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Energy Characteristics of Medium Pressure Steam Boilers

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Abstract. The object of this study is the thermal and energy characteristics of medium pressure boilers of CHPP-1, four boilers CKTI-75/39F-2-4 and two boilers TP-150-2. All boilers operate on a common steam collector of 32 atm, at 420 °C. Fuel is a mixture of blast furnace gas and natural gas in the ratio of 0.7-0.9 volume particles. The characteristics of the blast furnace gas are not constant: the elemental composition, humidity, and dustiness of blast furnace gas change significantly. Analysis of operation of CHPP-1 medium pressure boilers of OJSC "Mariupol Metallurgical Combinat named after P. G. Ilyich" was carried out on the basis of the technical documentation and materials obtained during the ecological and thermal-technical tests of the boilers CKTI-75/39F-2-4 No. 7–9, and TP-150 No. 11, 12 of SU "Promavtomatika". The main purpose of the analysis is to identify patterns that affect the operational characteristics of boilers, especially the efficiency. The analysis revealed the nature of the overall dependence of the efficiency on the load, as well as the dependence of the efficiency of the boilers on the load at different thermal parts of the blast furnace gas. After carrying out the balance tests, the dependencies of the exhaust gas temperature on the boiler load at different thermal parts of the blast furnace gas were established.

Keywords: medium pressure boiler, thermal efficiency, blast furnace gas, heat losses.

1 Introduction

One of the effective ways to save fuel at thermal power plants, district boilers, and other power plants is to optimize operating modes. It can be implemented if there are energy characteristics of the equipment that correspond to the actual technical condition.

The boiler equipment in intensive operation is rapidly changing (deteriorating) indicators. Many factors influence this process: load, fuel quality, structural

of even the same type of boilers differ dramatically depending on the duration of the operation.

Since 1998, "Rules for the Construction and Safe Operation of Steam and Hot Water Boilers" (DNAOP 0.00-1.08-94, Kyiv, Ukraine, provides for the distribution of loads between boilers based on the equality of specific increments of conventional fuel, determined from the energy characteristics:

Optimization of operational maintenance of gas-fired boilers generally includes the following elements:

– optimal load distribution between units;

– selection of the optimal number of working main units;

– optimization of the supply of the total amount of air (coefficient of excess air) to the boiler;

– optimization of the distribution of different fuels between boiler units in case of simultaneous combustion of several fuels;

– adjustment of optimal modes considering the

energy characteristics, they should be periodically adjusted to consider operational characteristics, for example, by adjusting according to rapid test data.

The efficiency of the use of different fuels depends on the type of furnace, the ratio of fuels, the method of combustion, etc. In theory, finding the optimal solution in the distribution of different fuels between the boiler in operating conditions is very difficult, so this task requires the design of appropriate experimental work.

2 Literature Review

The issues of mathematical and technical, and economic analysis of the efficiency of combined technologies, especially in the thermal power industry, are given special attention today. Developing approaches to mathematical modeling of such technologies, optimization methods, and related software allow us to choose effective solutions that ultimately lead to a decrease in the cost of production.

The solution of optimal energy problems began to be engaged from the middle of the last century when there were large energy systems, thermal power plants, and combined heat and power plants.

In [1], the results of experimental and numerical studies of the process of burning coal in a front coal-fired boiler are presented. The experimental part focused on the optimization of coal combustion to achieve better performance of the electricity generation process. The main purpose of the work was to increase the efficiency of the boiler based on the advanced technique of monitoring the boiler operating conditions. Experimental studies were conducted on the OP-650 front coal boiler located at the Polska Rybnik EDF power plant. In the process of optimization, modern measuring systems for flue gas temperature distribution and fuel-air distribution were used. The acoustic gas temperature measurement system allows online monitoring of the temperature distribution at the outlet of the furnace. The optimal combustion process was determined by the uniform temperature distribution measured online.

The study [2–4] considered the efficiency of the boiler units of the “Mazandaran Cement Plant” and two methods that are useful for increasing the efficiency of the boiler, based on the optimization of excess air and installation of the economizer. Of the two methods of controlling excess air in the boiler was more difficult than using an economizer. Under normal conditions, the boiler operated at 55 % of its capacity. The amount of excess air and boiler efficiency was 63.4 % and 77.5 %, respectively. Excess air was required during the combustion process to ensure complete combustion. On the other hand, minimal heat loss and, thus, maximum boiler efficiency occurred when using the optimum excess air level. The results show that installing an economizer on the boiler can reduce operating costs by reducing fuel consumption. This will also increase the efficiency of the boiler.

Investigation of the convective component of heat transfer both in the furnace and on the heating surfaces is very important. Thus, in [5], measures were taken to simultaneously calculate the thermal field both on the side of the casing and on the side of the pipes, as well as near the walls of the pipes in the convective zone of the boiler of the power plant. The calculation technique allows flexible modeling of heat transfer parameters in the covective zone of the boiler under variable load [6–8].

Aerodynamic processes and heat exchange in the furnace of a steam boiler with a secondary emitter were considered in the study [9, 10]. Water-fired boilers, which are common in industrial and municipal boilers, are used for the analysis and are used as sources of heat and steam supply. Implementation of measures to ensure environmental efficiency at an acceptable level was analyzed. The use of modern burners and the automation of boilers for worn out and outdated boiler structures require significant reconstruction and high financial costs. The results of the numerical study of the processes of heat exchange during the combustion of fossil fuels showed the efficiency of placement of the secondary tubular reverser in the volume of the furnace of the boiler. The author found that the radiant heat flux density increased by 15–20 %, the flue gas temperature at the outlet of the furnace decreased to 970 °C. The size of the flame of the torch precludes its contact with the surfaces of the screen tubes. During the combustion of the gas-air mixture, the concentration of nitrogen oxides at the outlet of the boiler furnace does not exceed 125 mg/m^3.

In the above studies, the authors simulated the energy characteristics of boilers and determined the effect of different mode parameters on the efficiency of boilers. However, there was no experimental study considering the regime parameters of the existing boilers and determining the effect of the convective component, which emphasizes the relevance of the study.

3 Research Methodology

3.1 Characteristics of boiler units

The medium pressure unit includes four boilers of CKTI-75/39F-2-4 and two boilers of TP-150-2. All boilers operate on a common steam collector of 32 atm, at 420 °C. Fuel is a mixture of blast furnace gas and natural gas in the ratio of 0.7–0.9 vol. The characteristics of the blast furnace gas are not constant: the elemental composition, humidity and dustiness of blast furnace gas changes significantly.

Specific operating conditions of medium pressure boilers in CHPP-1 in addition to the above are:

– work of boilers No. 7–10 on individual chimneys, and two TP-150-2 – on a common pipe;

– presence in the thermal scheme of the CHP-1 the P-12 bypass turbine between the steam lines of the hot steam 100 atm and 32 atm;

– on the boilers of CKTI -75/39F-2-4 and TP-150-2, the same direct-flow flat-burner burners (two) are installed, despite the fact that the productivity and volume of furnaces differ significantly.

Boiler No. 10 is being reconstructed by replacing all surfaces of heating, cladding, appliances, and automation. This allows us to determine the nature of the change in the operational characteristics of the boiler as contamination and wear of the heating surfaces.

3.2 Performance analysis of boiler units

For the analysis of the work, the data was taken from the bureau of accounting of CHPP-1. Specific dates and periods, chosen at random, are not relevant in this case, since the main purpose of the work is to optimize the operation of boilers at any given time.

Figure 1 shows the performance changes for each boiler. Characteristic of the CKTI and TP boilers is the general pattern of shifting during the day associated with shift work.

The total productivity change interval of all boilers is 30 tons per hour, i. e., it is the average resource within which load redistribution between boilers is possible.

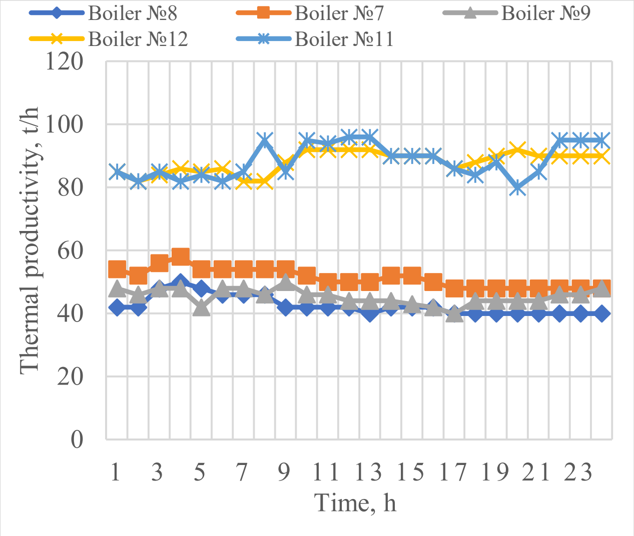

Figure 1 – Change in boiler load during the day

Figure 2 shows the change in the boiler load during the year. The load in this case is strongly averaged, and the nature of their change is associated with seasonality and downtime in repairs.

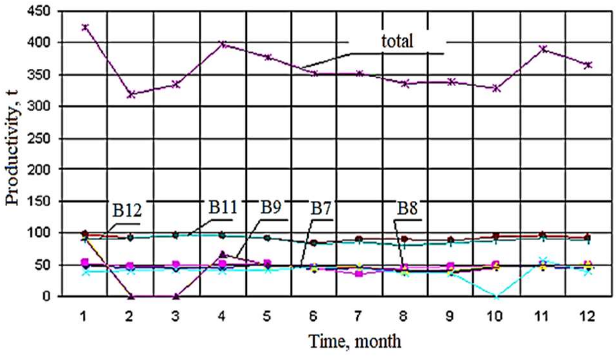

Figure 2 – Boiler load change throughout the year

Due to the strong annual average, it is advisable to analyze the main indicators of daily operation. Figure 3 shows the change in the efficiency of boilers No. 7–9 during the day.

These values were determined by boiler mode maps. Here the change in the average for the three boilers of the efficiency value is calculated. The graph clearly shows the reduction of technical and economic indicators of boilers at 4 a.m. and 4 p.m. This is understandable by reducing the total load when comparing the data in Figure 3. Other "failures" can be explained by the increase of pressure in the gas pipeline of the blast furnace gas (an increase in the thermal fraction of blast furnace gas).

It can also be summarized that all three boilers are significantly different in their technical and economic characteristics.

The average efficiency change interval is 2 % and the maximum is 3 %.

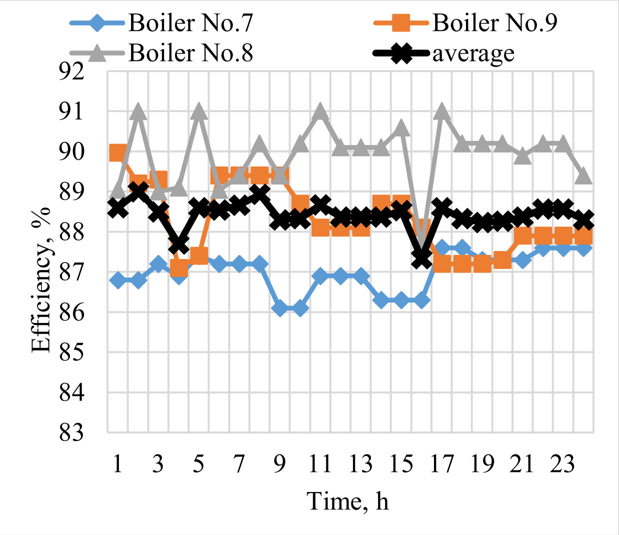

Figure 3 – Change of efficiency of boilers No. 7–9 and average during the day

Efficiency was also calculated from the daily balance sheet data. However, due to various reasons of the objective (inaccuracy of devices, lack of data on the characteristics of fuels) and subjective nature (errors in the reading of information by the operator, etc.), the values of the efficiency were inadequate (range from 60 to 120 %). Therefore, they were not considered for analysis and are not given here.

The foregoing analysis concludes that:

– efficiency must be determined on the reverse balance;

– there is a significant reserve for raising the average efficiency of medium pressure boilers (1.5–2.0 %).

3.3 Analysis of energy characteristics of medium pressure boilers

The notion of energy characteristics of the boiler is defined in the regulation "Revision (Development) of the Energy Characteristics of the Equipment, the Procedure for Determining the Regulatory Specific Losses and the fuel Savings of Energy Companies" (GKD 34.09.151-94) as the main and intermediate indicators of efficiency of its operation, which depend on the mode of operation of the boiler itself. Energy characteristics can be obtained by experimental and calculation methods. Each of these methods has several advantages and disadvantages. A combination of these two methods is required to obtain the operational energy performance of boilers in a wide range of operating modes and with all relevant factors in mind.

The use of calculated dependencies requires the determination of efficiency and fuel costs (fuel costs), depending on the variable variables.

The main energy characteristic of the boiler is the dependence of the efficiency on the load (specific consumption – inversely proportional). It has a specific character. This dependence is confirmed by a number of experimental studies. Figure 4 shows the dependencies for the LMZ-90 boilers installed at the Azovstal plant according to the technical report "Ecological - Heat Engineering Tests of the Boiler LMZ-90 PEVS, in 2001).

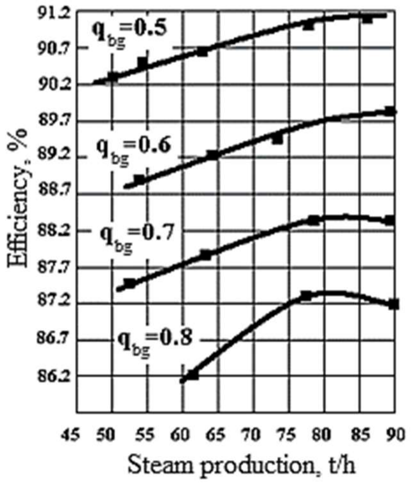

Figure 4 – Dependence of gross efficiency on load for the LMZ-90 boiler

These results confirm the existence of a maximum on the energy characteristic. In some works, this dependence is explained by the nature of the change in the components of the load loss:

$$\eta_b = 100 - q_2 - q_3 - q_4 - q_5, \tag{1}$$

where q_2 – heat loss with gases; q_3 – heat loss with a chemical burn; q_4 – heat loss with mechanical burn; q_5 – loss of heat to the environment:

$$q_5 = q_l \cdot D/D_l. \tag{2}$$

The nature of these dependencies for boilers is shown in Figure 5.

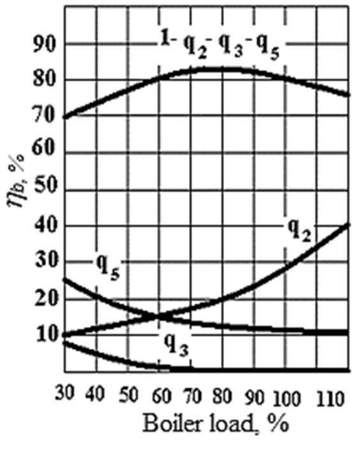

Figure 5 – The nature of the overall load efficiency

On the one hand, the value of q_2 within a 40 % change in load changes by 3–4 %, and the value of q_5 is defined as $q_5 = q_l\, D/D_l$, which is equal to the absolute change of losses by 0.4-0.8%. In the vast majority of cases, under normal operation and timely adjustments, the magnitude of the chemical incinerator losses is negligible or close to zero. Therefore, in expression (1), $q_3 = 0$ is considered in all cases according to GKD 34.09.151-94.

Thus, according to expression (3), the boiler efficiency in the load range changes by 0.2 % in absolute units. However, the results of numerous tests give an interval of values of change of efficiency of 2–3 % in the range of 40 % change in loading rather than nominal. This cannot be explained by the existing simple dependencies of the component of the load loss

To establish the true cause of the dependence of the Efficiency on various factors, to obtain reliable dependencies that consider the individual features of operation in several ways:

a) in-depth analysis of the dependence of the component losses on various factors;

b) on the basis of the thermal and aerodynamic mathematical model of the boiler;

c) based on the use of experimental data.

In this paper a combined approach to this task is made: a mathematical optimization model is developed, adapted on the basis of data obtained experimentally.

According to [11] the value of losses with gases in the industrial combustion of mixtures is defined as:

$$q_2 = K_Q \left\{ \begin{array}{l} \dfrac{1}{p_Q}\left[\begin{array}{l} \dfrac{t_{ex.g}}{100}\left(3035+9.34\cdot RO_2^{\max}+3524\cdot p_{H_2O}\right)+ \\ +\left(\dfrac{t_{ex.g}}{100}\right)^2\left(22.5+1.4\cdot RO_2^{\max}+51\cdot p_{H_2O}\right)+23\cdot p_{H_2O}+28 \end{array} \right]+ \\ +\dfrac{p_b}{p_Q}\left[\begin{array}{l} \left(\alpha_{ex.g}-1\right)\cdot\left(3113\dfrac{t_{ex.g}}{100}+28.7\cdot\left(\dfrac{t_{ex.g}}{100}\right)^2+20\right)- \\ -\left(\alpha_{ex.g}\cdot\left(31.5t_{c.a}+13\cdot10^{-4}t_{c.a}{}^2\right)\right) \end{array} \right] \end{array} \right\} \tag{3}$$

where $t_{ex.g}$ is the temperature of the exhaust gases; $t_{c.a}$ – cold air temperature; RO_2^{max} is the maximum content of triatomic gases in the source gases; P_{H2O}, K_Q, P_b, P_Q, are the fuel invariants of the mixture; $\alpha_{ex.g}$ is the coefficient of excess air in the exhaust gases.

Since 1986, according to "Instructions on Technology for Monitoring Heat Loss with Flue Gases and Efficiency of Power Units" at PTP Ukrenergochermet (Kharkiv, Ukraine), when burning a two-component mixture of blast furnace and natural gases the value of invariants is:

$$\begin{aligned} p_{H_2O} &= 0.38 + 0.013\cdot RO_2^{\max} \\ p_Q &= 1385 - 28.3\cdot RO_2^{\max} \\ p_b &= \frac{41 - RO_2^{\max}}{41 - 20.9\cdot 0.69} \end{aligned} \tag{4}$$

the RO_2^{max} characteristic for the mixture is defined as:

$$RO_2^{\max} = 100\,\frac{V_{RO_2}^{oDG}x_{DG} + (1-x)V_{RO_2}^{oNG}}{xV_{\text{сг}}^{oDG} + (1-x)V_{\text{сг}}^{oNG}} \quad (5)$$

where x is the volume fraction of blast furnace gas in the mixture; V_{dg} – volumes of dry gases at combustion of blast furnace and natural gases respectively; V_{RO2} – volumes of triatomic gases at combustion of blast furnace and natural gases respectively.

The values of volumes and dry gases for each of the fuels are determined depending on the composition of the components of the fuel mixture. The technique was developed, tested, and recommended for processing the results of the balance tests at the operation of boilers on multi-fuel mixtures. The values of the invariants (4) are averaged and are independent of the volumetric fuel particles in the mixture.

The magnitude of losses with gases in the industrial combustion of mixtures can be defined as:

$$q_2 = \frac{I_{ex.g} - \alpha_{ex.g} I_{x.a}}{xQ_{bf.g}^{c} + (1-x)Q_{n.g}^{c}} \quad (6)$$

where $I_{ex.g}$ is the enthalpy of gases; $I_{c.a}$ – enthalpy of cold air; $Q_{bf.g}$ – blast furnace gas combustion heat; Q_{ng} – the heat of combustion of natural gas.

Calculations of heat losses with gases by formulas (3) and (6) showed that the differences between them increase with the increase of the share of blast furnace gas in the mixture. Calculations with average invariants according to the formulas (7) without considering the volume fraction of components in the mixture give a significant difference compared to the calculation of the same invariants and considering the real characteristics of the combusted mixture.

Since 1998, environmental heat losses were determined by the formula from the normative method of "Thermal Calculation of Boilers" ("NPO CKTI", Saint-Petersburg):

$$q_5 = \frac{D_{nom}}{D}(0.818 - 0.001128D_{nom} + 0.000000934{D_{nom}}^2 + +0.000000000134{D_{nom}}^3) \quad (7)$$

where D_{nom} the bottom is the nominal steam capacity of the boiler; D is the actual boiler load.

Thus, a more accurate technique (cumbersome for rapid manual processing of test results), with the use of modern modeling methods, gives better results and allows you to identify the main dependencies more deeply. It is considered as the basis for the construction of a mathematical model and optimal load distribution.

4 Results

The analysis of the operation of medium-pressure boilers of CHPP-1 was carried out based on materials obtained during the ecological and thermal-technical tests of the boilers CKTI-75/39F-2-4 No. 7–9, and TP-150 of No. 11, 12 of SU "Promavtomatika", as well as on the three technical reports of the OJSC "MMK named after Ilyich" (Mariupol, Ukraine) "Ecological - Heat Engineering Tests of the Boiler CKTI-75/39F-2-4 (Boiler No. 7–9) of the CHPP-1" (2001–2002).

The primary purpose of the analysis is to identify patterns that affect the operational characteristics of boilers, especially the efficiency of boilers.

Figures 6, 7 show the dependencies of the efficiency of the boilers CKTI-75/39F-2-4 No. 7–9, from loading at different parts of blast furnace gas. The analysis of these dependencies indicates a general pattern in the change in the efficiency of the load: the presence of maximum and nonlinear character.

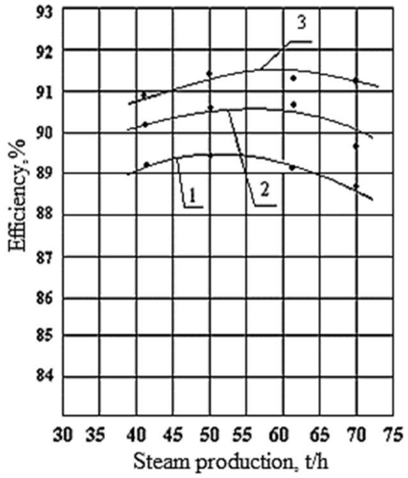

Figure 6 – Dependence of boiler efficiency No. 8 on load at different thermal parts of blast furnace gas: 1 – 0.75; 2 – 0.65; 3 – 0.50.

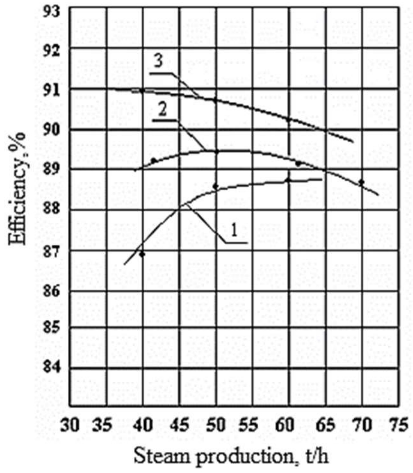

Figure 7 – Dependence of boiler efficiency No. 7–9 on load at blast furnace gas 0.75: 1 – boiler No. 7; 2 – boiler No. 8; 3 – boiler No. 9

All dependencies are individual for each boiler and depend on many factors. The difference between the maximum and minimum values of efficiency in the studied interval reaches 2 %, which is consistent with the conclusions made earlier and speaks in favor of the need for optimal load distribution between boilers. Moreover, the difference is, the greater the proportion of blast furnace gas in the mixture. This is due to the increase of the convective component in the total heat flux with the increase of the blast furnace gas fraction, as well as to the different nature of the effect of air suction on the heat exchange in the furnace and in the convective part of the boiler. By increasing the fraction of blast furnace gas in the mixture, the number of ballast components in the source gases (including nitrogen and carbon dioxide) increases. Such an increase in its effect on the efficiency is equivalent to an increase in the suction pumps in the boiler. Suction pumps reduce boiler efficiency by absolute value.

The result obtained is only partially consistent with theoretical calculations by the normative method. This indicates the need to adjust the calculated dependencies of the mathematical model on the results of field tests. In particular, it concerns the establishment of clear values of the coefficients of the efficiency of the surfaces, the nature and degree of influence of the load on the value of the suction pumps and the output temperatures after the heating surfaces.

Dependences of the exhaust gas temperature on the load can be obtained from the balance tests of the boilers. So Figure 8 shows these dependencies for the CHPP-1 boiler. No. 8.

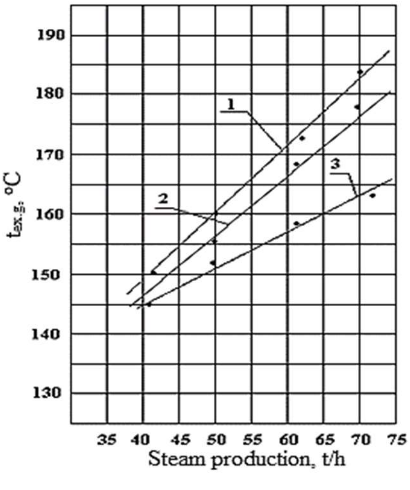

Figure 8 – Dependence of the temperature of the exhaust gases on the load of boiler No. 8 at different thermal particles of the blast furnace gas: 1 – 0.75; 2 – 0.65; 3 – 0.50.

The temperature of the exhaust gases depends on many factors, the most important of which is the condition of the heating surfaces, the coefficients of excess and air suction, as well as the thermal fraction of the fuels.

Figure 9 shows the experimental dependences of the temperature of the exhaust gases of boilers No. 7–9 on the load at the thermal fraction of the blast furnace gas 0.75.

We approximate the curves of Figure 8 by linear dependences of the exhaust gas temperature on the performance and thermal fraction of the blast furnace gas, we obtain:

– for CKTI-75/39F-2-4 boiler No. 7:

$$t_{ex.g} = 149.3 + 0.6D\,; \tag{8}$$

– for CKTI-75/39F-2-4 boiler No. 8:

$$t_{ex.g} = 101.8 + 1.163D\,; \tag{9}$$

– for CKTI-75/39F-2-4 boiler No. 9:

$$t_{ex.g} = 98.56 + 1.16D\,. \tag{10}$$

For CKTI-75/39F-2-4 No. 7, the generalized two-factor linear dependence of the flue gas temperature on the performance and the fraction of blast furnace gas has the form:

$$t_{ex.g} = 194.24 - 1.423D - 38.19X_{bf.g} + 2.23DX_{bf.g} \tag{11}$$

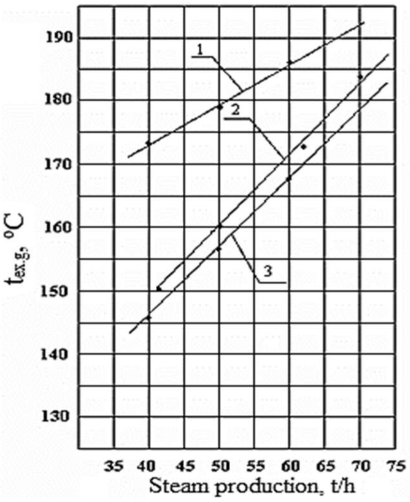

Figure 9 – Dependences of the temperature of the exhaust gases of boilers No. 7–9 on the load at thermal fraction of blast furnace gas 0.75: 1 – boiler No. 7; 2 – boiler No. 8; 3 – boiler No. 9

In the general case, the temperature of the exhaust gases depends not only on the load of the boiler and the thermal fraction of the fuels, but also on the coefficient of excess air in the exhaust gases, the temperature of cold air, the combustion heat of the fuels of the mixture, etc. Such dependence can be shown in the form:

$$\eta_b = f(D, X_{bf.g}, \alpha_{ex.g}, t_{c.a})\,. \tag{12}$$

In this formula, the efficiency is uniquely related to the following performance characteristics:

– boiler productivity;

– characteristics of fuels (composition and humidity) and their thermal particles;

– coefficient of excess air;

– cold air temperature;

– air suction in the furnace and on the heating surfaces.

The formula calculates the efficiency calculations for some modes of operation of boiler No. 9. The results of these calculations were compared with the regimes of daily data. The regimes were taken as the basis of information every hour. According to the information, the load of the boiler and the thermal fraction of blast furnace gas in the mixture were selected. The composition and combustion heat of the blast furnace and natural gases are taken as averaged according to the data from the blast furnace workshop.

The coefficients of excess and suction on the surfaces were determined by gas analysis.

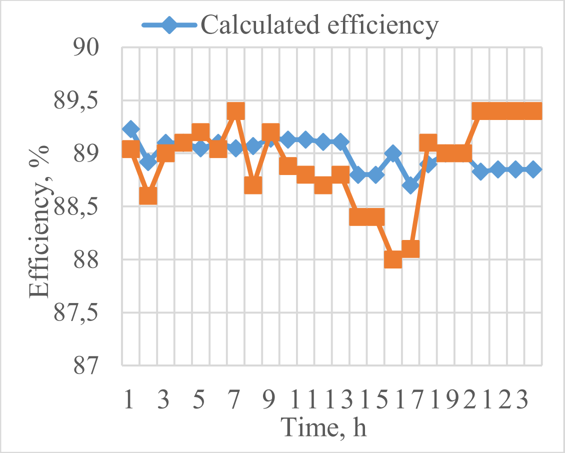

Figure 10 – Comparative values of boiler efficiency No. 9.

For comparison, the efficiency of the mode map for the same modes of daily data were determined.

5 Conclusions

The proposed dependencies allow with a sufficient degree of accuracy to determine the efficiency of boilers, depending on the composition of fuels, thermal fraction of blast furnace gas, load, suction, coefficient of excess air, cold air temperature. Dependencies were obtained, which allow us to calculate all intermediate modes not specified in the mode map. The calculated dependences completely correspond to the experimental data and confirm the individuality of the energy characteristics of the boilers. Boiler efficiency highly depends on loading conditions. More efficiently, the efficiency depends on the thermal fraction of the blast furnace gas, which speaks in favor of the need for comprehensive optimization of operating modes.

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