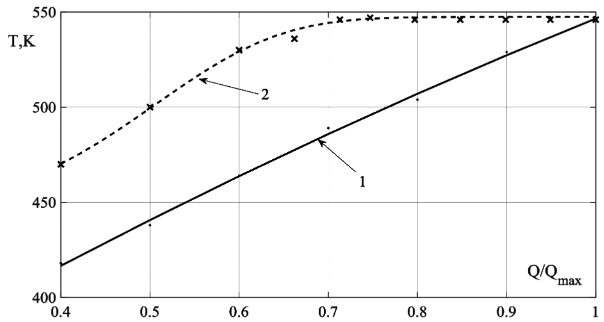

Fig. 3. Variation of flue gas temperature for different combustible gases at changing boiler load:
1 – NG; 2 – NG+BFG of variable ratio

in their mixture are proposed. The method allows determining both the characteristics of the combustible gas mixture at given flue gas parameters and the quantity of flue gases at given fuel characteristics.

3. Two possible methods for controlling the power of the installed equipment by changing the share of low-calorific gas in the fuel mixture are considered. The impossibility of power reduction at an attempt to keep the flue gas volume flow rate constant has been revealed. Moreover, in this case the power (and adiabatic temperature of combustion) increases with increasing the share of low-calorific gas. The reason for such an effect is revealed, which requires modernisation of the fuel gas path and increase in the area of heat-exchange surfaces (economiser).

4. The possibility of power control while ensuring the constancy of the volume flow rate of the combustible gas mixture is revealed. With increasing the share of low-calorific gas the power of the equipment decreases. The possibility of keeping flue gas parameters similar to the case of pure methane use is shown. This feature allows using the installed equipment without modernisation for combustion of a mixture of gases with simultaneous reduction of the share of carbon dioxide, which refers it to greenhouse gases.

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Спосіб управління обсягом продуктів згоряння при різному навантаженні котла

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Мета. Розробка методу керування обсягом продуктів згоряння за різного навантаження котельного обладнання. Досягнення мети може дозволити керувати температурою димових газів і відповідно ККД для його збільшення.

Методика. Управління величиною обсягу димових газів, що грунтується на основі визначення відповідного складу суміші паливних газів.

Результати. Виявлено ефект підвищення температури димових газів при використанні паливних газів меншої калорійності та збільшення кількості баластових газів. В якості останніх може виступати повітря, що використовується як окислювач, при значному його надлишку. Запропоновано механізм такого ефекту внаслідок збільшення кількості та швидкості димових газів. Передбачено параметр, що визначає обсяг димових газів, який виробляється на одиницю теплотворної здатності різних паливних газів. На основі цього параметру запропоновано метод розрахунку складу суміші різних газів для забезпечення сталості об'єму димових газів при змінному навантаженні.

Наукова новизна. На прикладі результатів перевірочного теплового розрахунку розглянута зміна температури димових газів і величини ККД. Виявлено нестандартний характер їх зміни. На відміну від випадку використання паливного газу постійного складу, зі збільшенням навантаження, температура димових газів залишалася близькою до постійної, а величина ККД збільшувалася.

Практична значимість. Отримані результати вказують на можливість управління температурою димових газів і ККД котла при заданому навантаженні. Це дозволяє, на відміну від використання паливного газу постійного складу, збільшити ККД саме за максимального навантаження, одночасно уникаючи таких режимів роботи котла, за яких відбувається випадіння конденсату при мінімальному навантаженні. З'являється можливість економії викопного газу і, отже, зменшення парникової частки у викидах CO_2.

Ключові слова: *суміш газів, ККД котла, температура димових газів, об'єм димових газів*

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